EP-DT
Detector Technologies

VERTEX/2017
The 26th International Workshop on Vertex Detectors

Advanced Cooling Techniques

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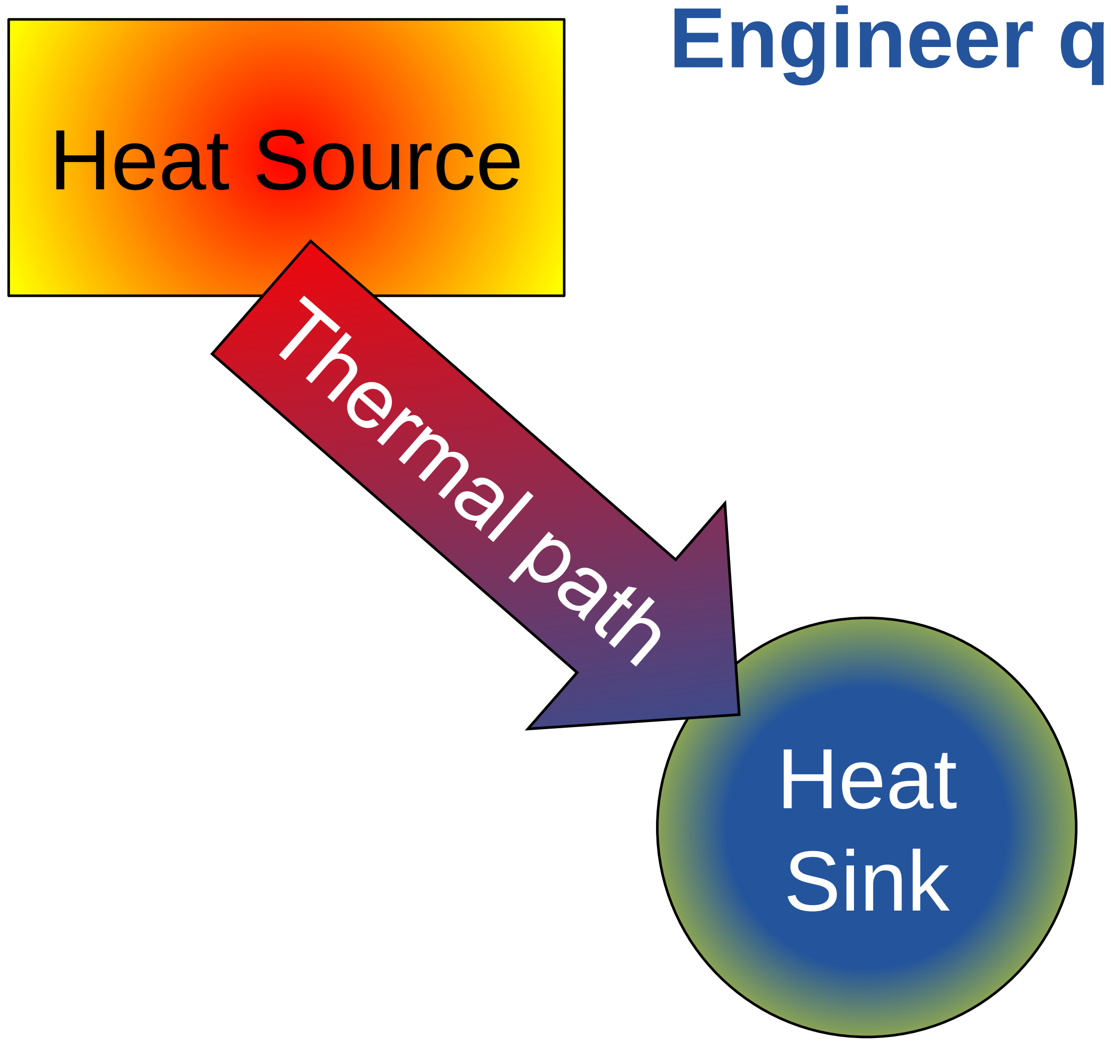
VERTEX/2017

Las Caldas 11-15 September 2017

Thermal management of electronics

Electronics produces heat during operation: recent technical advancements following the explosion of micro- and nano-technologies greatly help in reducing power consumption but they also push towards implementing more functionalities, more speed, more "intelligence" in the chips, therefore increasing the power.

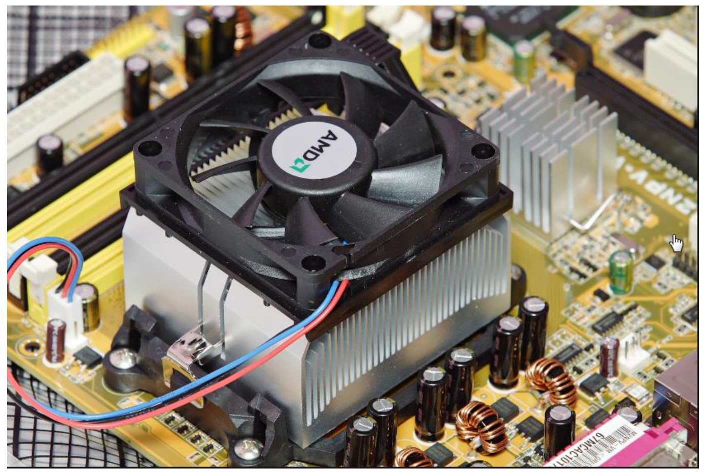
So, the problem of "electronics cooling" basically stays the same:



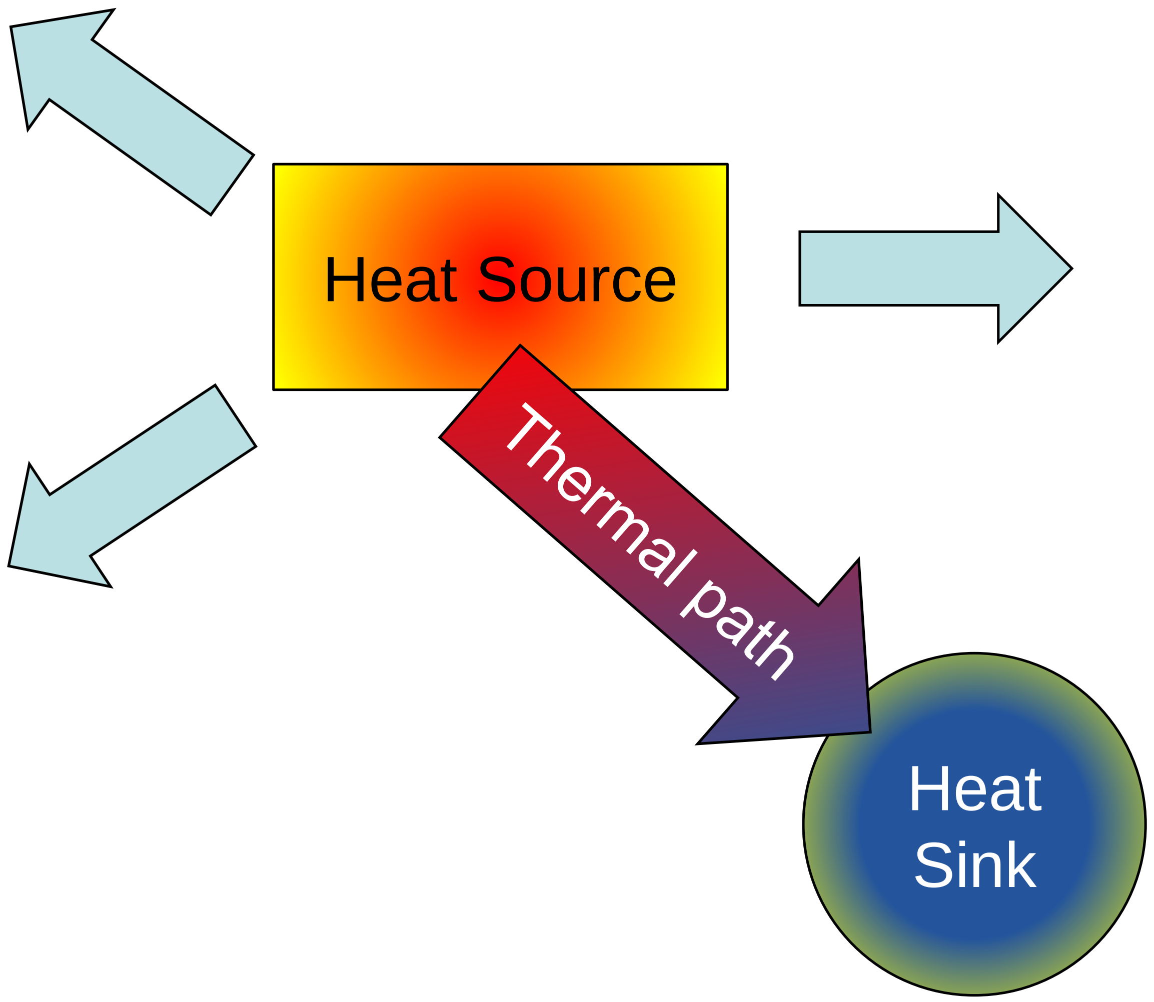
Engineer questions:
Amount of heat produced by the Source?
Max temperature of the Heat Source?
Type of Heat Sink?
Temperature of the Heat Sink?
Position of the Heat Source?
Heat Source / Heat Sink interface?
Space available?
Material issues?
Environmental issues?
Cost issues?
Reliability?
Lifespan?

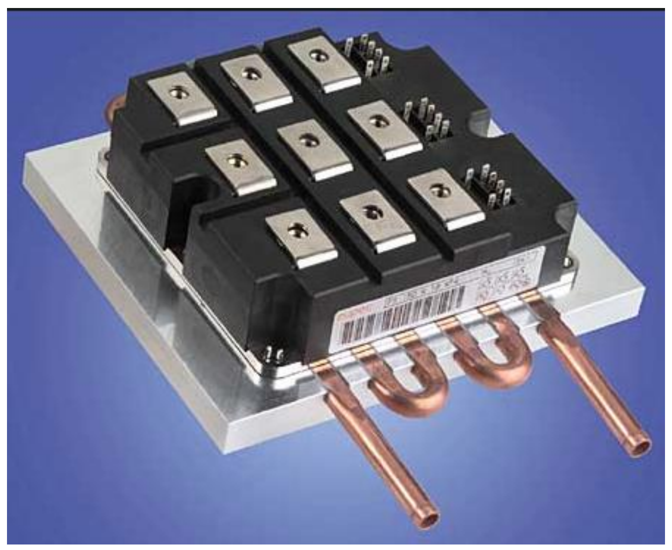
Thermal management of electronics

Based on the answers to the above questions, you can basically find three big classes of approach to the thermal management of electronics (examples shown for high power computing chips, probably the most demanding application in commercial electronics):

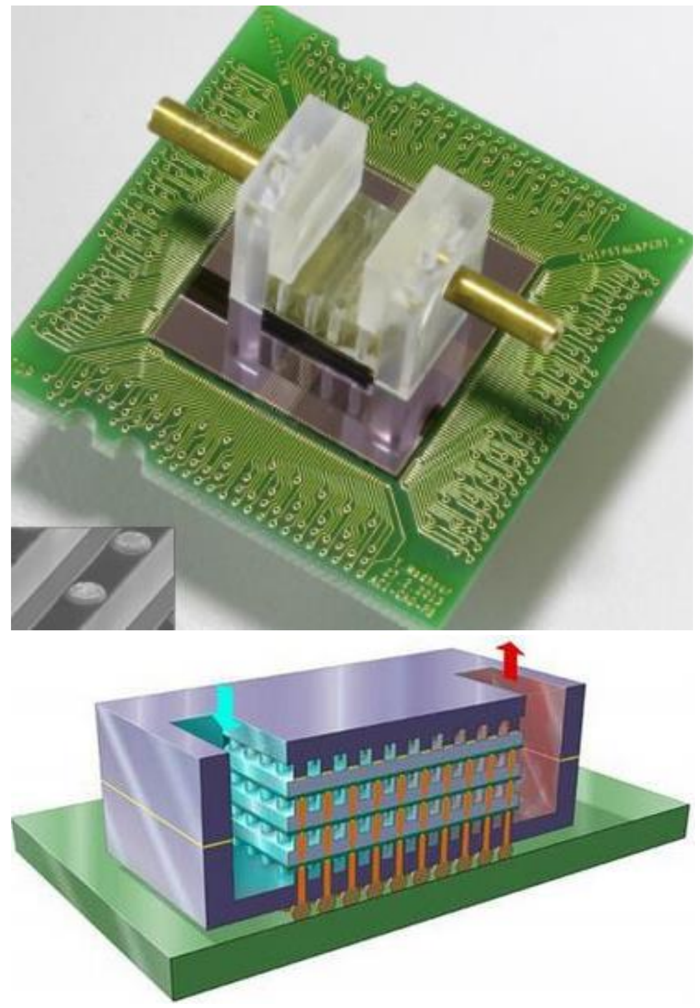


Direct air cooling
(forced convection)





Pipe-flow cooling
(1- or 2-phase)



Micro-channel cooling
(1- or 2-phase)
Or other innovative techniques, e.g. direct spray, pool boiling, etc…

Thermal management of silicon detectors

Modern silicon detectors for HEP pose very specific constraints to the answers to be given to the list of “thermal engineering questions”. This is in particular true for vertex (pixel detectors).

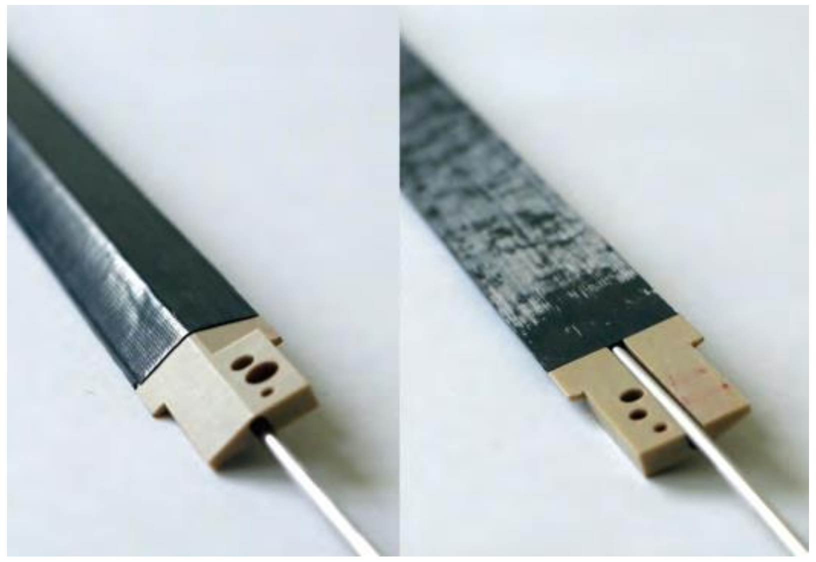
This typically produces the same VOLUME power density $\mathcal{O}(10^2)$ W/dm^3 for both high power electronics and modern pixel detectors

PIXEL DETECTOR SPECIFICITIES :

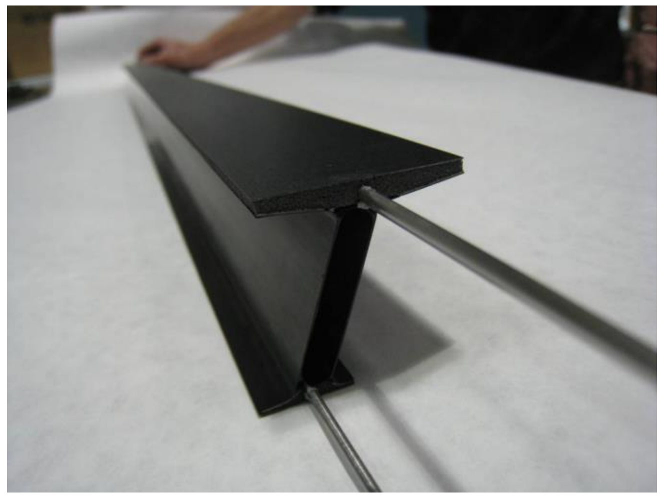
- Low power density per chip but high density of chips
- Material must be minimized in terms of X/X_0
- (@LHC) sensor temperature < 0 ˚C (<< 0 ˚C @ HL-HLC)
- Refrigerant T cannot be lowered at will
- Heat Source highly distributed on convoluted surface
- Source / Sink interface must account for high stability
- Space available usually extremely tight
- Environment: high magnetic field and (@LHC) high radiation
- Absolute reliability
- Typical lifespan of the order of 10 years or more
- Cost issues less critical than in industry (good news!)

Cooling & Structure Optimization

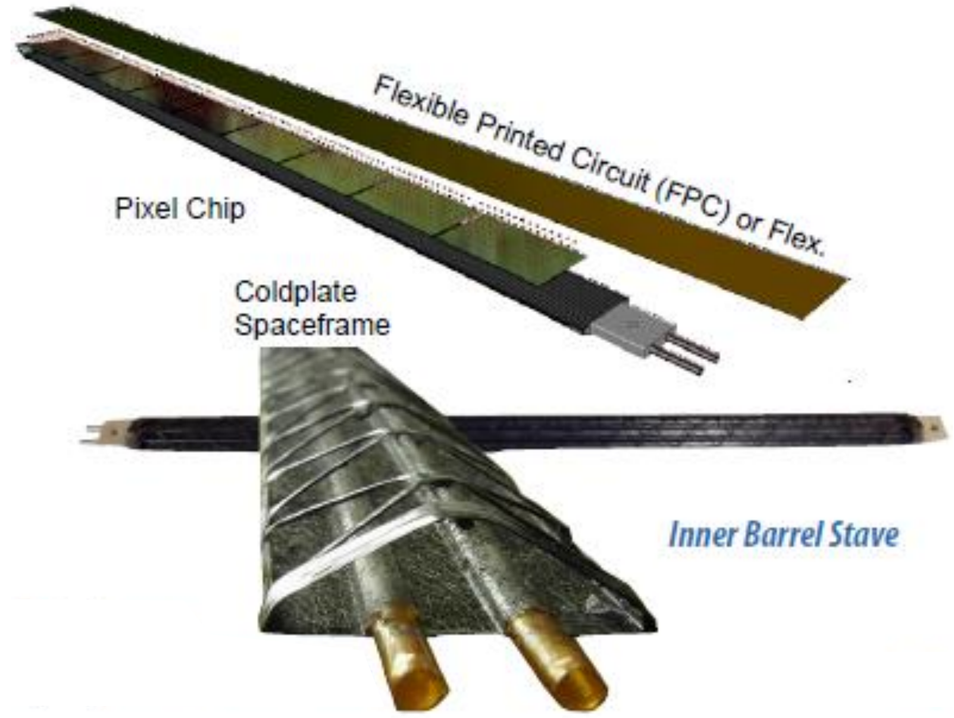
Great attention to early design and integration of optimized support structures and thermal management solutions is **mandatory** for the present and the coming generation of Vertex detectors: not surprisingly all "classes of approach" are represented!



ATLAS IBL

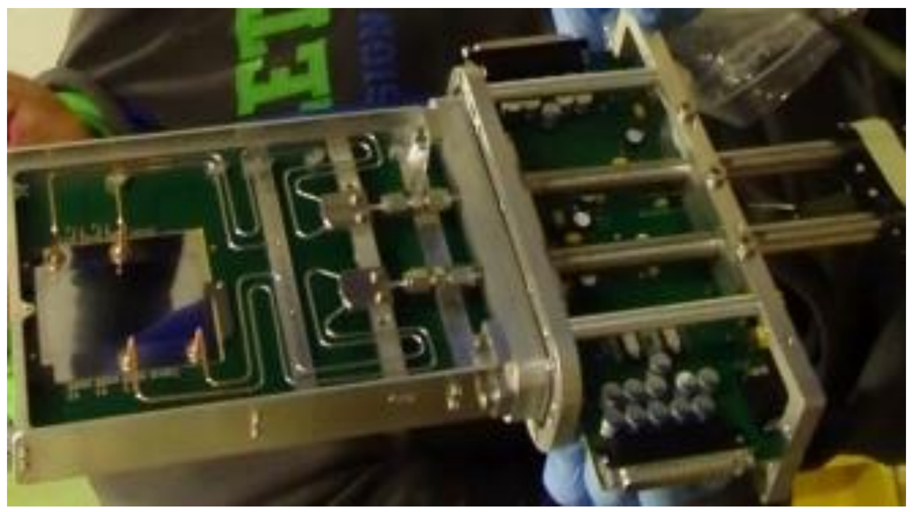


ATLAS PIXEL upgrade (study)

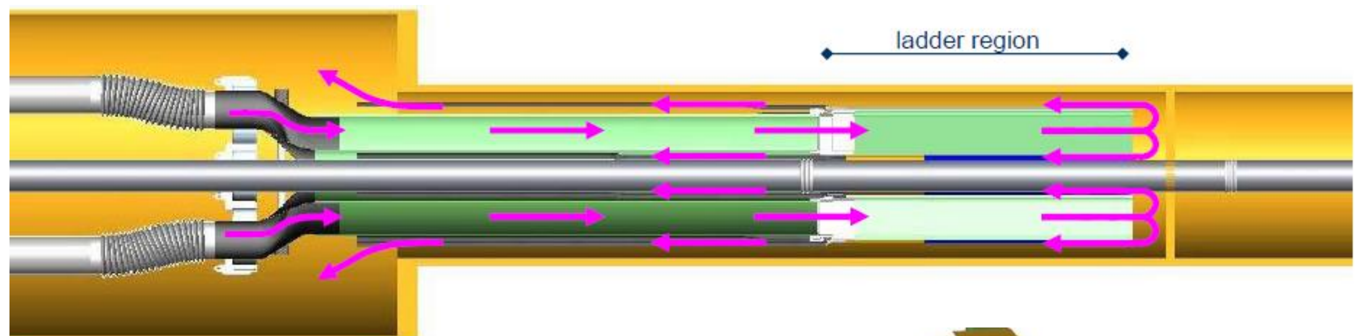


ALICE ITS upgrade

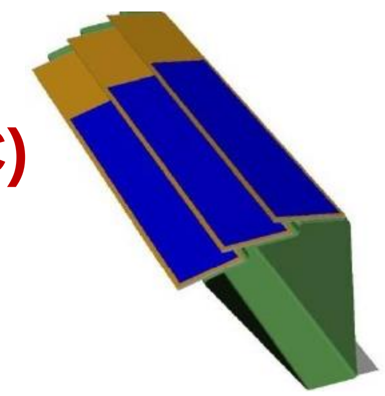
CMS PIX upgrade



NA62 GTK



STAR PXL (@ BNL RHIC)



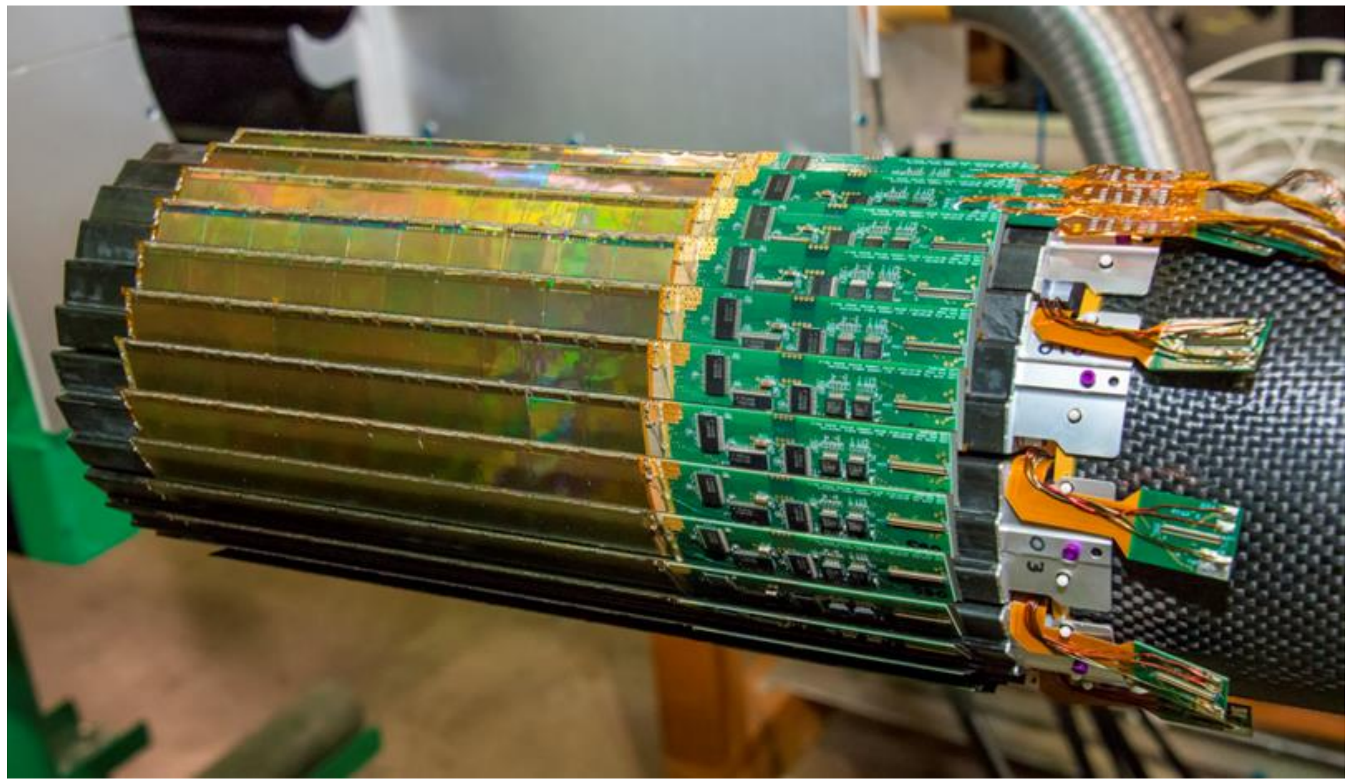
Focus of this talk:

1. Air cooling: the dream solution for minimal X/X_0
2. Integration of cooling and support structure: the adopted compromise for large LHC detector
3. CO_2 evaporative cooling: low temperature cooling standard at LHC / HL-HLC
4. Distributed microchannel cooling: the solution for unparalled thermal performance

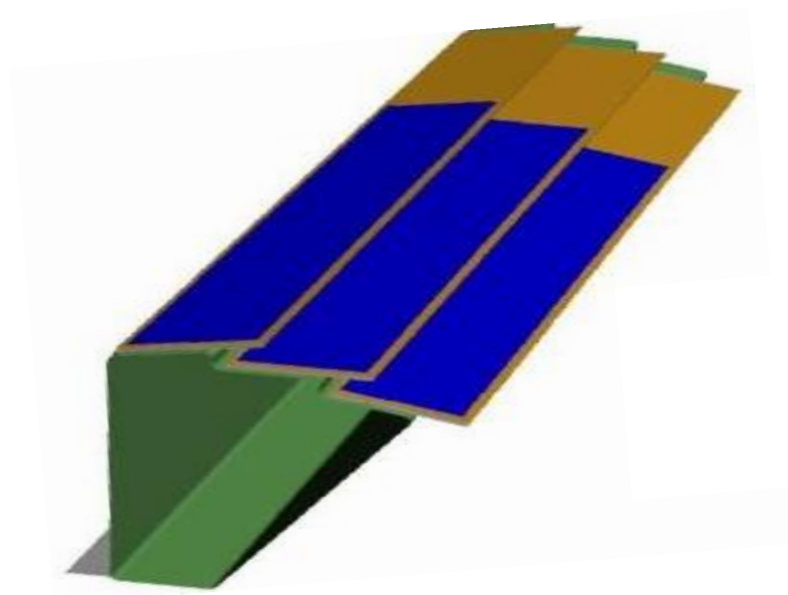
Air Cooling: possible?

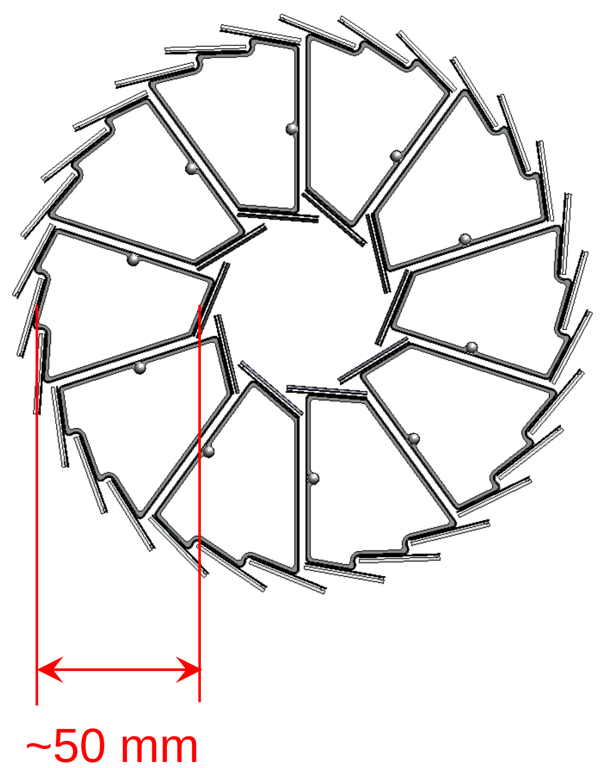
The PXL subdtetector of the STAR HFT @ RHIC is the first silicon detector operating on a collider successfully cooled by air…
But there are very specific conditions for this to work (e.g. studies on the ALICE ITS upgrade failed to provide satisfactory performance).

Details: G. Contin, *MAPS-based Vertex detectors: operational experience in STAR and future Application* (VERTEX2017, Monday afternoon session)



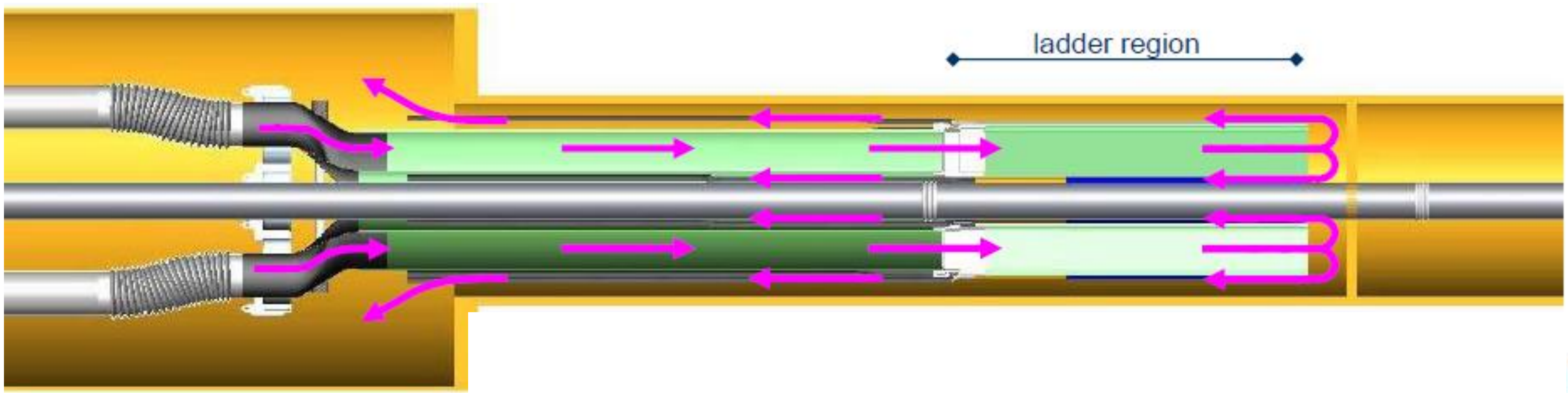
- CMOS MAPS technology
- Goal X/X_0 = 0.37% per layer
- Room temperature operation
- Max T on sensor = 40 ˚C
- Radiation tolerance up to 90 kRad/year
- Fluence $2x10^{11}$ to 10^{12} 1MeV n_{eq}/cm^2
- 1st to 2nd layer gap: **<u>50 mm</u>** (!)

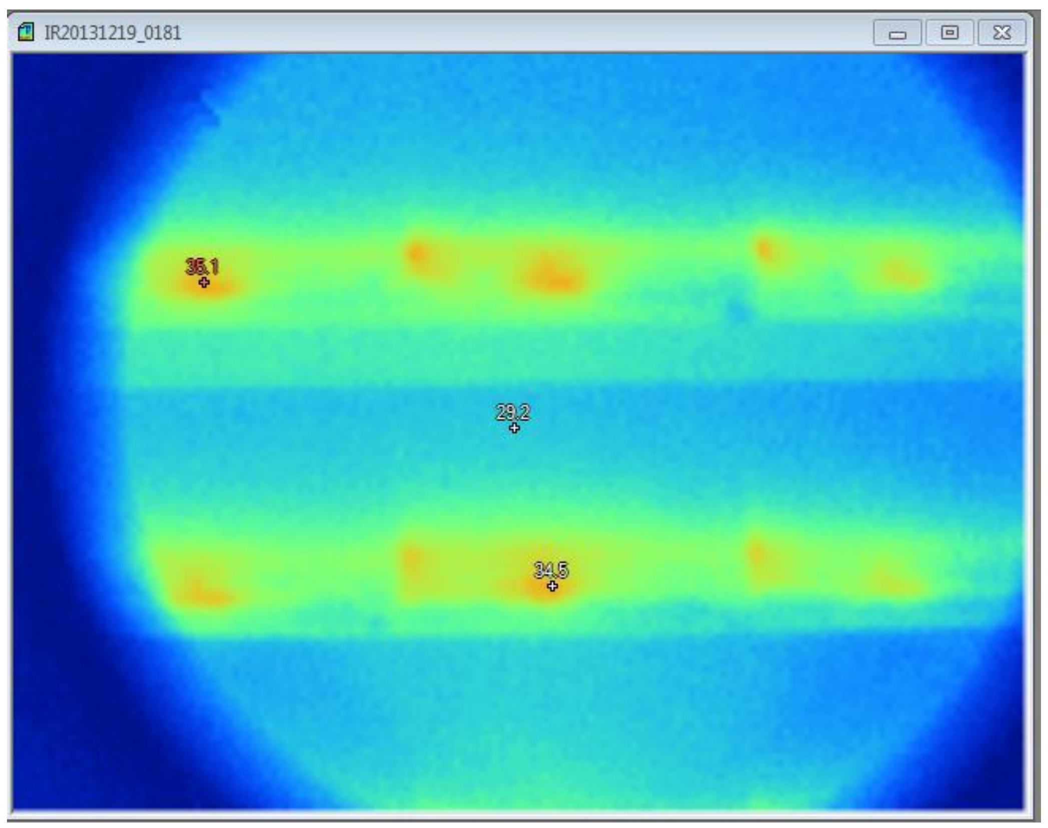




Air Cooling: possible?

The support structure is expressly designed for smooth air flow: the air is conveyed inside the “sector tubes” and then flows directly on top of the outer and inner ladders on its return path to the exit.





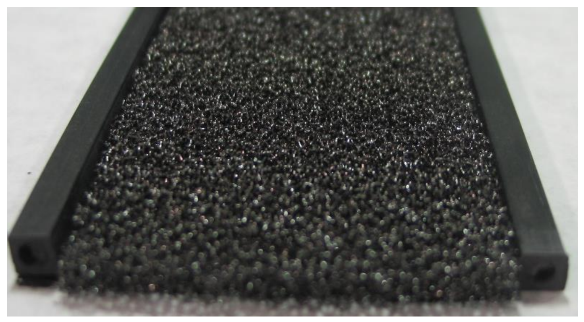
- Chip dissipation = 0.17 W/cm^2
- Total power ~350 W (chips + drivers)
- Air flow T = 23 ±1 ˚C
- Air speed = 10.1 m/s
- ΔT air-detector = 12 - 13 ˚C

Useful parameter:
“Thermal Figure of Merit” (**TFM**) =(ΔT fluid-sensor) / (power density)
(Similar to the R-value - or “insulance” - of an insulating material)
In this case we get: **TFM = ~70 [K·cm^2/W]**

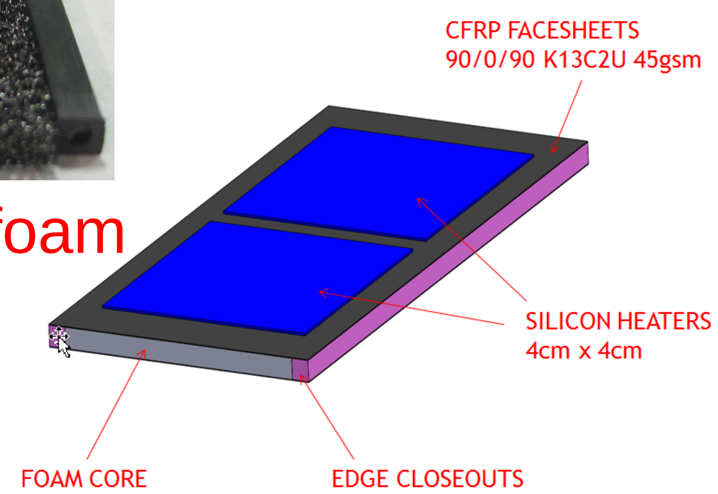
Advanced studies on air cooling at LBL

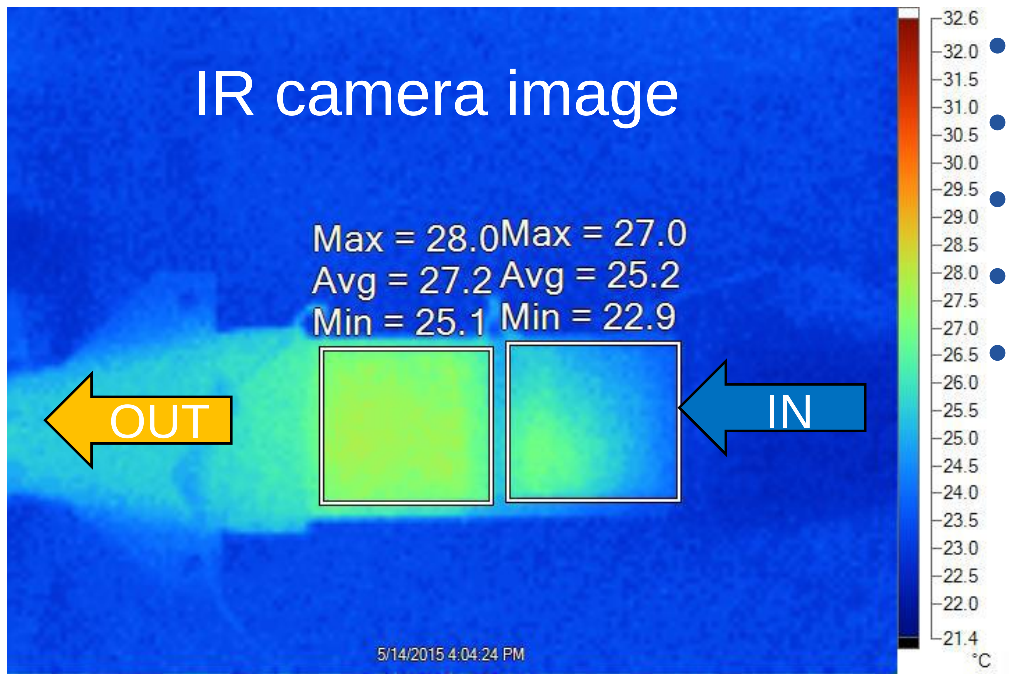
However, "external" air flows require a dedicated geometry and can be extremely susceptible to modified boundary conditions.
Interesting studies are ongoing at LBL on the combination of air cooling with micro-fluidics through carbon foams:

E. Anderssen et al., *Advanced Materials and Tools Research*, Forum on Tracking Detector Mechanics 2015 (Amsterdam, NL): https://indico.cern.ch/event/363327/contribution/34



Allcomp carbon foam (CVD)

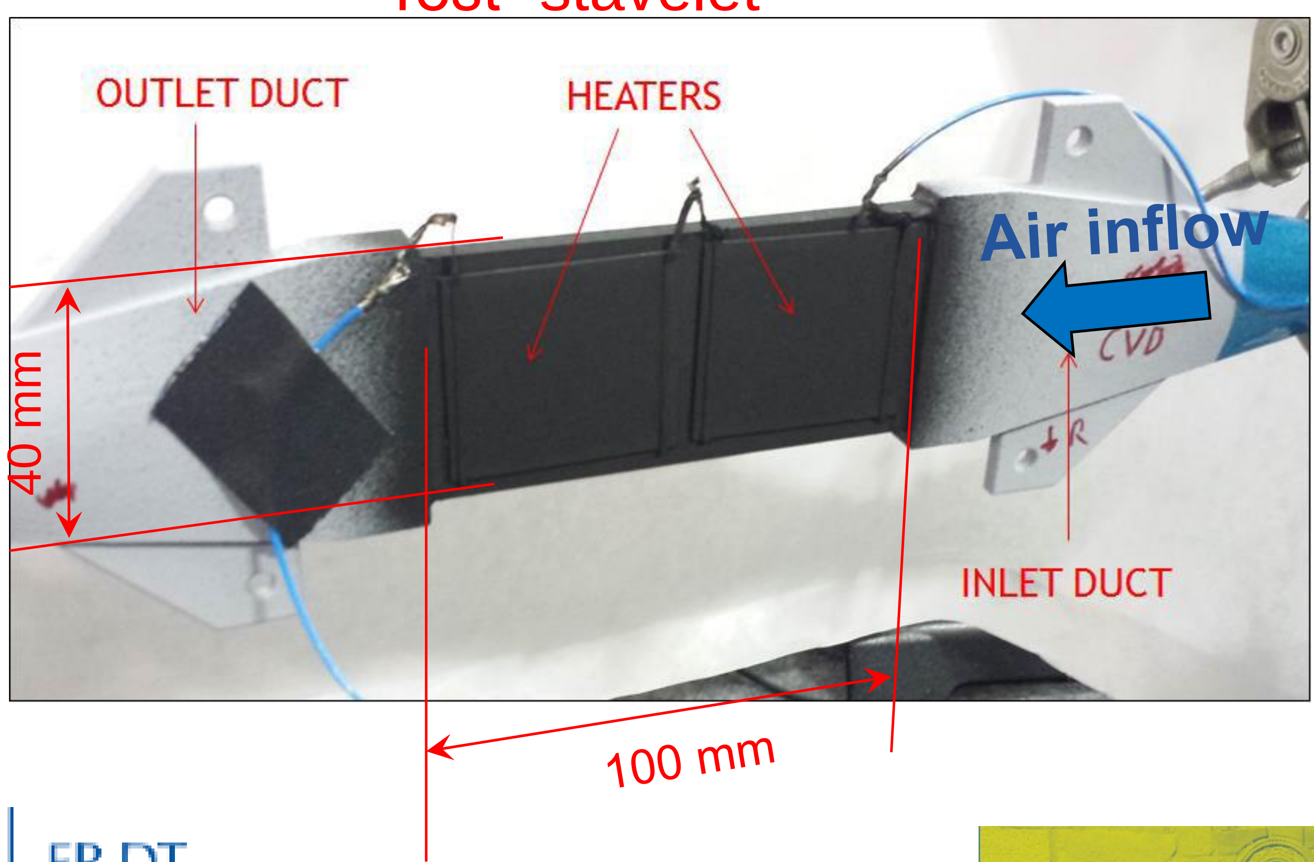


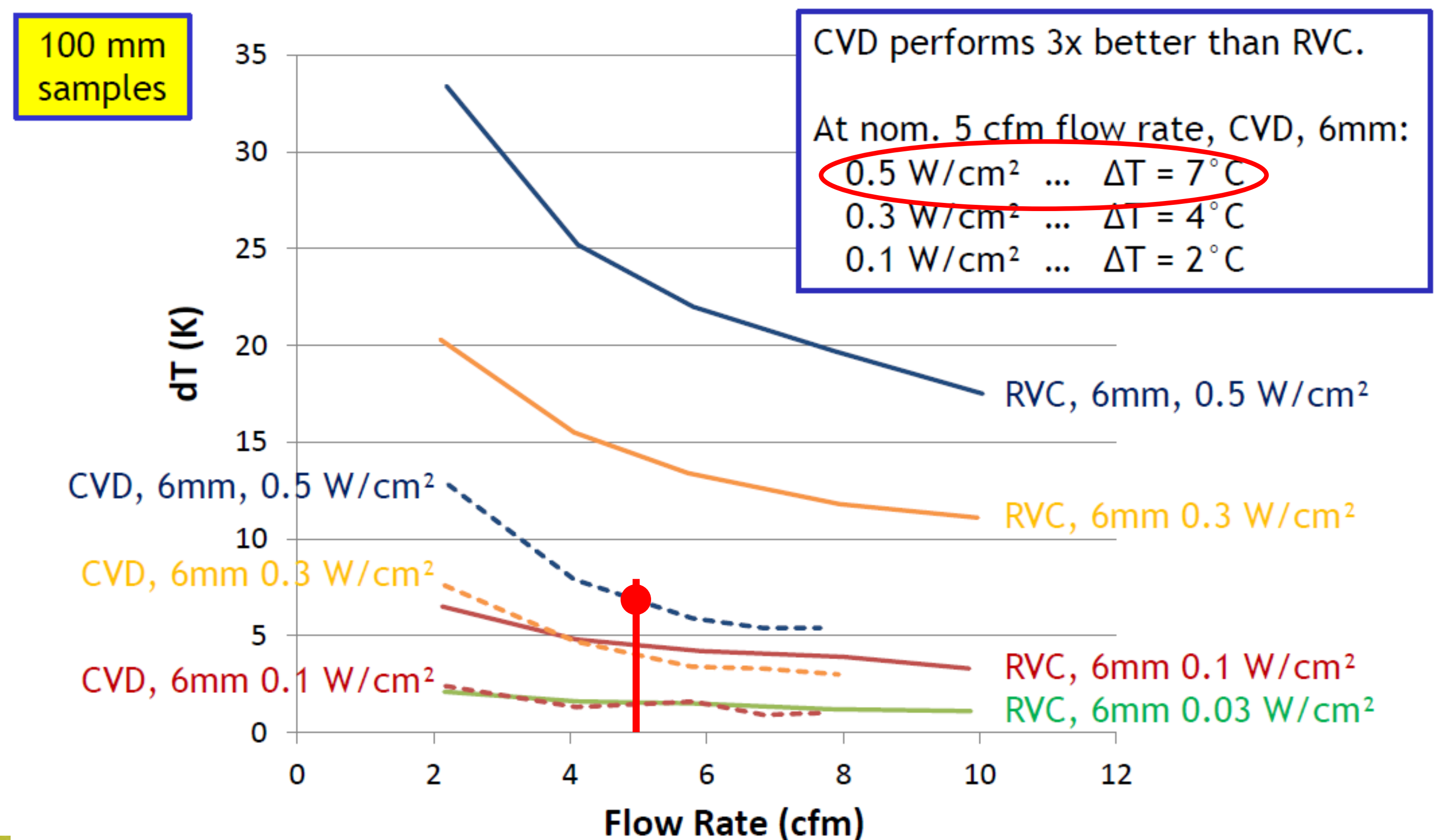


- Room temperature
- Air flow rate = 0.14 m³/min (5 cfm)
- Air speed ~ 10 m/s
- Foam thickness = 6 mm
- Power density = 0.5 W/cm²

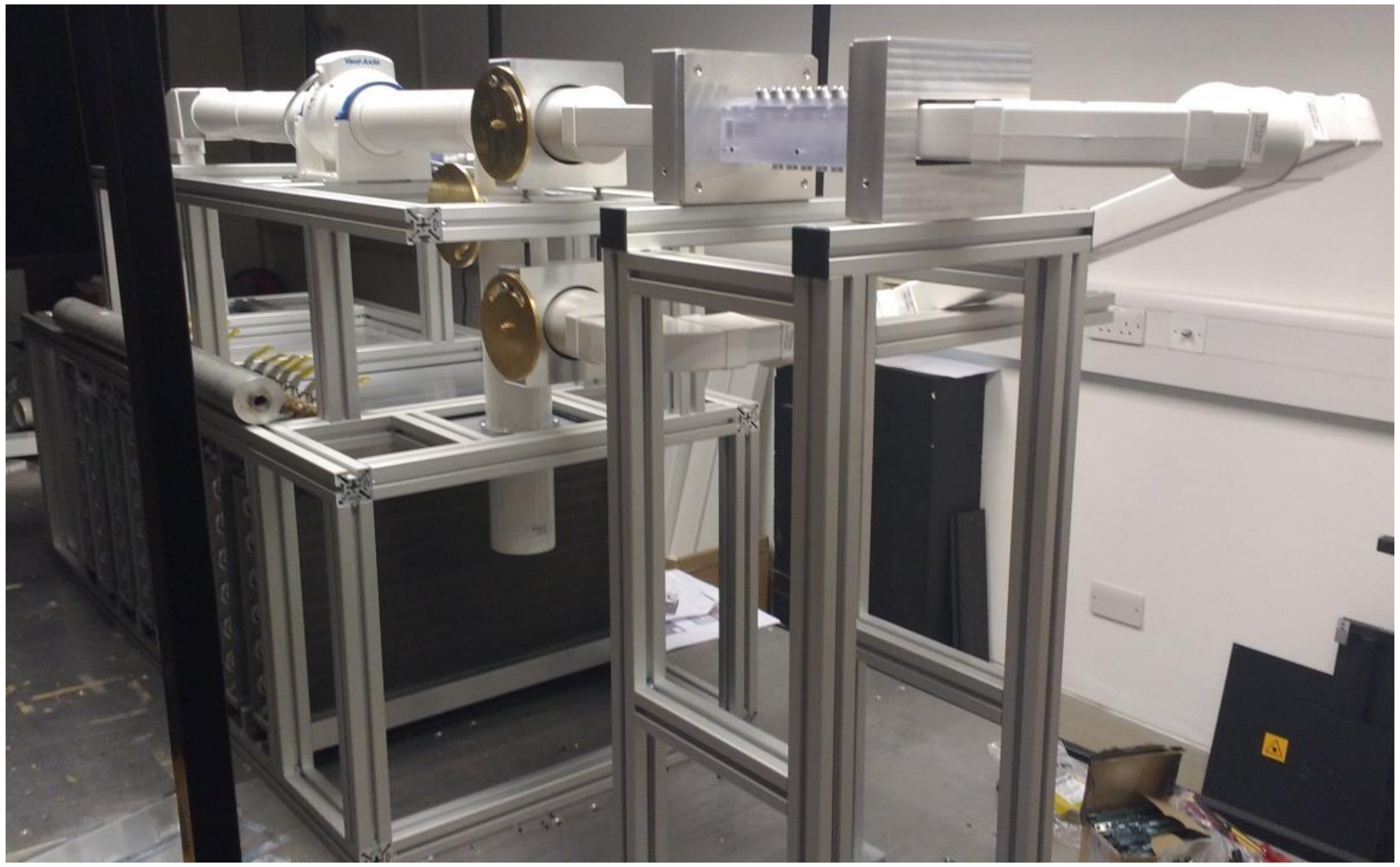
TFM = 14 [K·cm²/W]
(on a 100 mm length)

Test "stavelet"



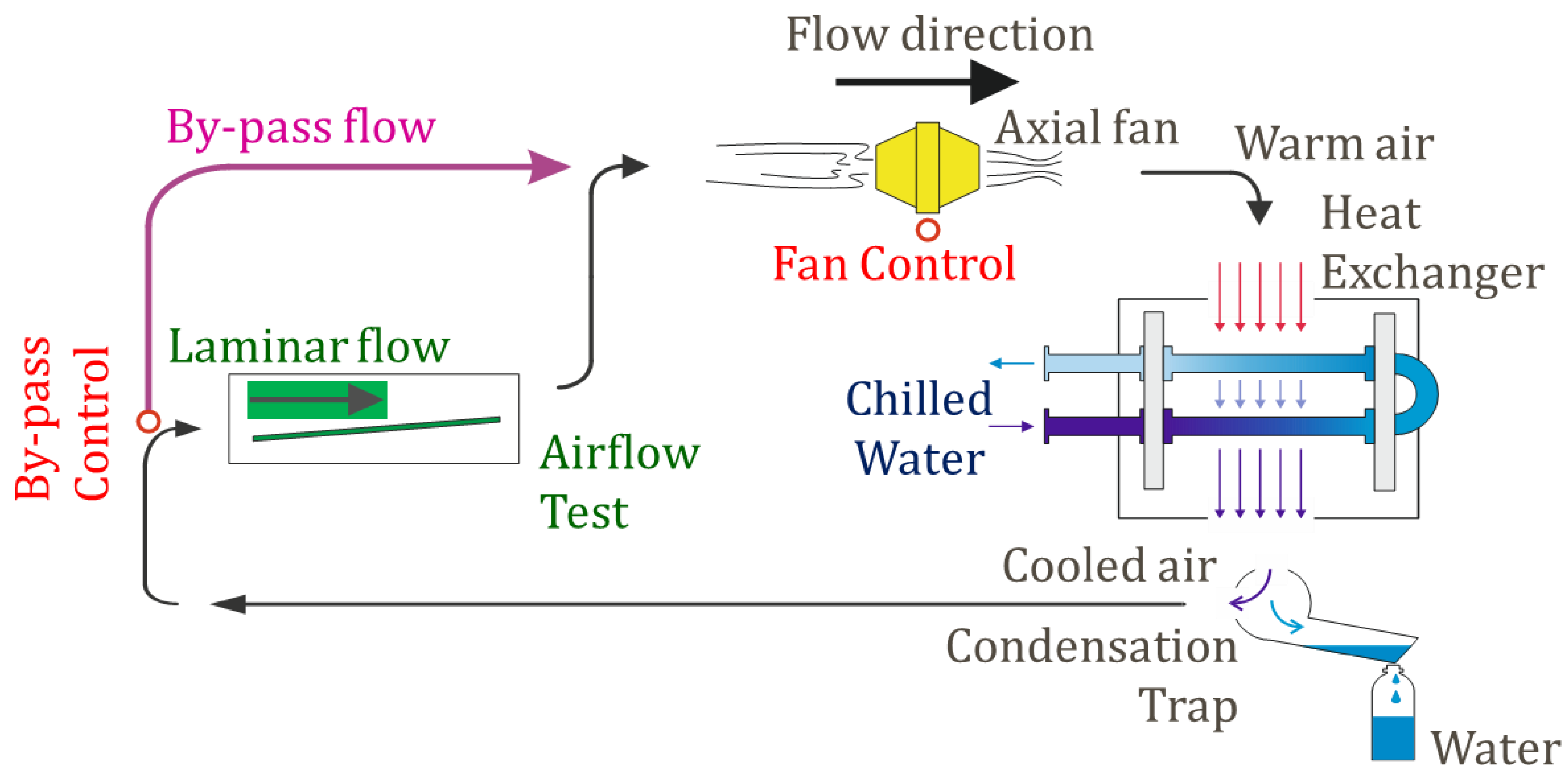


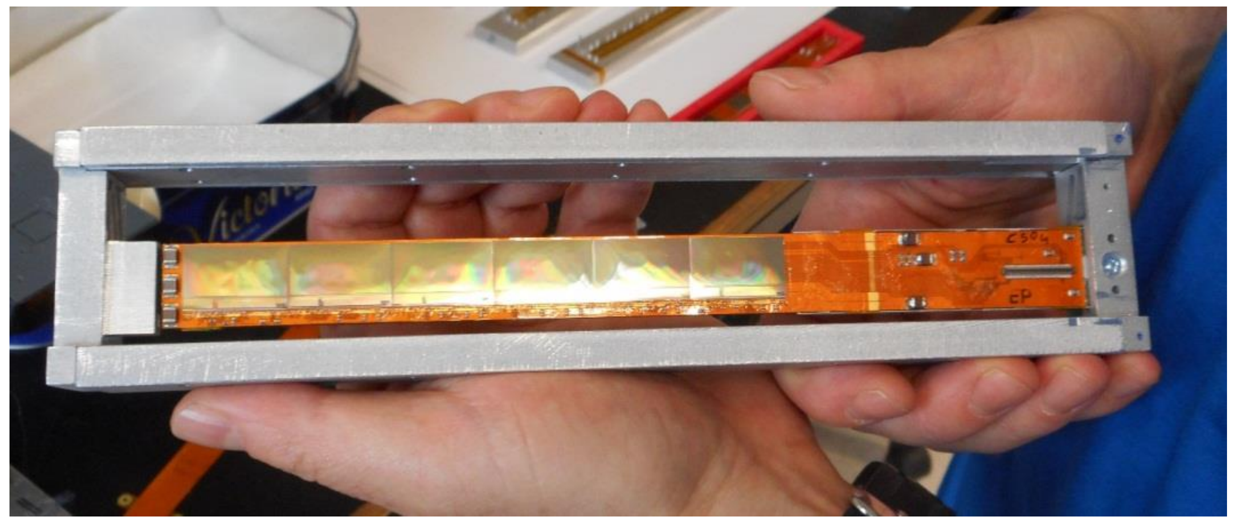
New air cooling test facility (Oxford):



In the context of the WP9 of AIDA-2020 a brand new facility dedicated to detector air cooling testing has been designed and built in Oxford.

The facility is conceived for external access, initially mainly within AIDA-2020 but then to a much wider community



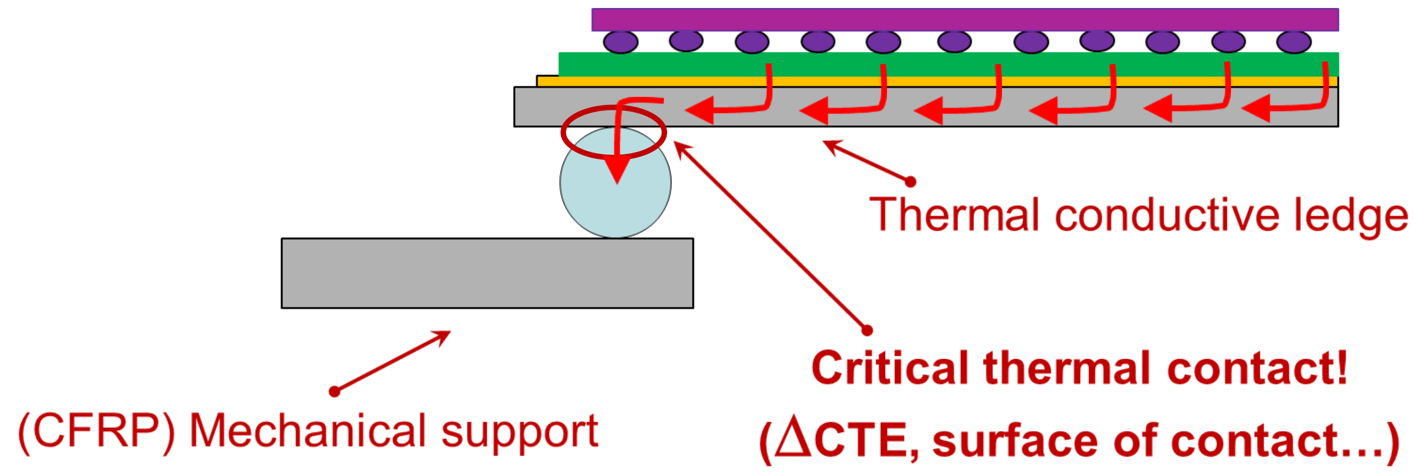


Cooling & Structure Integration

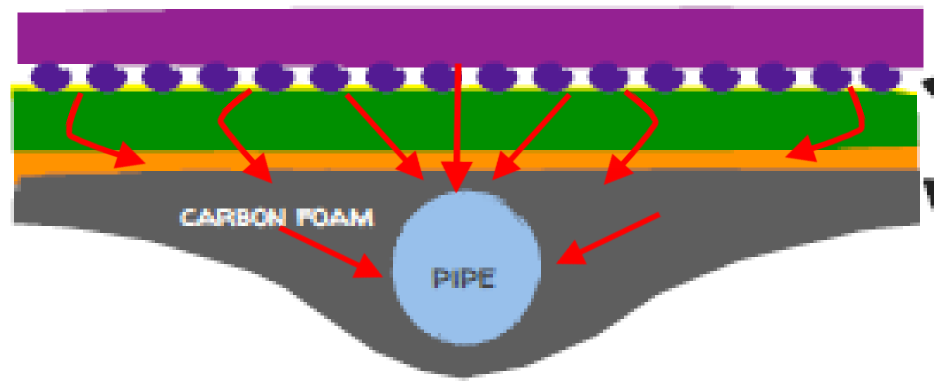
The most diffused and generally effective approach to the thermal management of modern silicon-based Pixel detectors is the integration of cooling and CFRP structures:

"Traditional" approach:

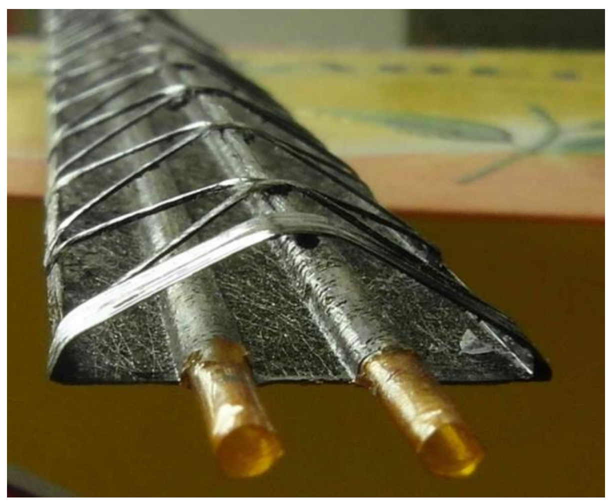
fair enough for STRIPS

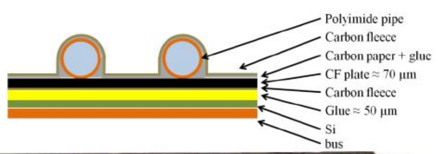


"Integrated" approach



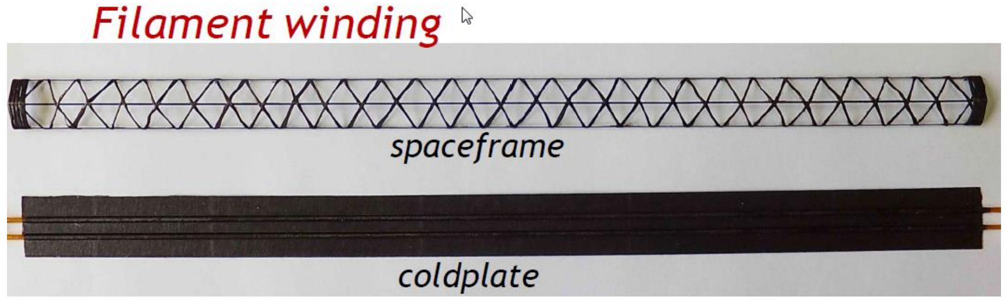
- Integrate the pipe(s) in the structure
- Thermal conductive structure
- Optimize thermal interfaces
- Reduce pipe X/X0

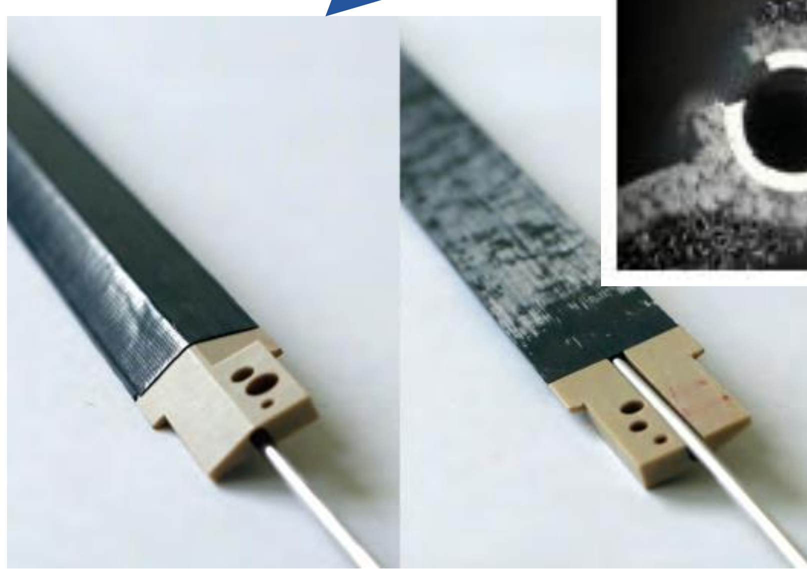


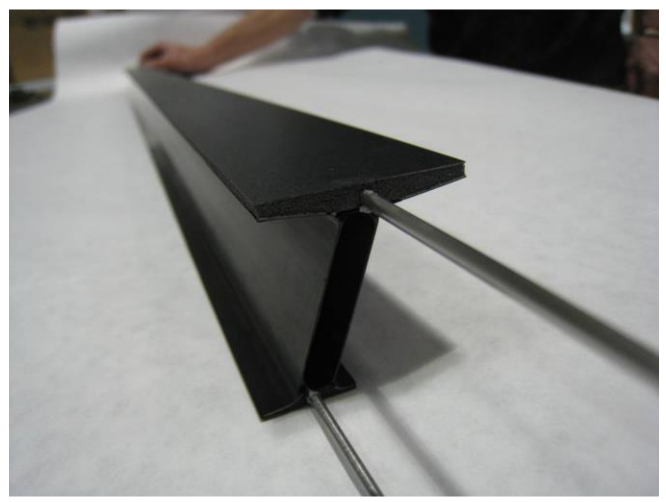


Wound Truss Structure plus Carbon Plate with Embedded Pipes

Filament winding

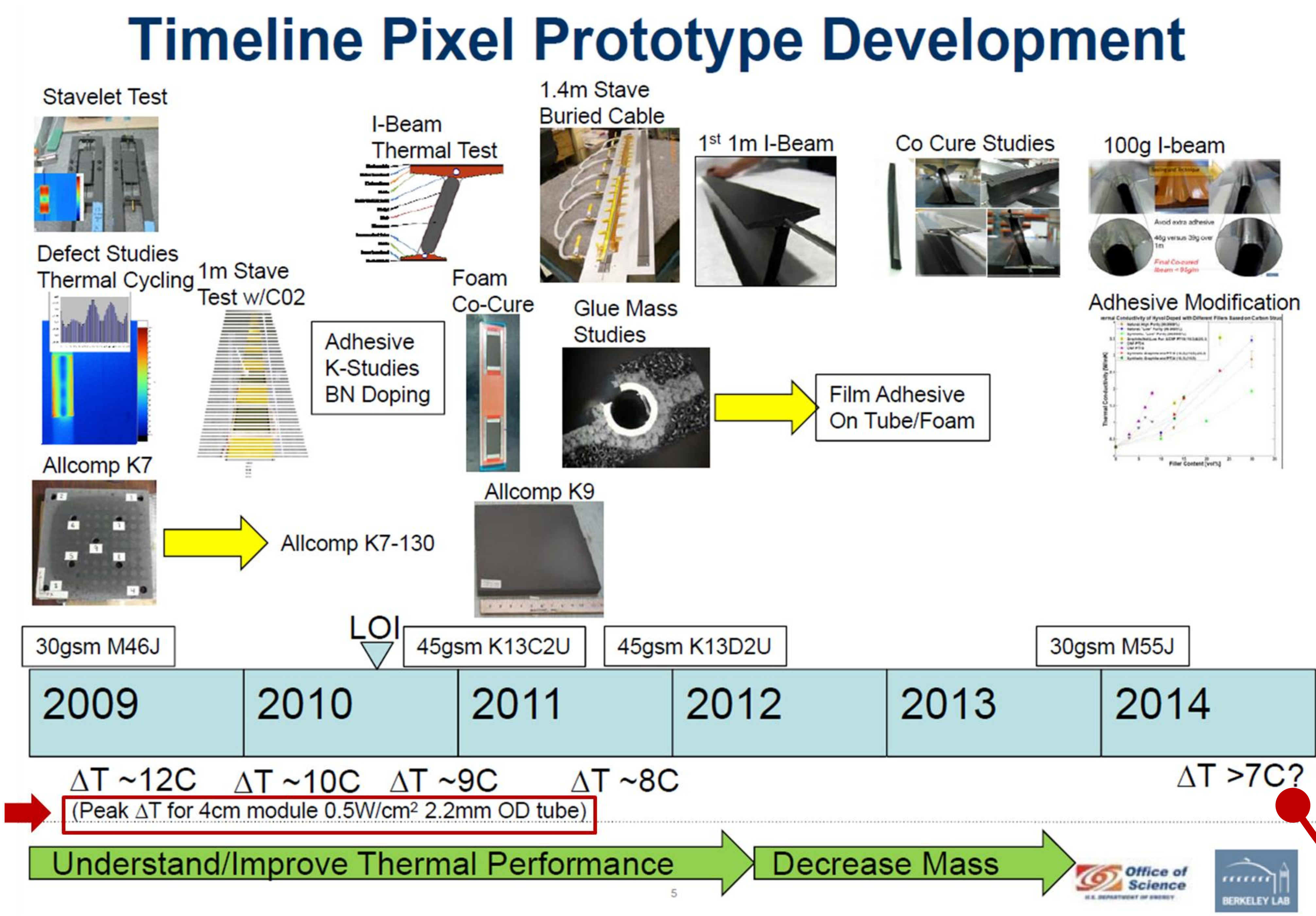




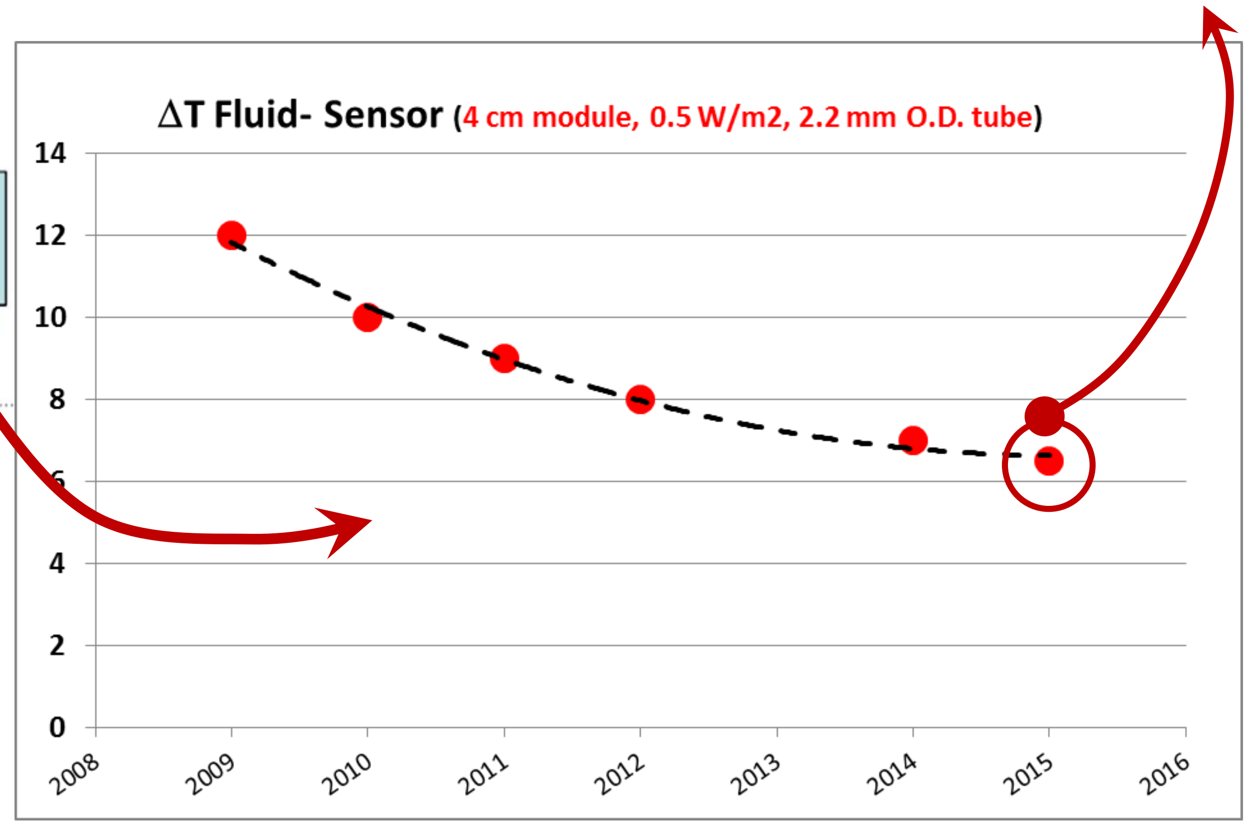


Cooling & Structure Integration

There are however "physiological" limits to the attainable performance.
From the previously quoted presentation by E. Anderssen:



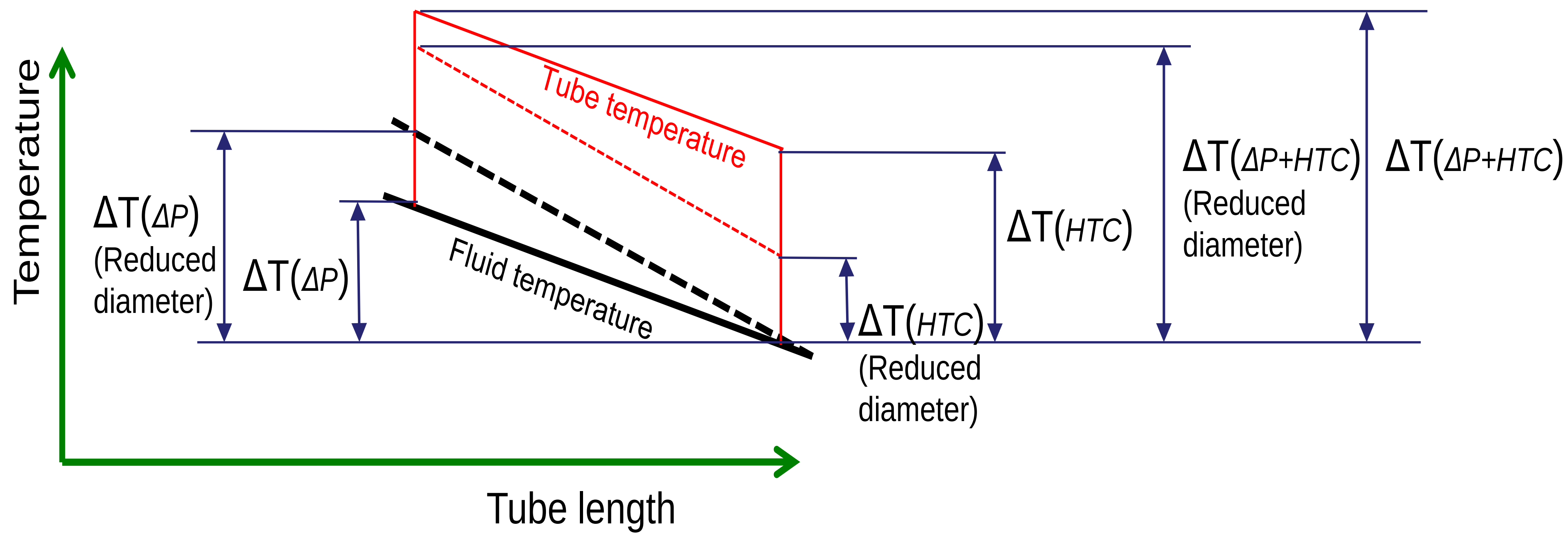
ADDITIONAL POINT
D. Giugni private communication June 2015:
"There are presently indications to about 6.5 ˚C"

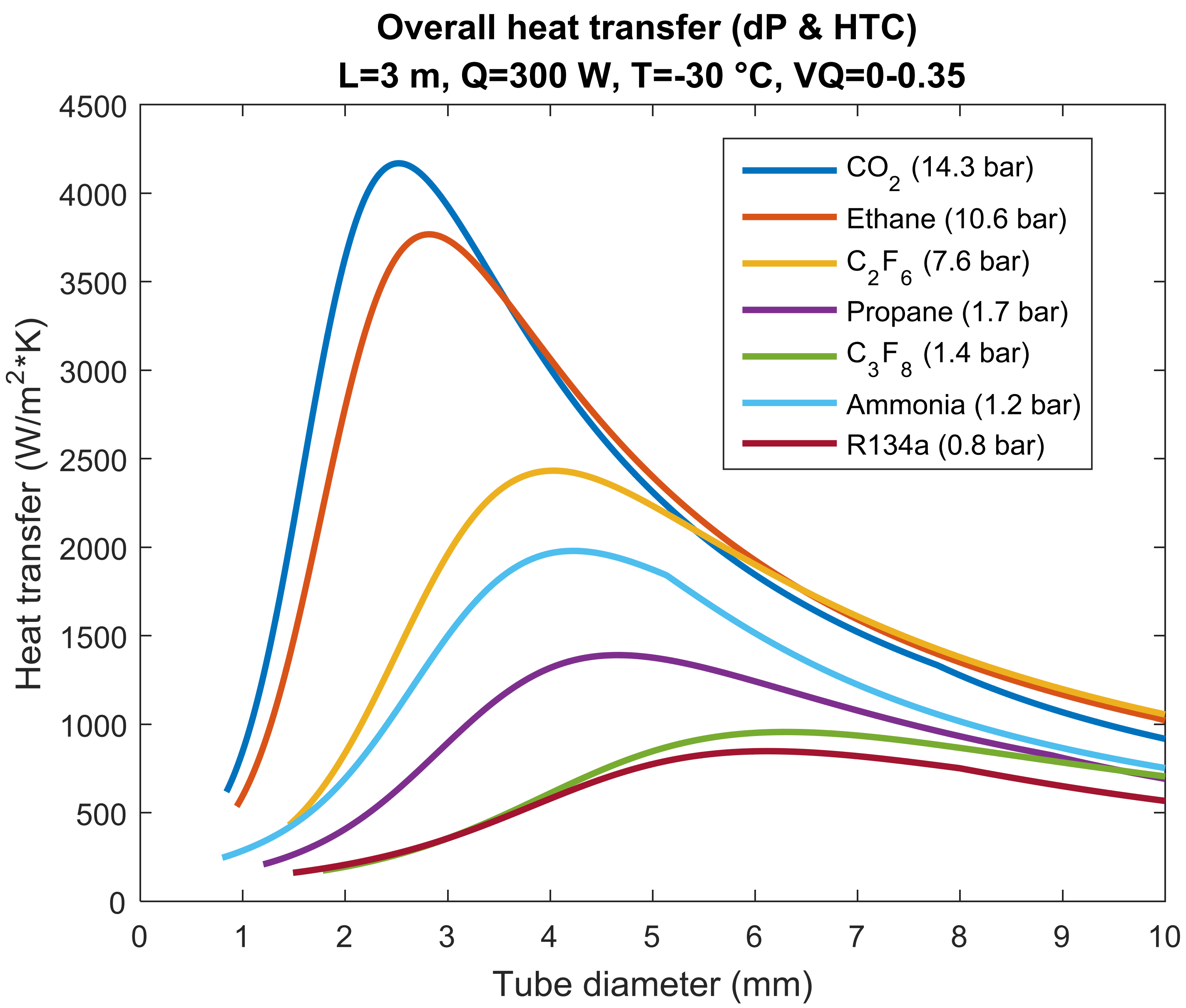


- **Assuming a 2015 best ΔT of 6.5 ˚C for 0.5 W/cm²**
- **One gets a 2015 best TFM performance of 13 [K·cm²/W]**
- **~ Asymptotic value…?**

CO_2 evaporative cooling

For best performance, beside working on the thermal conduction part of the chain, one needs to work on the thermal convection part: look carefully for optimum pipe **Pressure Drop** and **Heat Transfer Coefficient**

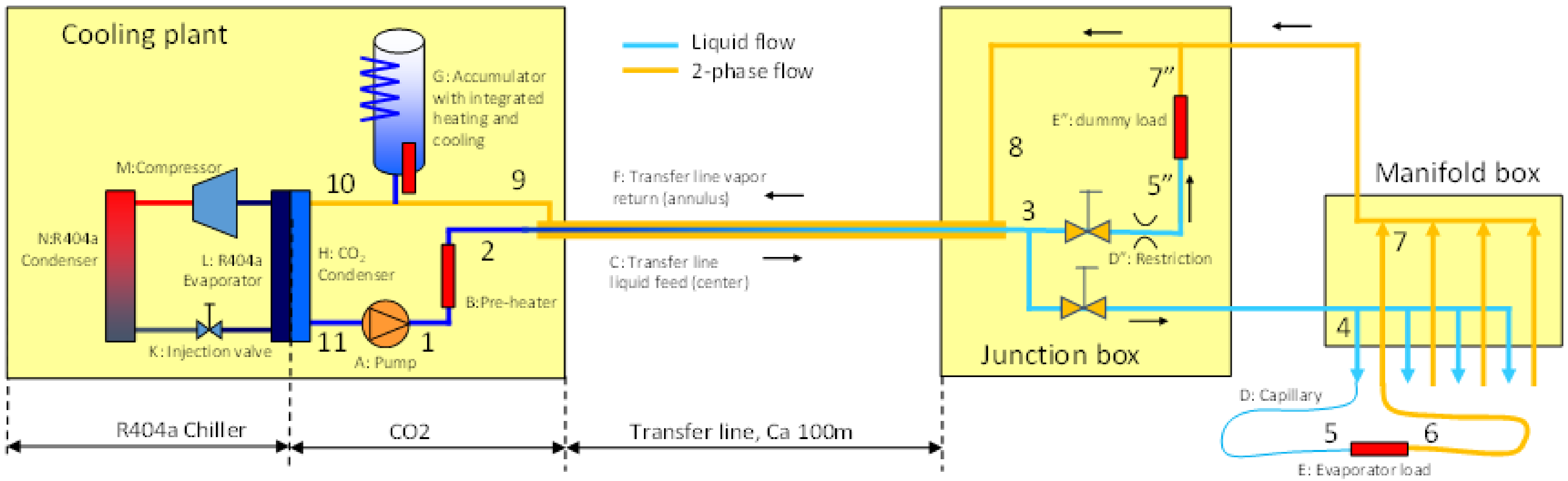


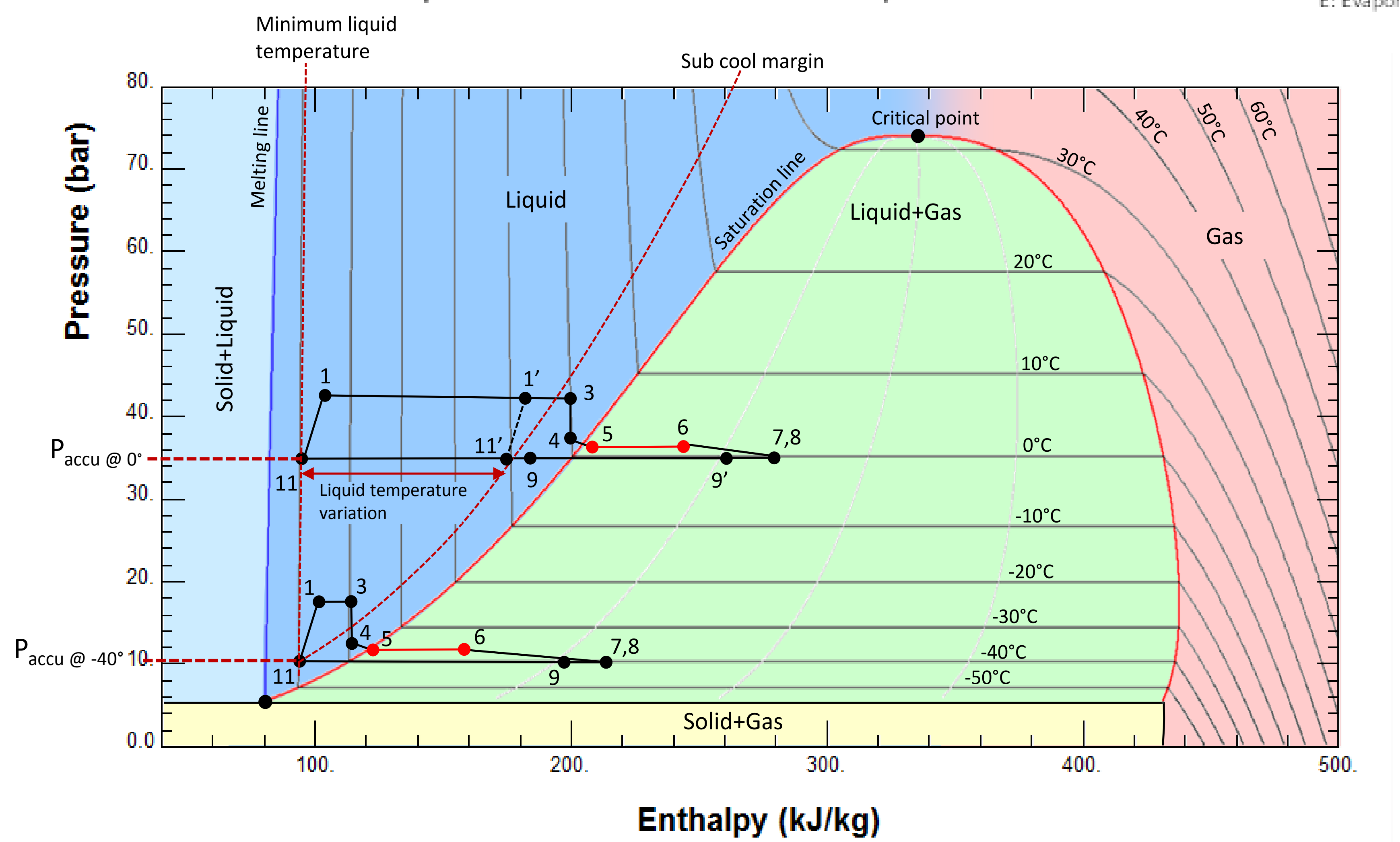


Beside being a natural refrigerant with the lowest GWP, CO_2 proofs to be the best suited for the typical operational conditions of LHC and HL-LHC trackers: with respect to other two-phase refrigerants it shows the highest “combined heat transfer” (accounting for both Δp and HTC) at the minimum diameter.

CO_2 evaporative cooling

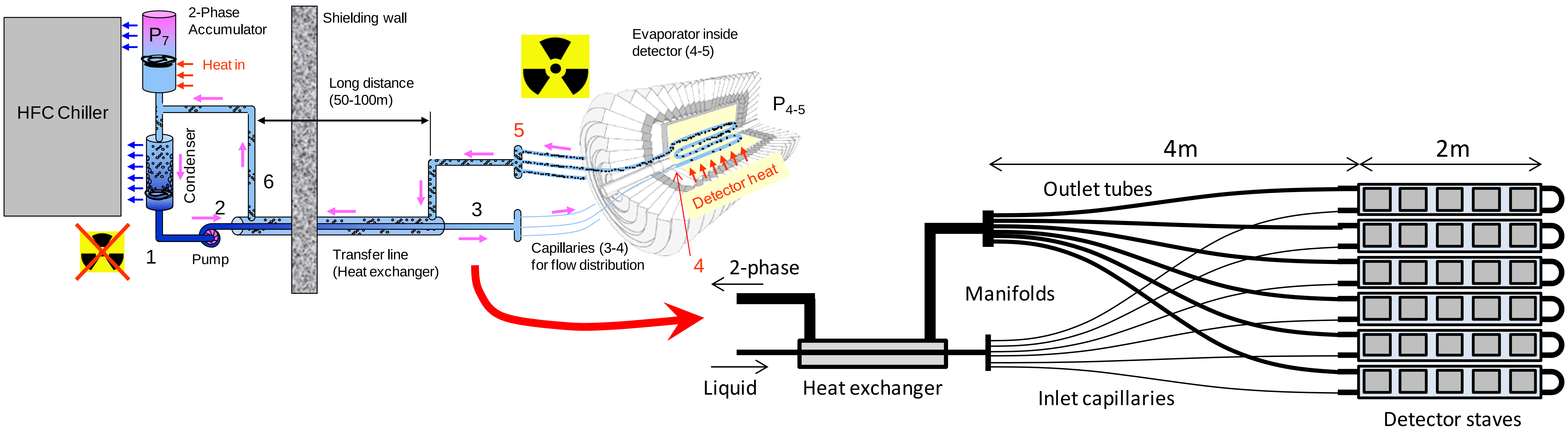
The adopted refrigeration cycle is not the standard Rankin "frigo" cycle, but a specific two-phase pumped loop (2-PACL), originally developed for the AMS TRD and for the LHVb Velo.





CO_2 evaporative cooling

The 2-PACL cycle allows for very stable and precise evaporation temperature control over very long distances without the use of compressors (only oil-free machinery in the loop) and with no need of active components on the detector side of the system



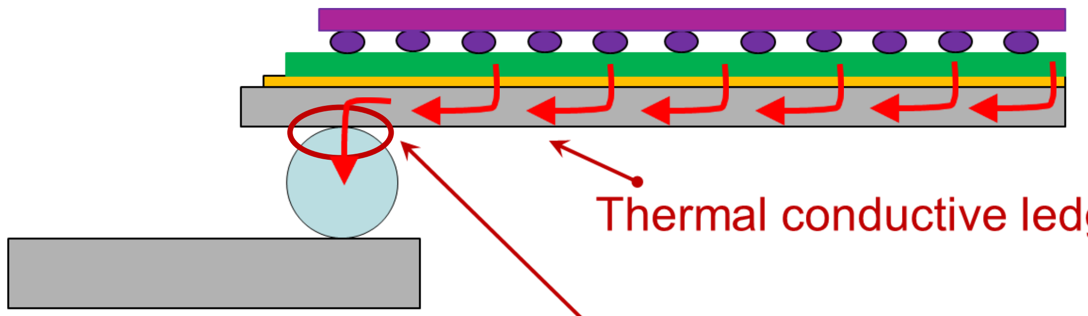
However, for an effective performance it is mandatory to have from an early stagean integrated vision of the full system “plant + transfer lines + manifolds + evaporator”!

Lots of development on-going (back-up slides). Suggested general reading:
P. Petagna, B. Verlaat and A. Francescon, Two-Phase Thermal Management of Silicon Detectors for High Energy Physics, Encyclopedia of Two-Phase Heat Transfer and Flow III (Vol. 4), pp 335-412 (in print)

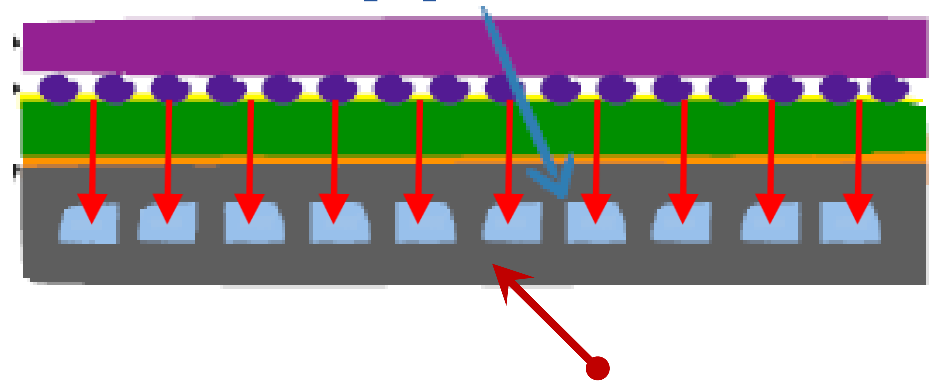
Microchannel cooling for HEP

A radically different (and innovative) approach

"Traditional" approach:
fair enough for STRIPS



Silicon microchannel approach



- Locally distributed cooling where needed
- Large thermal exchange surface
- Minimal path of thermal resistances

} = **minimal TFM**

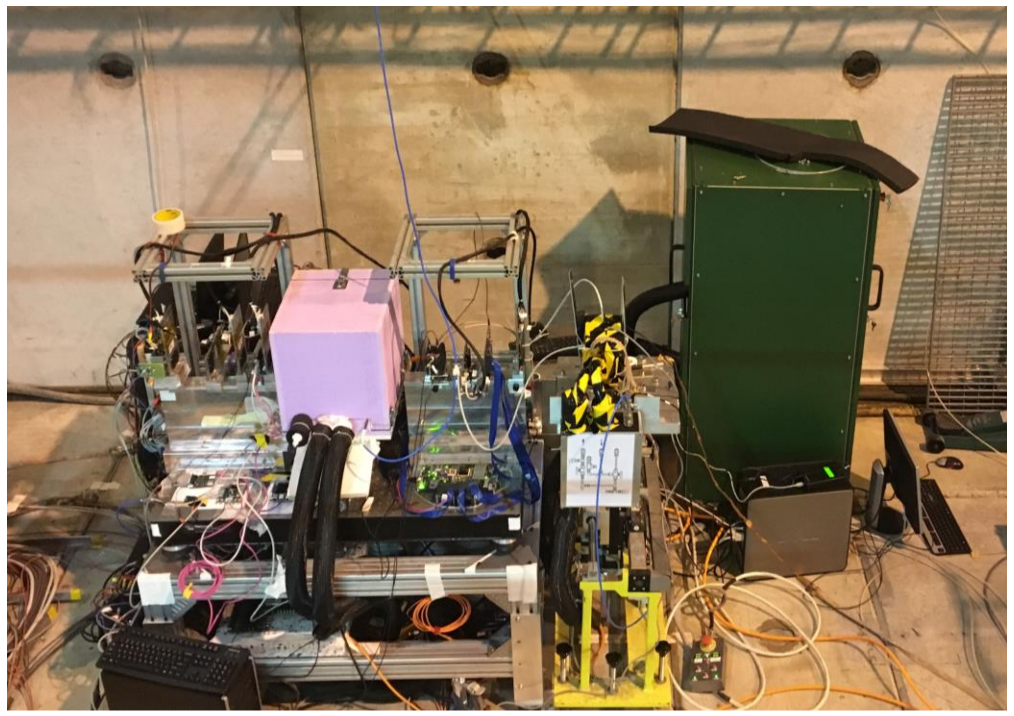
- Minimum material budget (except for air cooling)
- No CTE mismatch (if silicon is used as substrate)
- Radiation hard
- Compatible with all "HEP fluids"

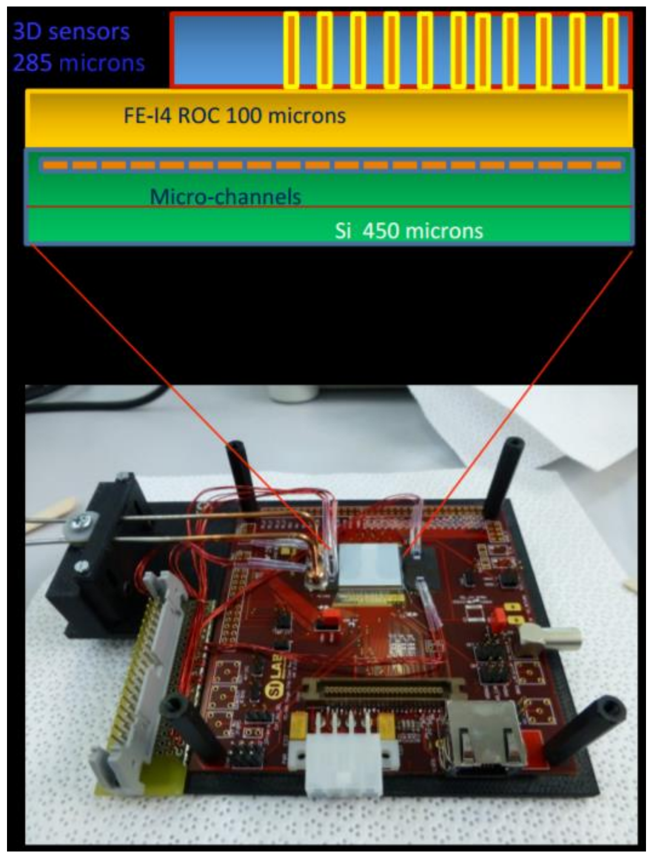
Microchannel cooling

Silicon micro-structured cold plates featuring arrays of hydraulic channels can be produced with standard MEMS-derived micro-fab techniques and can be successfully operated in

- Liquid phase -> A. Mapelli, *The NA62 GTK, from silicon microchannel cooling plates to tracking detectors* (VERTEX2017, next talk)
- Evaporative (CO_2) flow -> O. Augusto, *Microchannel cooling techniques at LHCb* (VERTEX2017, further next talk)

In all cases this technique features the lowest TFM of its category





2016 example:
1st complete module (3d+FEI4, "end-of-lifetime") cooled by a CO_2 μ-channel device (T=-22 ˚C) and read out in a test beam **(TFM < 3 K·cm^2/W)**

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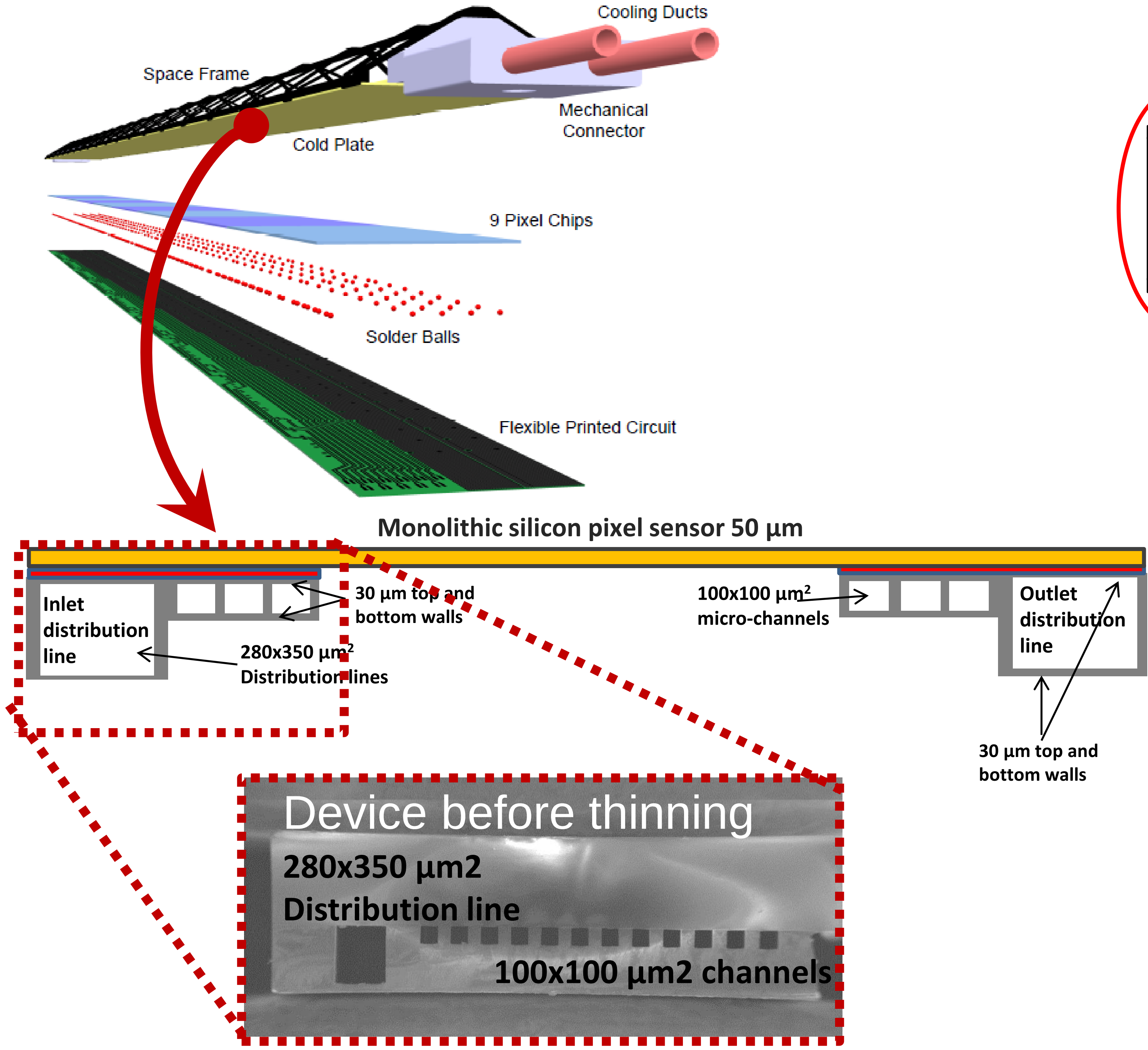
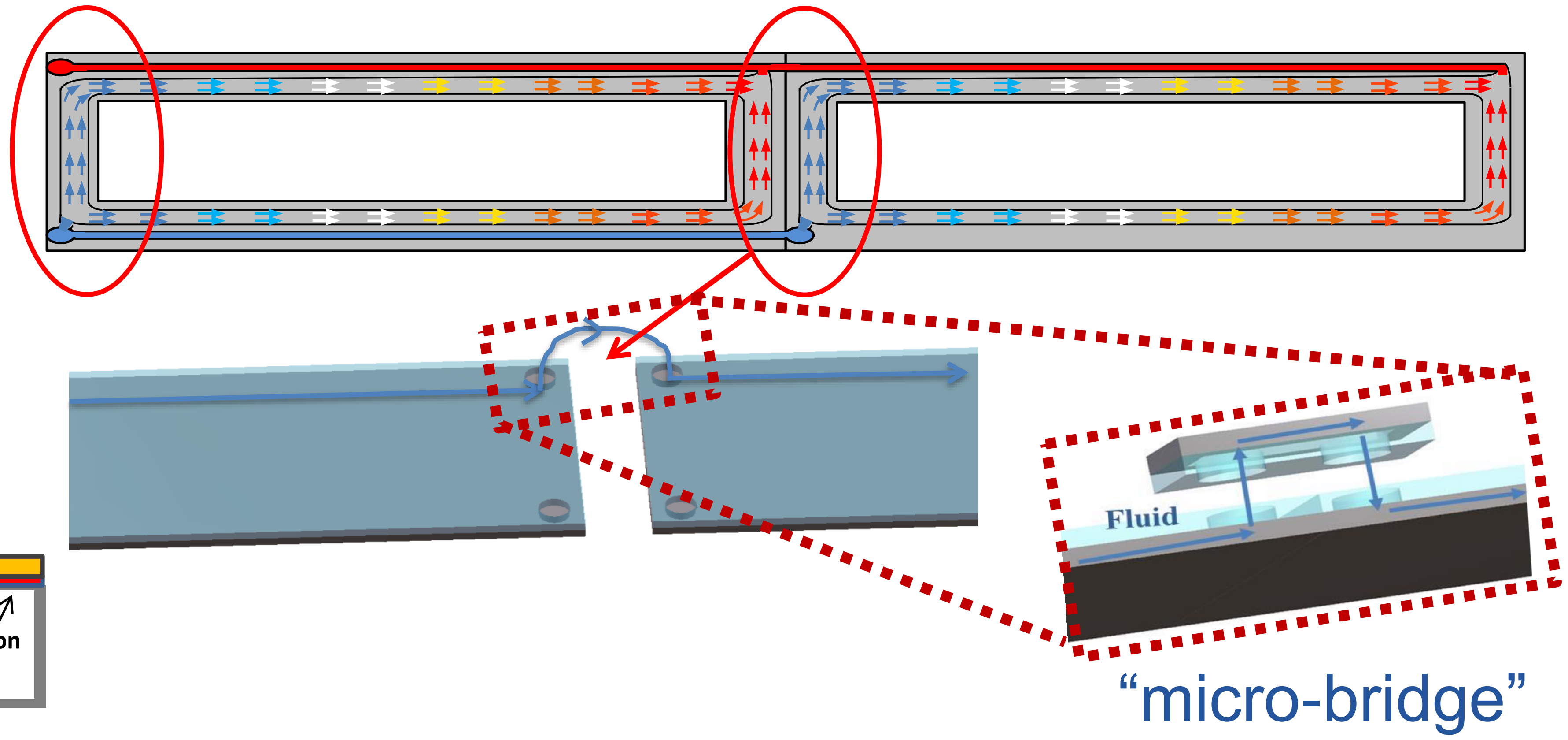
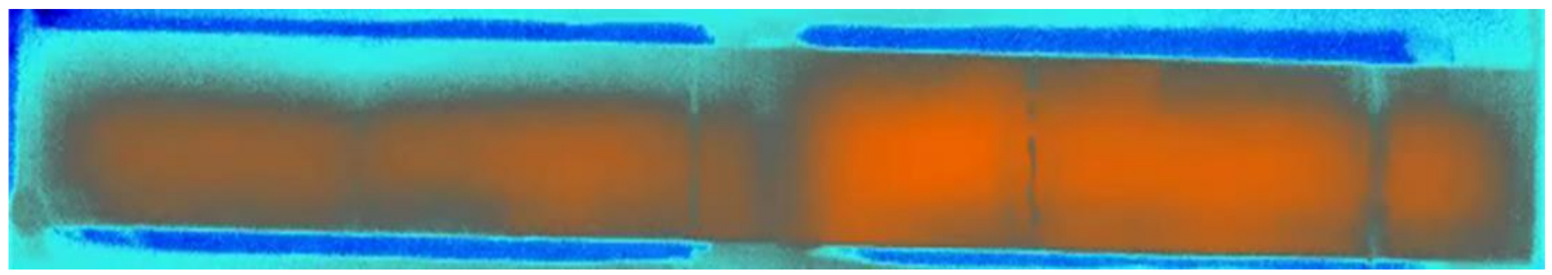
ALICE ITS upgrade alternative studies





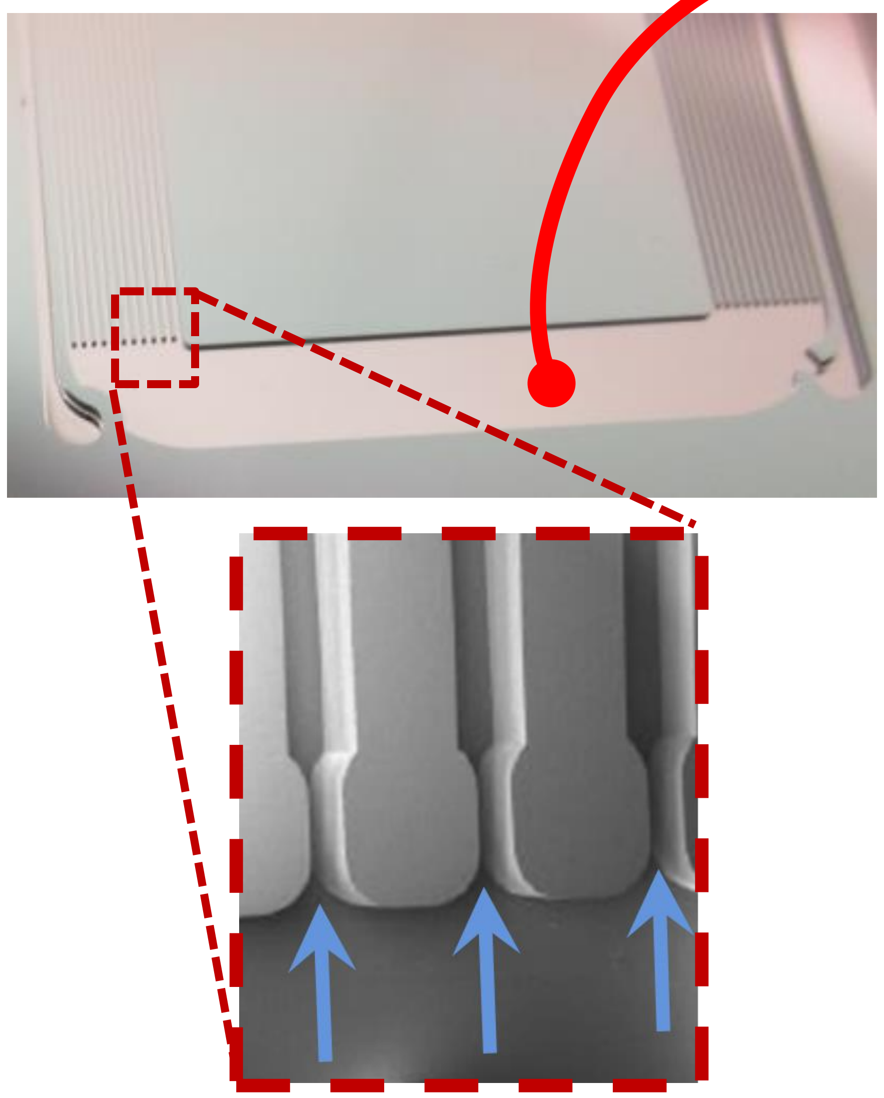


First successful interconnection of two microfluidic devices (in two-phase flow!)

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*, Applied Thermal Engineering 93, 2016, pp 1367-1376

Boiling issues

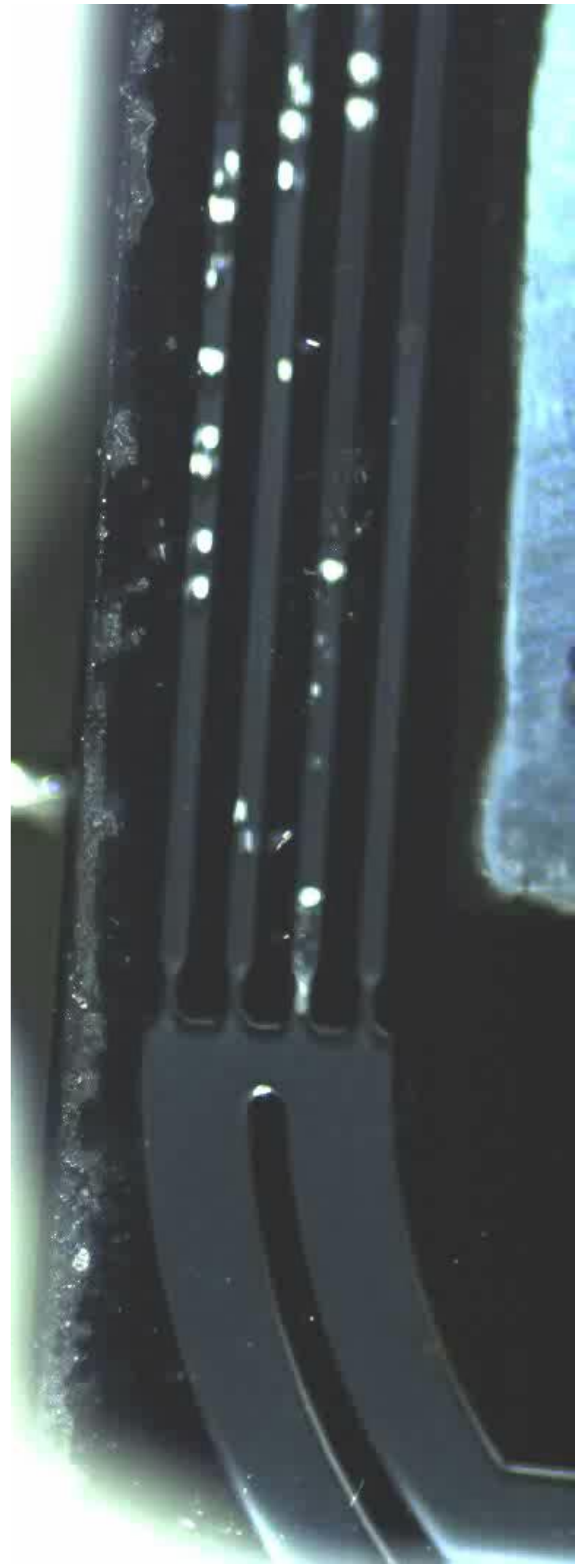
Proper control of boiling flows in parallel channels might always reserve surprises, but this is increasingly true at smaller scales, as the bubble size becomes quickly comparable to the channel size



Common distribution manifold for both frame "legs"

- Design for room temperature evaporative cooling with C_4F_{10}
- Liquid distribution and evaporation in the "legs"
- Restrictions at the inlet of the channels stabilize the two-phase flow avoiding back-flow and non-uniform distribution

… **Or they SHOULD avoid it**…



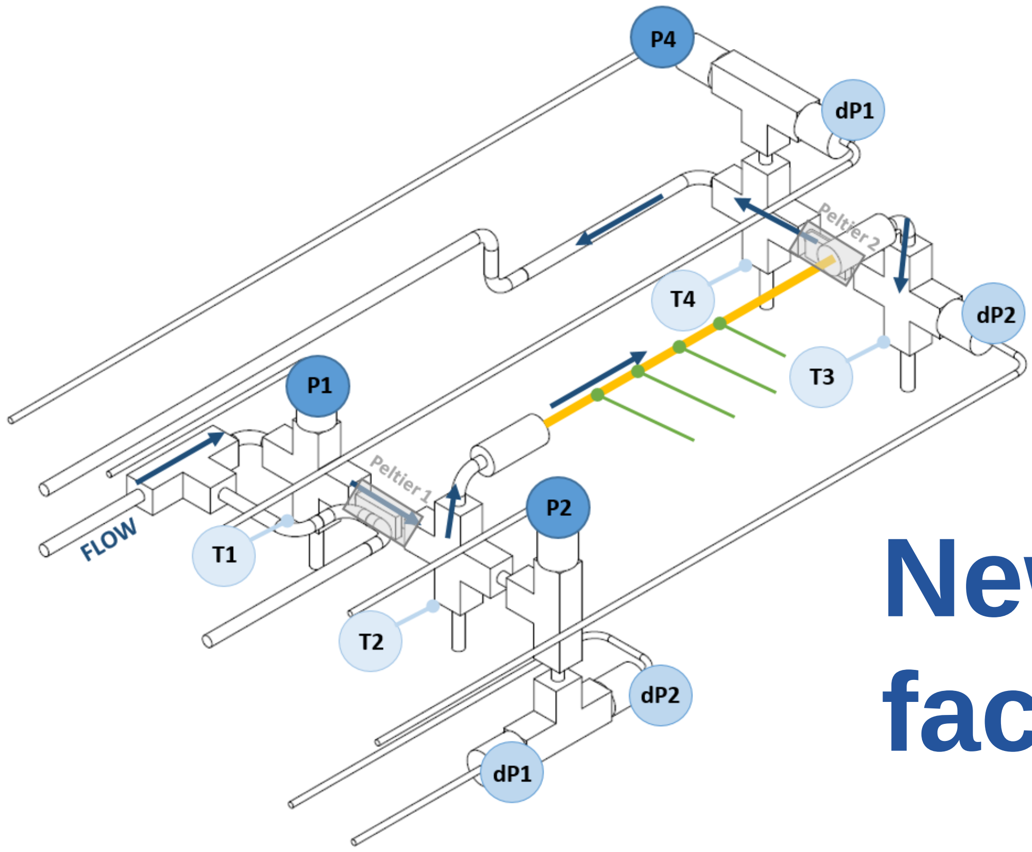
High Speed Camera movie taken in Padova. Courtesy of A. Francescon

Paolo.Petagna@cern.ch

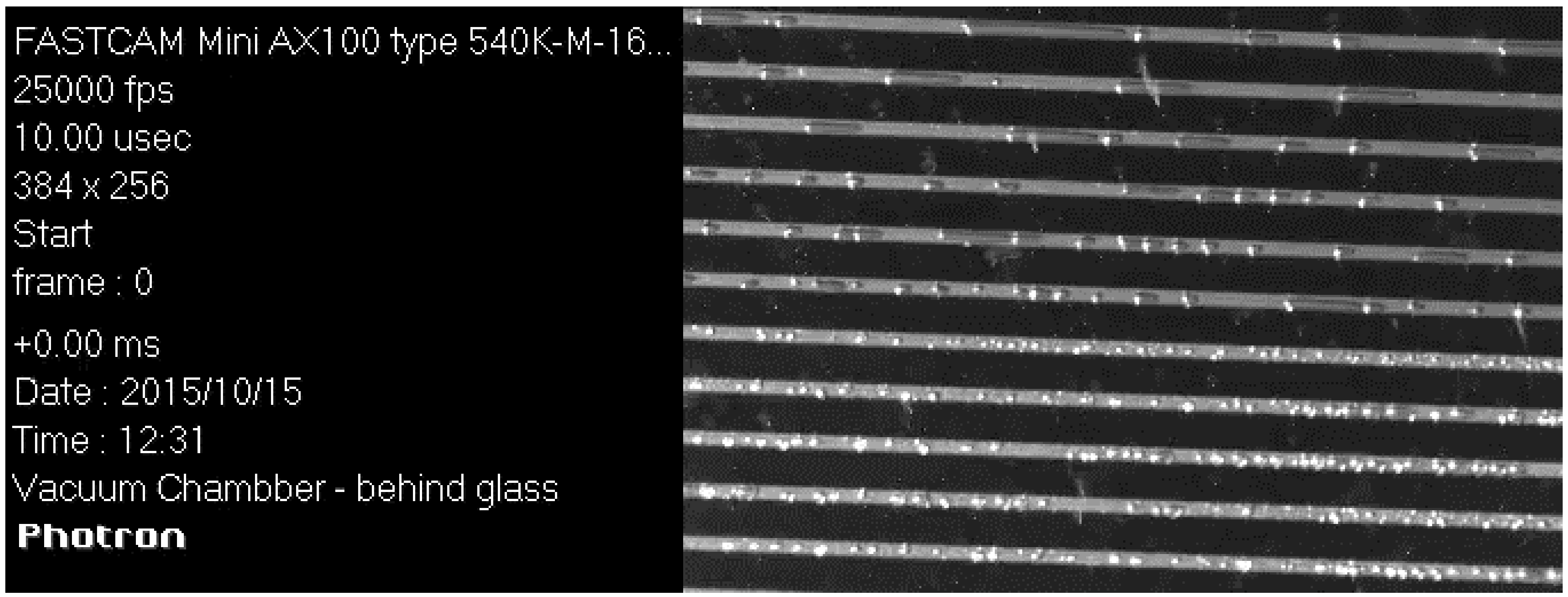
AIDA-2020 WP9: FFWD on open issues

CO_2 thermo- fluid dynamics at the micro scale

P. Petagna, *New support structures and micro-channel cooling: status*, AIDA-2020 Second Annual Meeting, https://indico.cern.ch/event/590645/contributions/2464220/



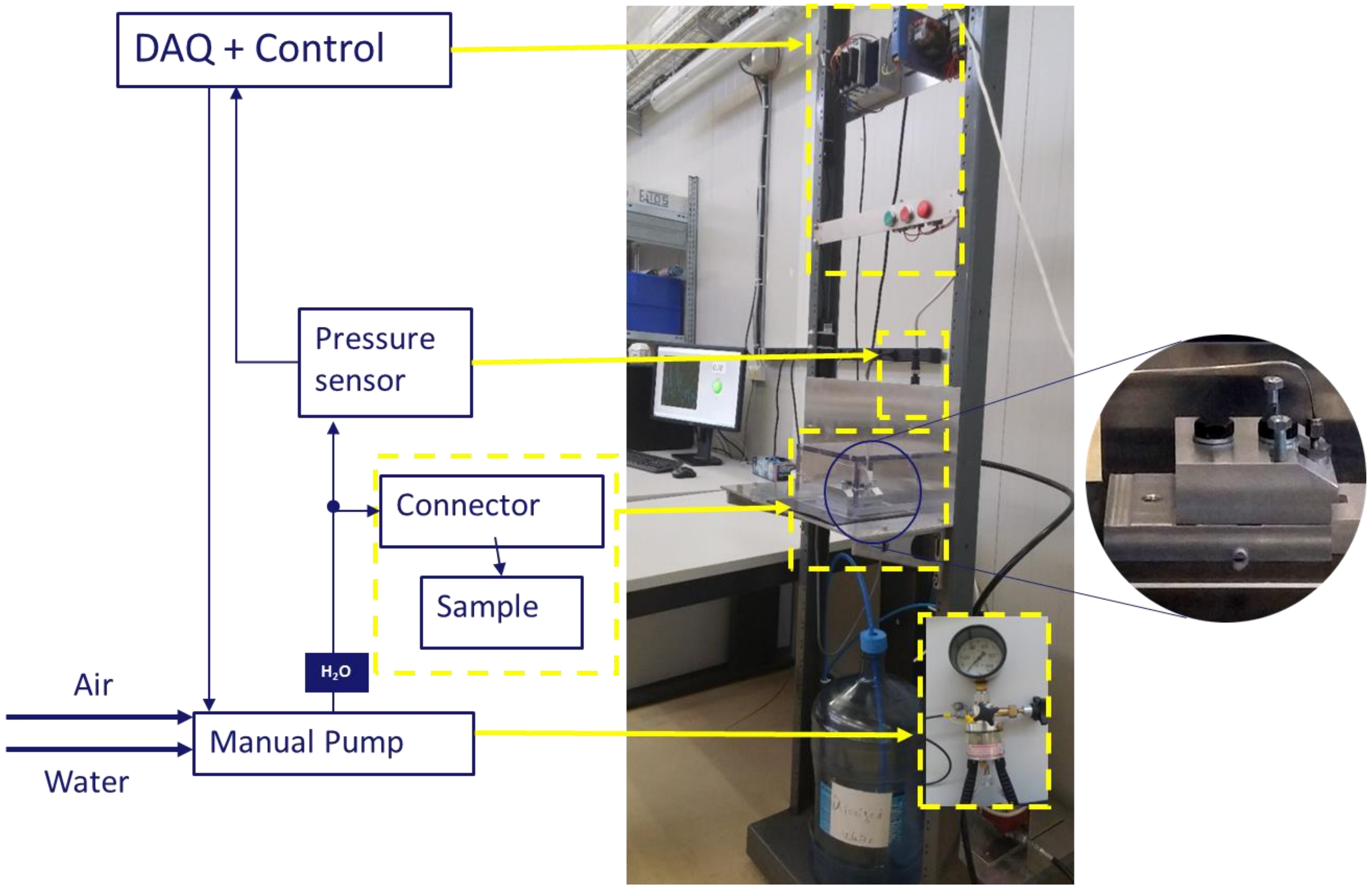
New dedicated test facility at CERN

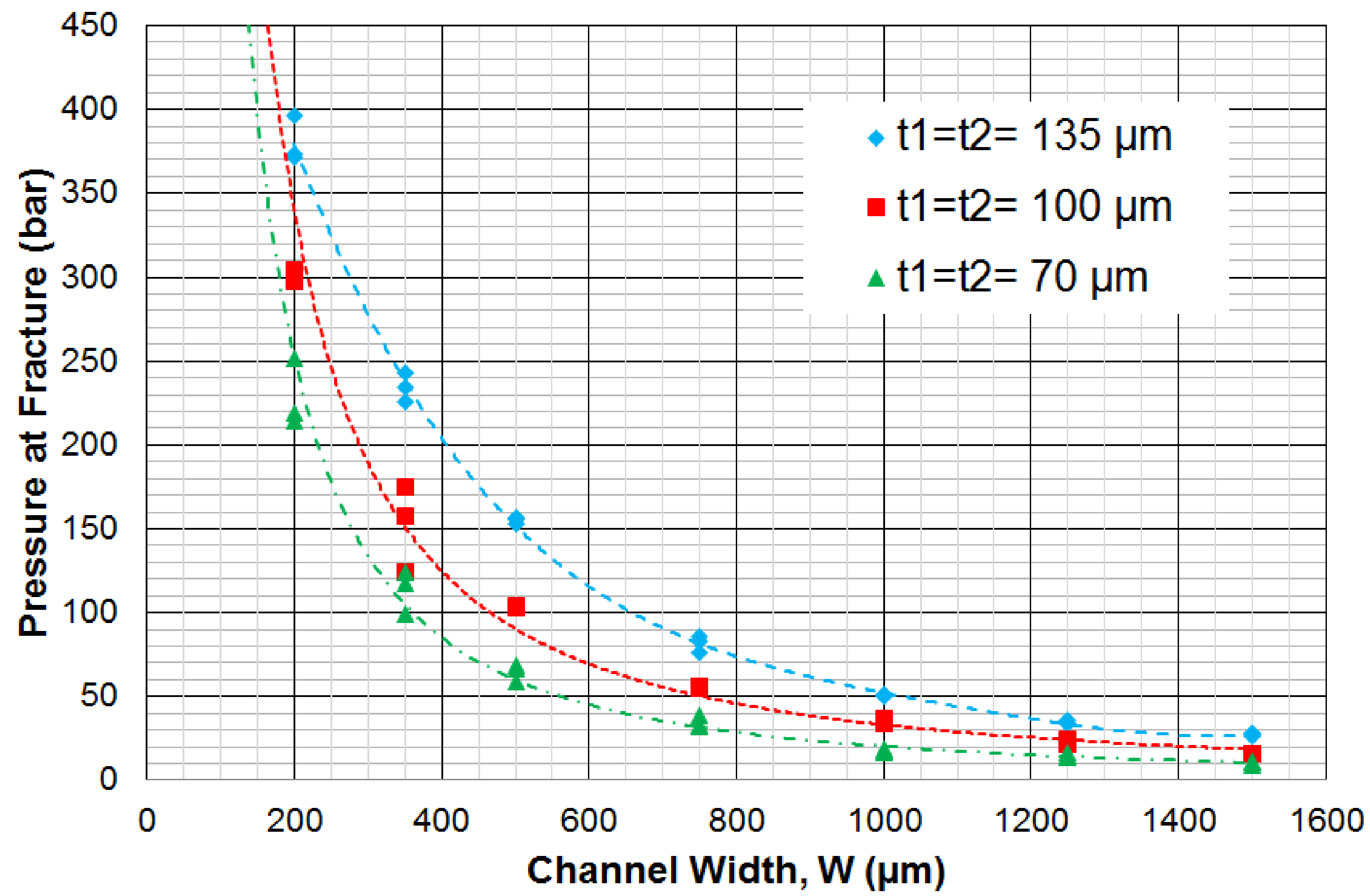


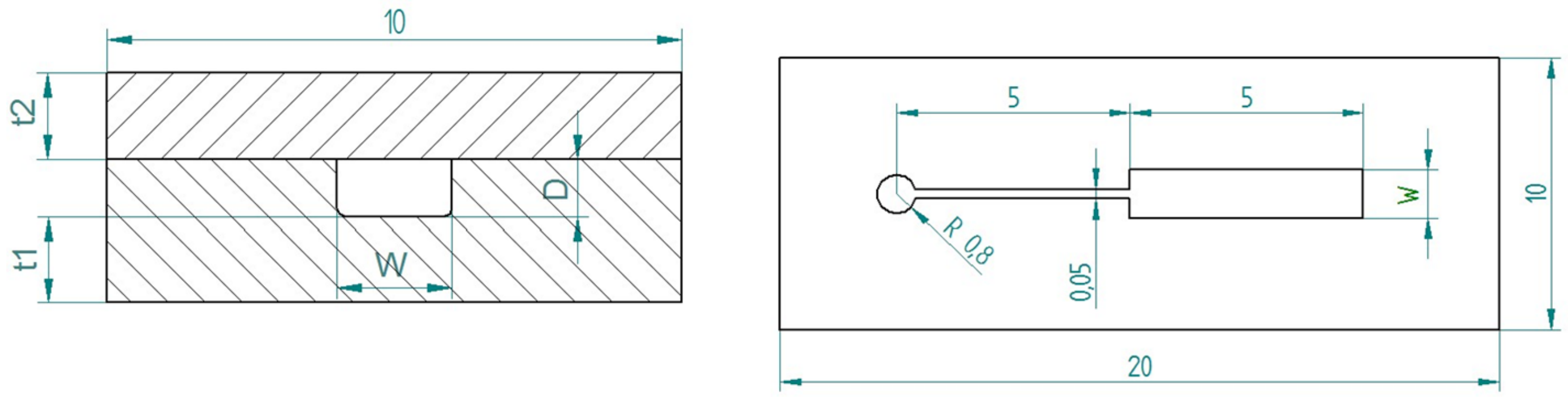
AIDA-2020 WP9: FFWD on open issues

Pressure resistance of silicon and device acceptance

Improved test stand



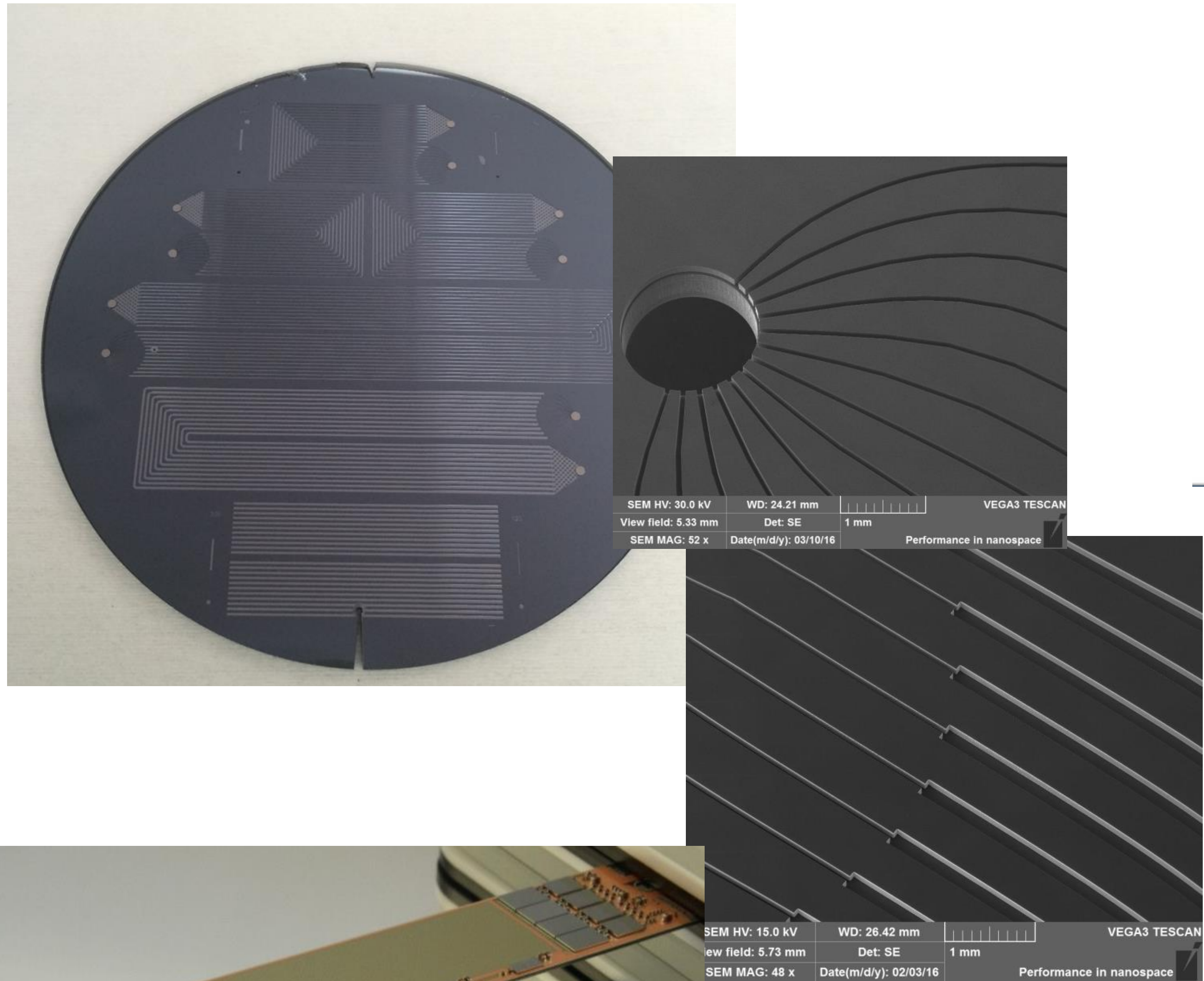


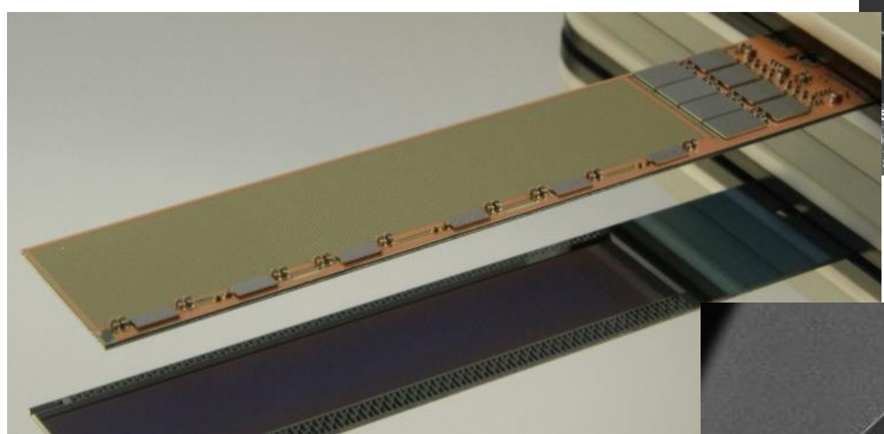


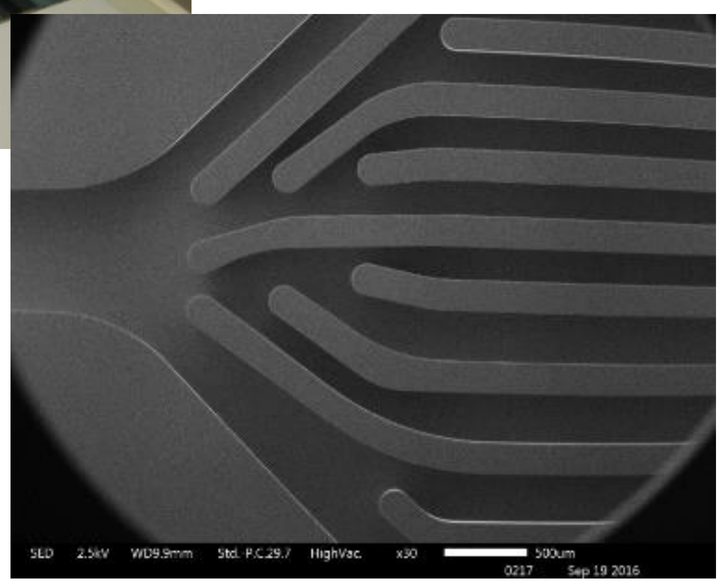
Standardized sample design

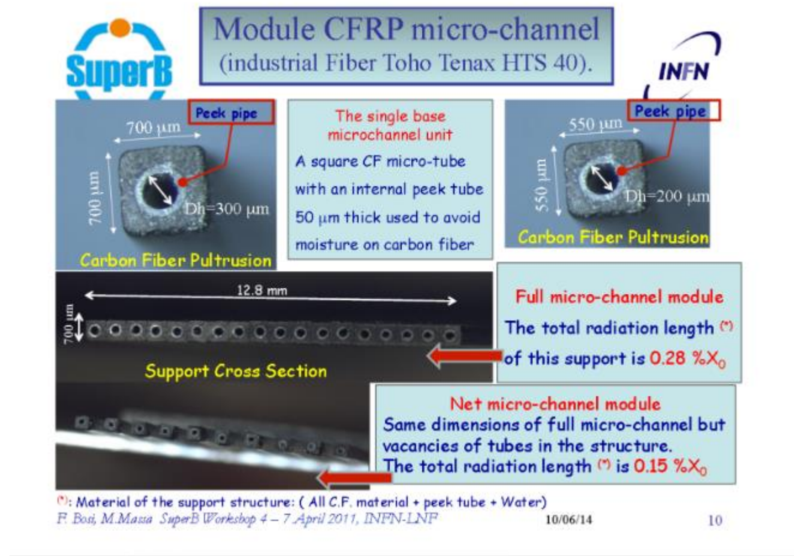
AIDA-2020 WP9: FFWD on open issues

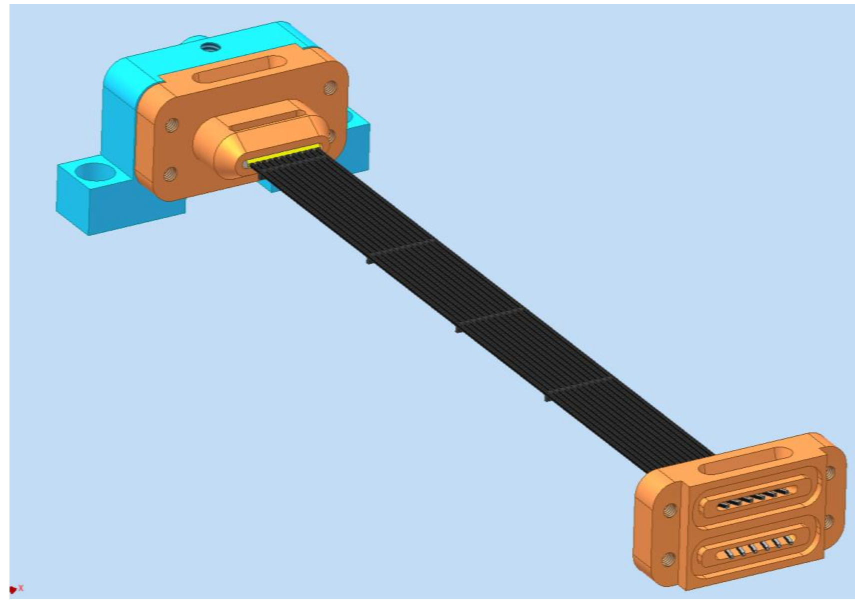
MEMS-derived and alternative production methods











BURIED CHANNELS APPROACH

Silicon buried channels for pixel detector cooling

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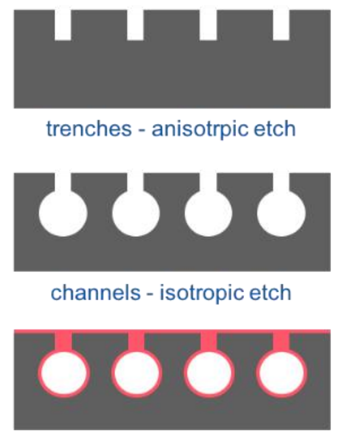
Nuclear Instruments and Methods in Physics Research A 718 (2013) 297–298



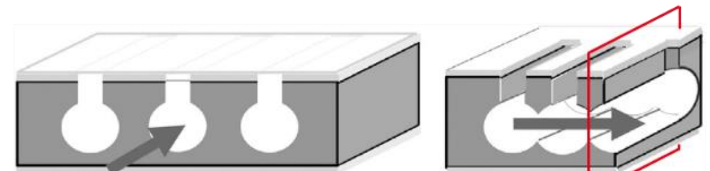
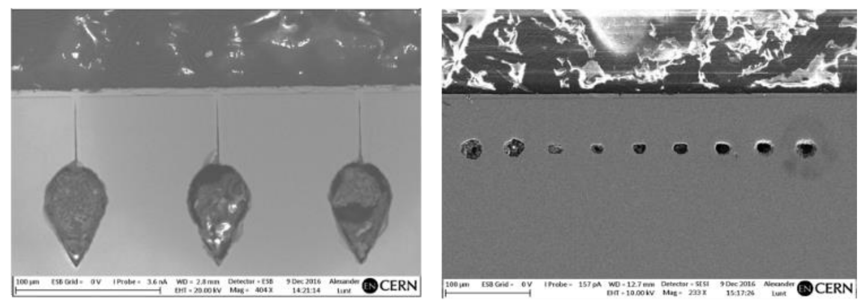


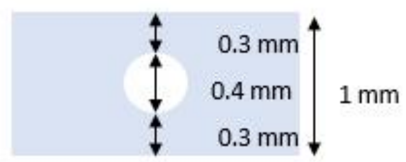
Fig. 1. Process sections for longitudinal and transverse channels.

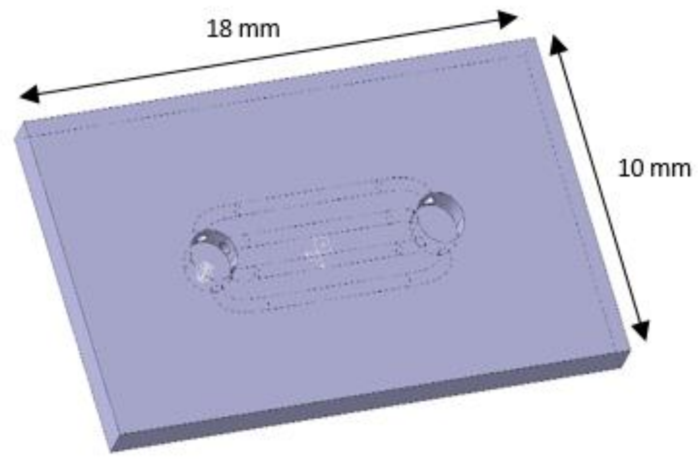


10 mm channels

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

Pure Alumina (99.8 %)

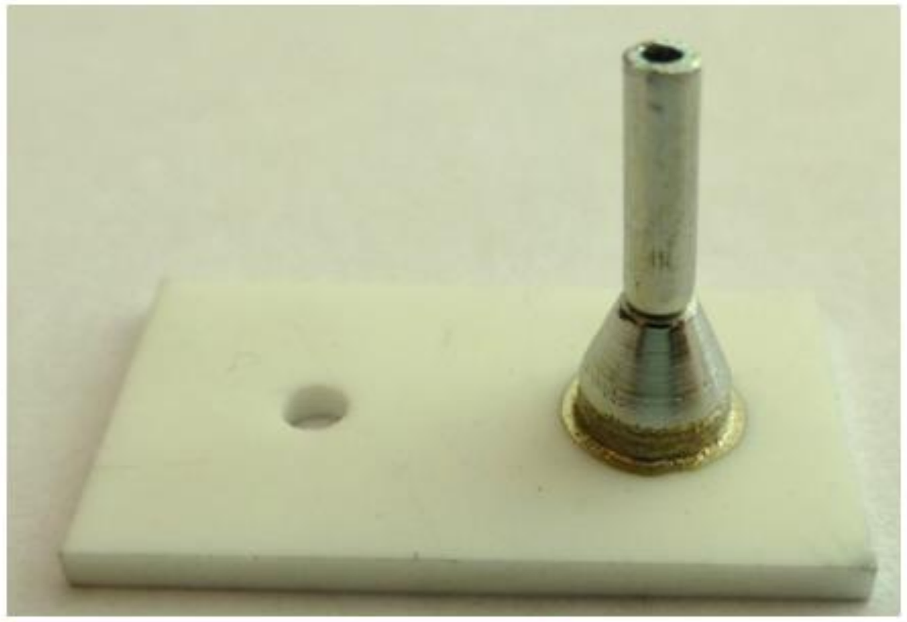




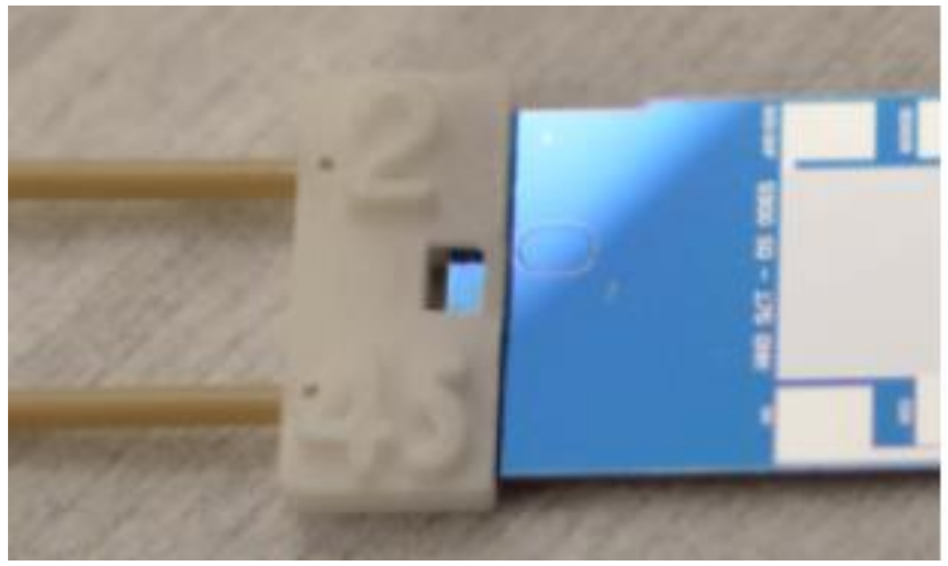
AIDA-2020 WP9: FFWD on open issues

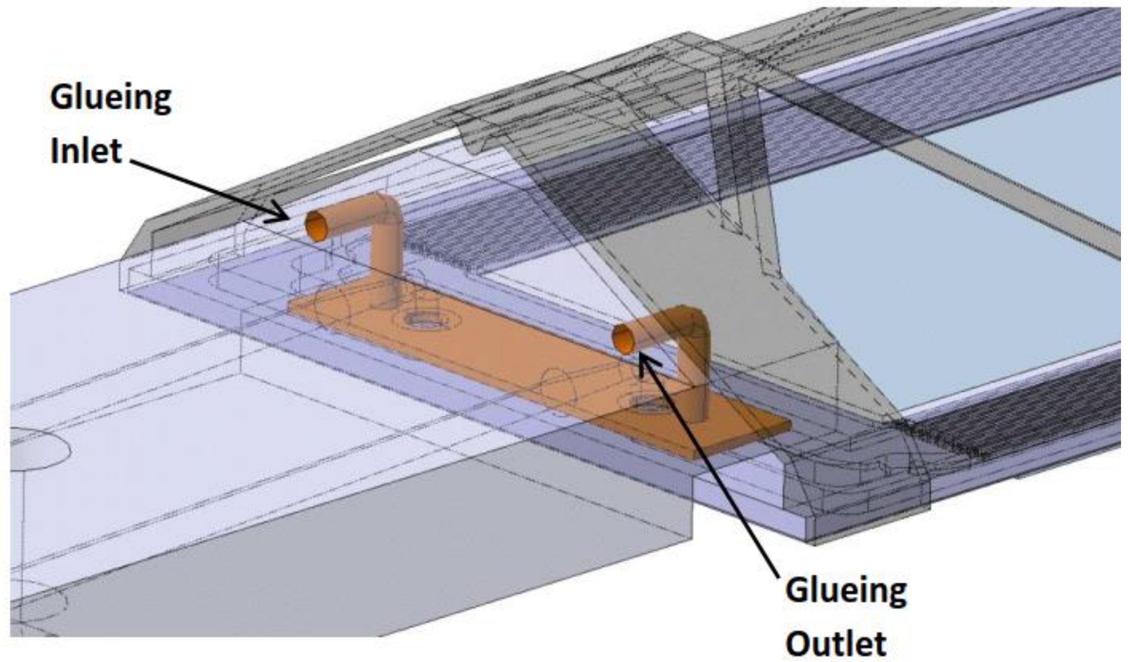
Connection and interconnection techniques

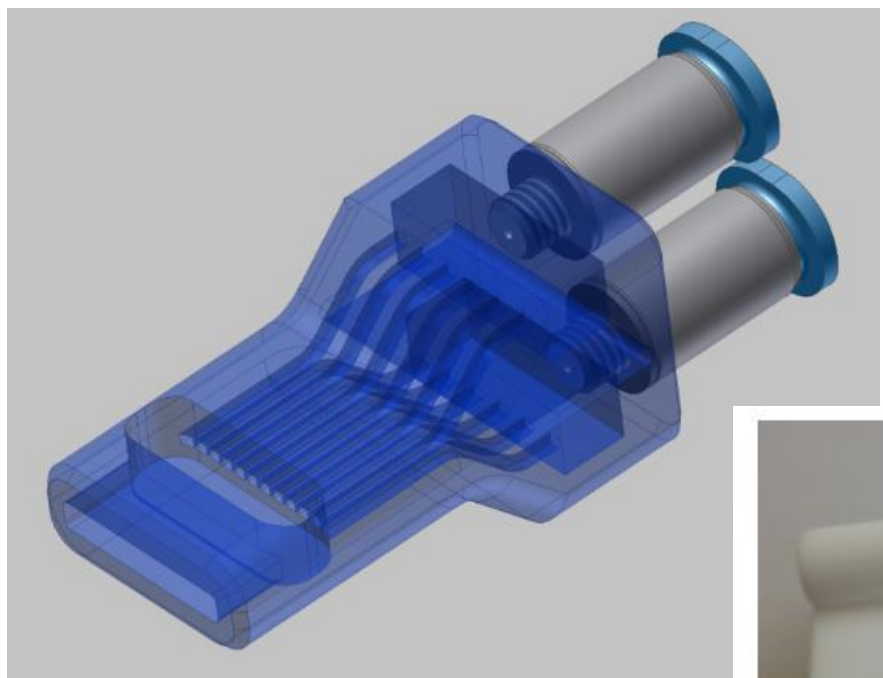
Vacuum brazing around 800°C
ABA CuSil foil
(Ag 63.0%, Cu 35.25%, Ti 1.75%)

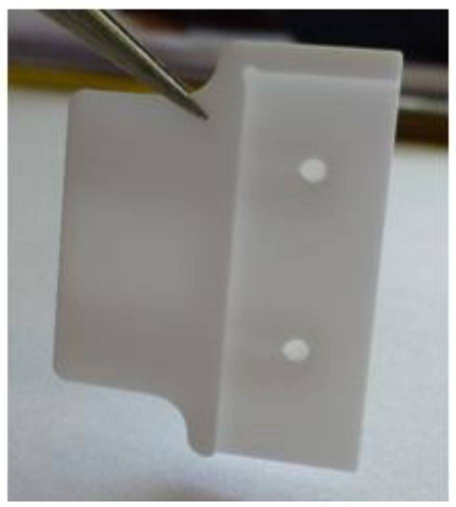


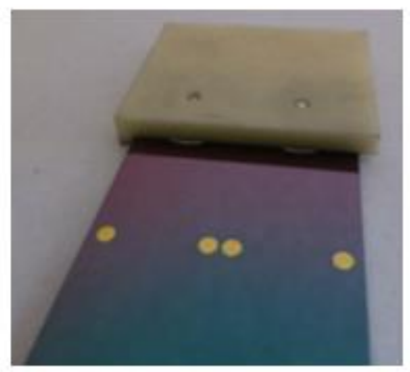
Leak test with helium 3.1×10^{-10} mbar l/s → no leaks!!!
Pressure test with water: 400 bar → no cracks

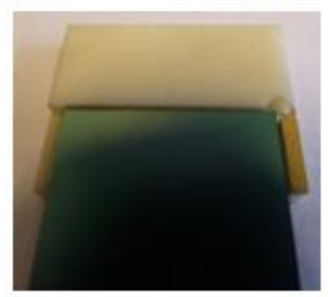












Soldering test with metallized ceramic on silicon

So… why not μ-channels everywhere?

- μ-c cooling technique is well suited for thermal management of high performance vertex detectors: very low X/X_0 coupled to extremely low TFM and no CTE mismatch problems (with silicon)
- Flexible technique: single-phase and two-phase (evaporative) cooling possible, perfectly adapted to run with CO_2

- No “universal” design: very much configuration-dependent
- Many technical issues still require careful investigation, in particular for barrel (stave) configurations (AIDA-2020 WP9)

- Production costs and complexity of the integration fairly high
- Not adapted to very large scale implementation in detectors

μ-c cooling is in principle perfectly suited for the first layer(s) of HL-LHC pixel detectors, where volumes are extremely compact and minimal X/X_0 and TFM are sought in combination

Conclusions

- The thermal management of the coming generations of Vertex detectors requires careful design and early integration
- Recent spectacular technical advances make available several effective approaches to the detector designer
- No single thermal management scheme is by definition better suited than the others for all configurations: careful analysis of the design parameters and of priorities (the “engineer questions”) must guide towards the optimal choice
- Early integration of the preferred cooling approach in the design concept is in any case a must!

THANK YOU
(BACK-UP SLIDES FOLLOW)

Thermal management of silicon detectors

Comparing rough numbers for a typical LHC Vertex detector and a typical high power multi-stacked chip application, one thing is clear:

Never underestimate the challenges of removing the heat produced from the detector volume (while keeping the sensor cold)

	LHC PIX detector	High Power multi-stacked chips
Surface Power Density	$\mathcal{O}(10^0)$ W/cm^2	$\mathcal{O}(10^2)$ W/cm^2
Silicon Surface	$\mathcal{O}(10^0)$ m^2	$\mathcal{O}(10^{-4})$ m^2
Total Power	$\mathcal{O}(10^0) \div \mathcal{O}(10^1)$ kW	$\mathcal{O}(10^{-1})$ kW
Confined Volume	$\mathcal{O}(10^1) \div \mathcal{O}(10^2)$ dm^3	$\mathcal{O}(10^{-1})$ dm^3
Volume Power Density	$\mathcal{O}(10^2)$ W/dm^3	$\mathcal{O}(10^2)$ W/dm^3
Target Temperature	T < -10 °C	T < 60 °C
Easy maintenance	…ah! ah! ah!...	No problem
X/X_0	Minimize!	"X what?"
Space consumption	Minimize!	Be reasonable
Design Lifetime	~ 10 years	~ 5 years
Number of Cooling Loops	$\mathcal{O}(10^1)$	$\mathcal{O}(10^0)$

Future CO_2 cooling plants @ LHC/HL-LHC

2[nd] ECFA High Luminosity LHC Experiments Workshop 21-23 October 2014 (Aix-les-Bains)

2014

CMS Pix-Ph1:
- **2 x 15 kW** independent plants for 2 detectors
- Temporary swapping back-up possibility
- **T = -25 ˚C**

ATLAS IBL:
- **1+1** plants with swapping possibility
- Each unit **3.3 kW @ -35 ˚C**

2015-16:
plant construction

LS2 (2018)

LHCb Velo + UT:
- **2 x 7 kW** independent plants for 2 detectors
- Temporary swapping back-up possibility
- **T < -30 ˚C**
- Plants installation and commissioning in **EYETS 2016/17**

LS3 (2023)

(preliminary ideas)

ATLAS ITK :
- **5+1** plants with swapping possibility
- Each unit **30 kW @ -35 ˚C**
- **Very large CO_2 volumes!**

CMS TRACKER & HGCal:
- **(3+1) + (4+1)** plants with swapping possibility
- Each unit **45 kW @ < -30 ˚C**
- **Very large CO_2 volumes!**
- **Additional unit** for partial detector tests on surface

(2015)

TRACI V3

industrial outsourcing

(2016…)

PROPOSAL

ATLAS/CMS Common prototype(s):
- **30-45 kW (?)** @ -35 or -40 ˚C
  - two stage chiller
  - Distribution lines
  - multiple remote head pump
- **Large CO_2 volumes management**
- **HW and outsourceable production**
- **Simulation tools**

Common DT+ATLAS+CMS R&D projects

Simulation tools

CO_2 models for evaporation in horizontal pipes down to ~1mm size have been quite successfully implemented in the past into a 1-D calculator (CoBRA). They must be **refined,** extended to the case of evaporation in long **vertical pipes** and compiled into a **user-friendly code**, ideally to be **coupled with a standard FEA** software

The application of dynamic simulation techniques would allows for **modelling the time varying behaviour** of a cooling plant under any condition. This process simulation technique provides important benefits through the whole project life:

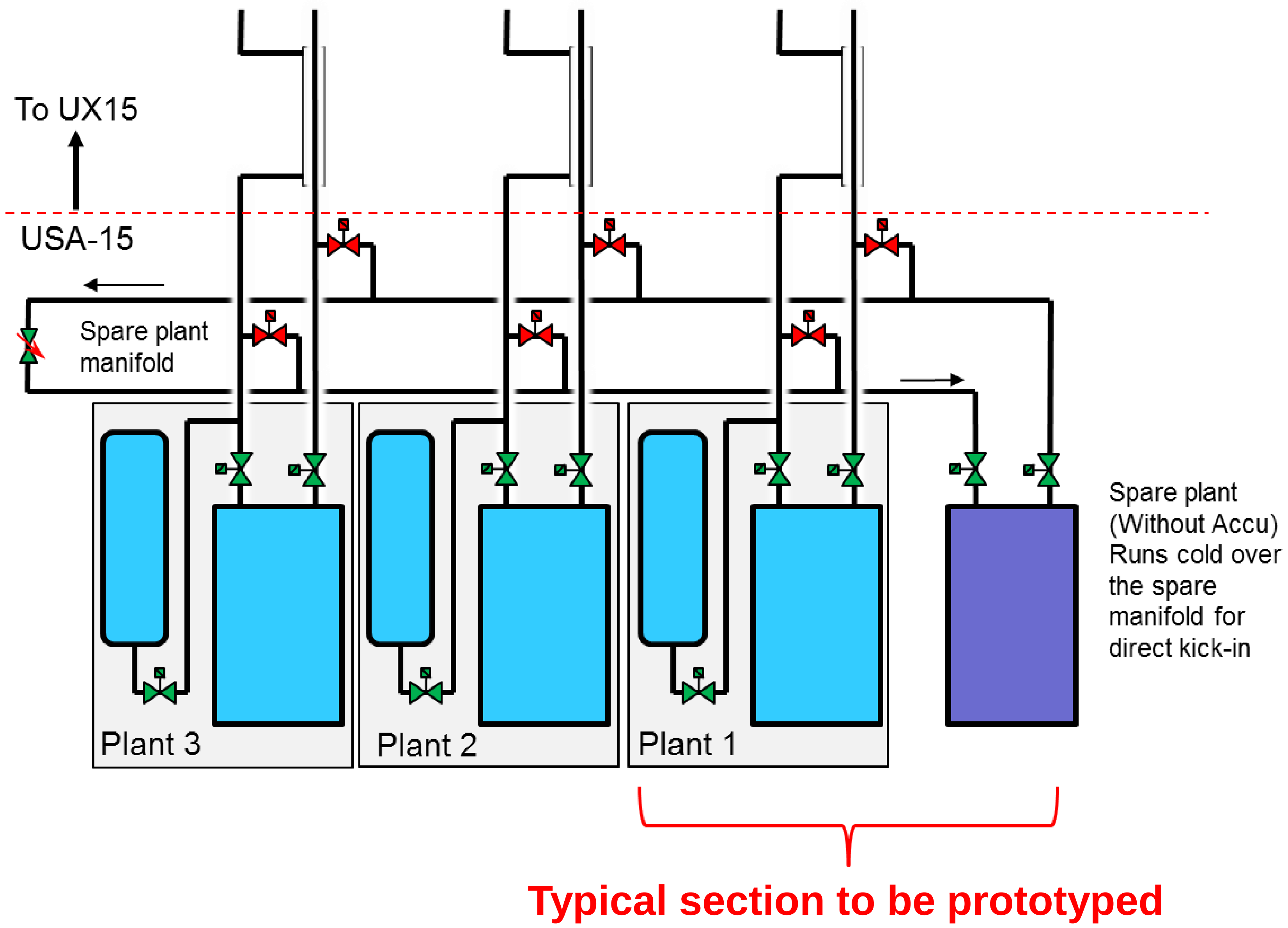
- **Design phase:** Check global process behavior/transients
- **Commissioning phase:** Virtual commissioning of control systems
- **Operation phase:** Operator training and control optimization

Specific investigation programmes are being launched

Operation: unit swapping and recovery

For the Phase2 upgrades a redundancy scheme is proposed involving the installation of one **spare cooling plant** and a **swapping scheme** smoothly allowing to substitute each one of the n plant in use (faulty or requiring maintenance) with the spare unit.

One possible idea: modular 2PACL concept



This very appealing scheme has several implications not only at the level of integration, but also of **plant hardware** design, **process optimization** (stop / swap / recover) and **control implementation**.

To be investigated with a common prototype

Accumulation and CO_2 storage

The accumulator is the key element of the 2PACL cycle. It is basically a **temperature-controlled high pressure vessel** containing CO_2 in gas and liquid phase: the pressure in the accumulator determines the evaporation pressure on the detector lines

In the present plants the accumulator also acts as CO_2 **storage tank**.

The ~70 kg CMS Pix-Ph1 plant accumulator has about the **maximum size** that can be built with standard certified techniques and safely stored underground.

The large volumes of CO_2 required for the thermal management of the Phase2 detectors requires a thorough **reconsideration** of the concept:

- Multiple accumulators per plant (control complexity)?
- Separate large storage tank and a small accumulator?
- Cold storage or warm storage?
- Where to store the large CO_2 volumes? In surface? How to transfer?
- …

To be investigated with a common prototype

High power pump (30 to 60 kW)

The experience gathered with the Lewa pumping units adopted for ATLAS IBL and CMS Pix-Ph1 must be combined in the new pump needed to cope with Phase2 detector requests

ATLAS IBL:
Triple head "local"
3.3 kW

CMS Pix-Ph1:
Single head "remote"
15 kW

FUTURE:
Triple head "remote"
Up to 45 kW?

Technical feasibility has been declared by the producer (Lewa).

However this will be an unknown product, likely to require some **technical R&D**, in particular for its implementation in the new cooling units.

To be investigated with a common prototype

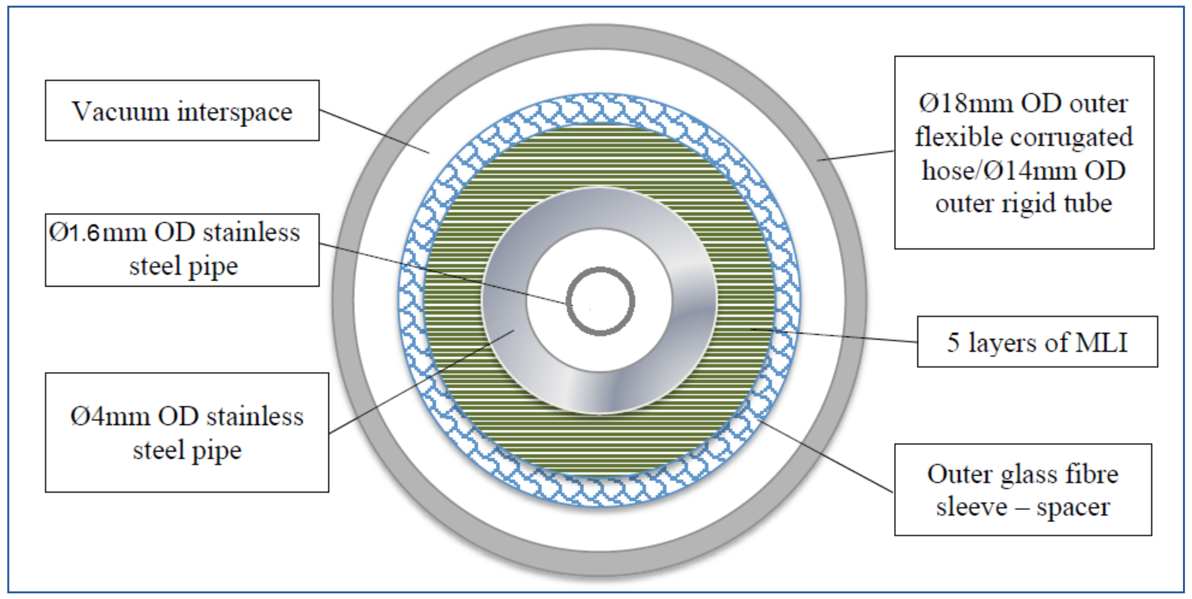
Transfer lines

Efficient transfer lines combining the inlet and outlet lines with a vacuum insulation in a triple coaxial geometry have been first adopted for the ATLAS IBL and the CMS Pix-Ph1 projects.

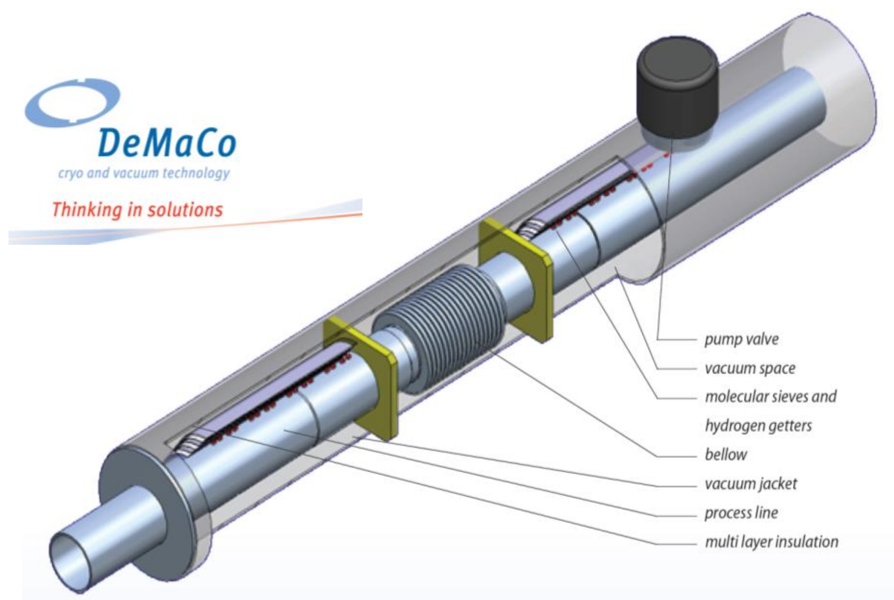
While long **rigid** lines have been industrially produced and can be operated with “passive vacuum”, very practical **flexible** lines have been custom designed and produced for critical IBL regions: however these require today active vacuum pumping. Can they be designed for “**passive vacuum**” too?

Can the **cross section** of the transfer lines be further reduced?

Very long transfer lines in complex geometries with well insulated walls can also present local “siphons”, where cold fluid can be trapped for long time. **Experience** must be built-up.



Cross section of a triple coaxial vacuum insulated transfer line



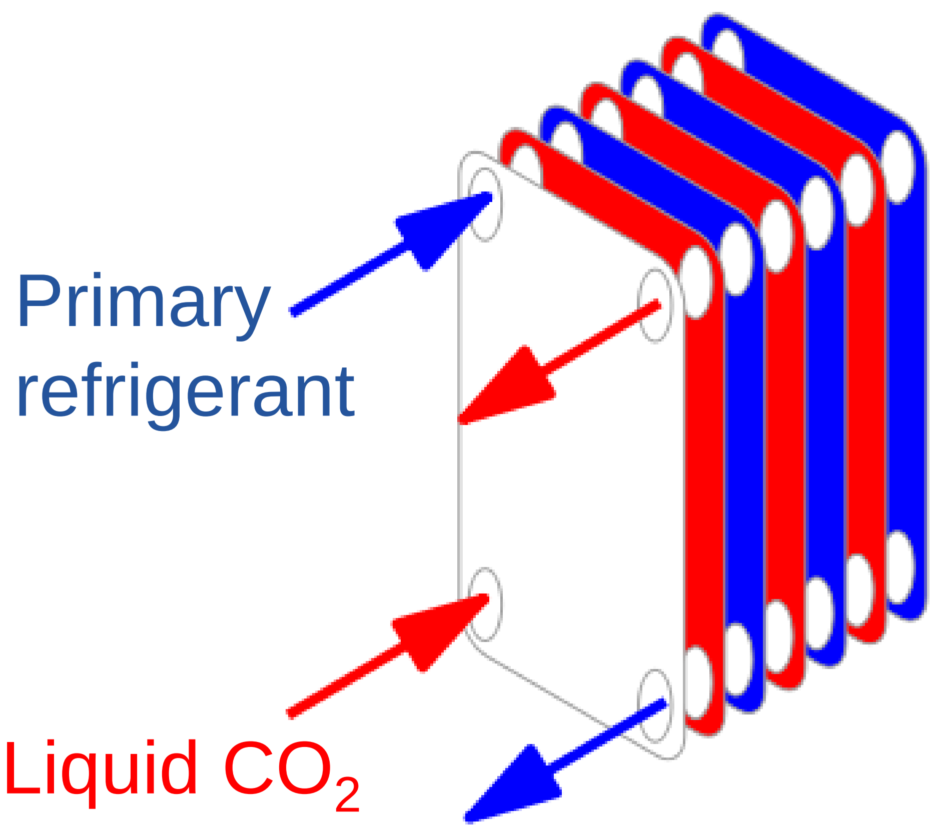
Rigid transfer line

Custom flexible transfer lines

To be investigated with a common prototype

Plant optimization for minimum T_{evap}

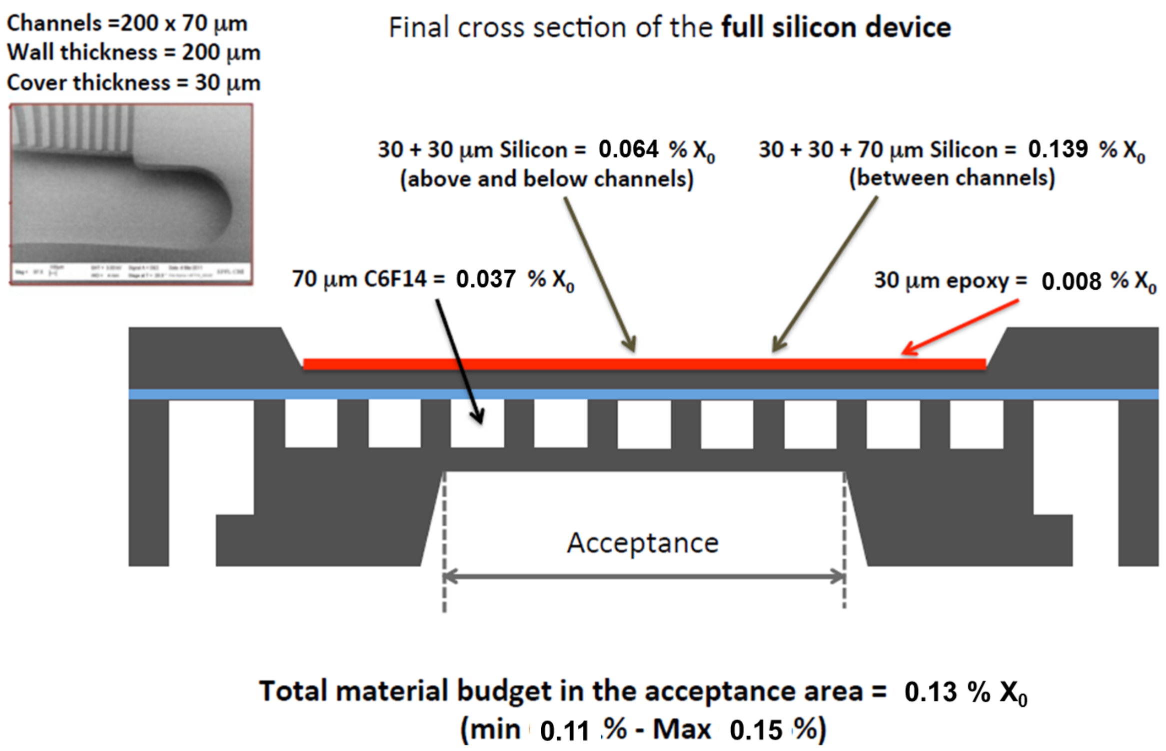
PLANT HEX

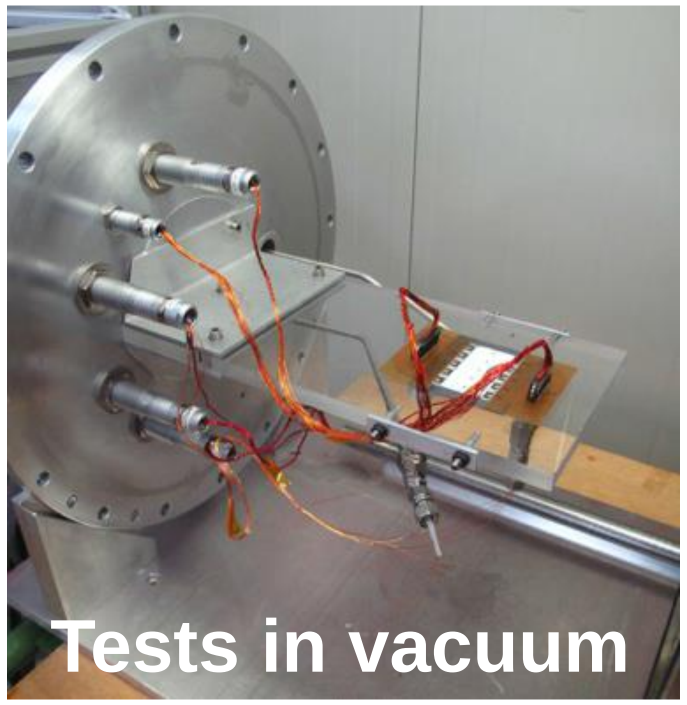


- Liquid CO_2 must be fed to the pump with adequate subcooling w.r.t. the desired saturation temperature (typically 10 ºC)
- CO_2 freezes at -56 ºC
- Planning to exit the plant HEX with liquid CO_2 for the pump at -50 ºC or lower requires a careful selection of the HEX and a very careful design of the controls of the primary chiller!

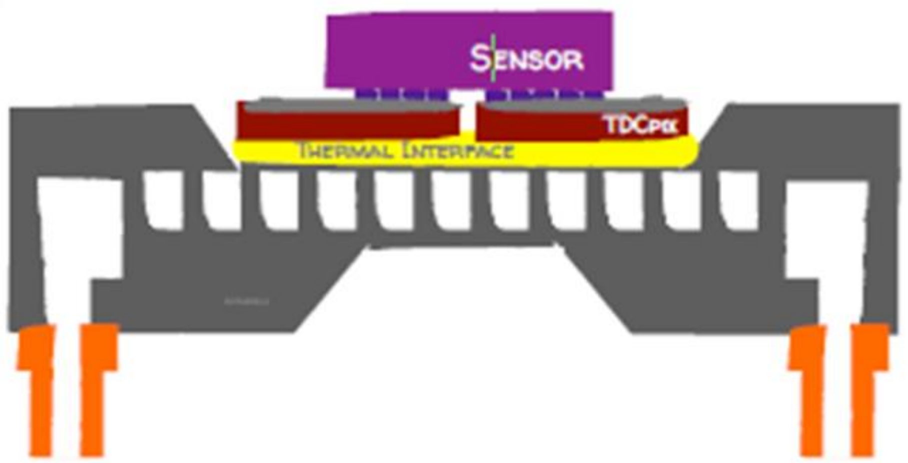
To be investigated with a common prototype

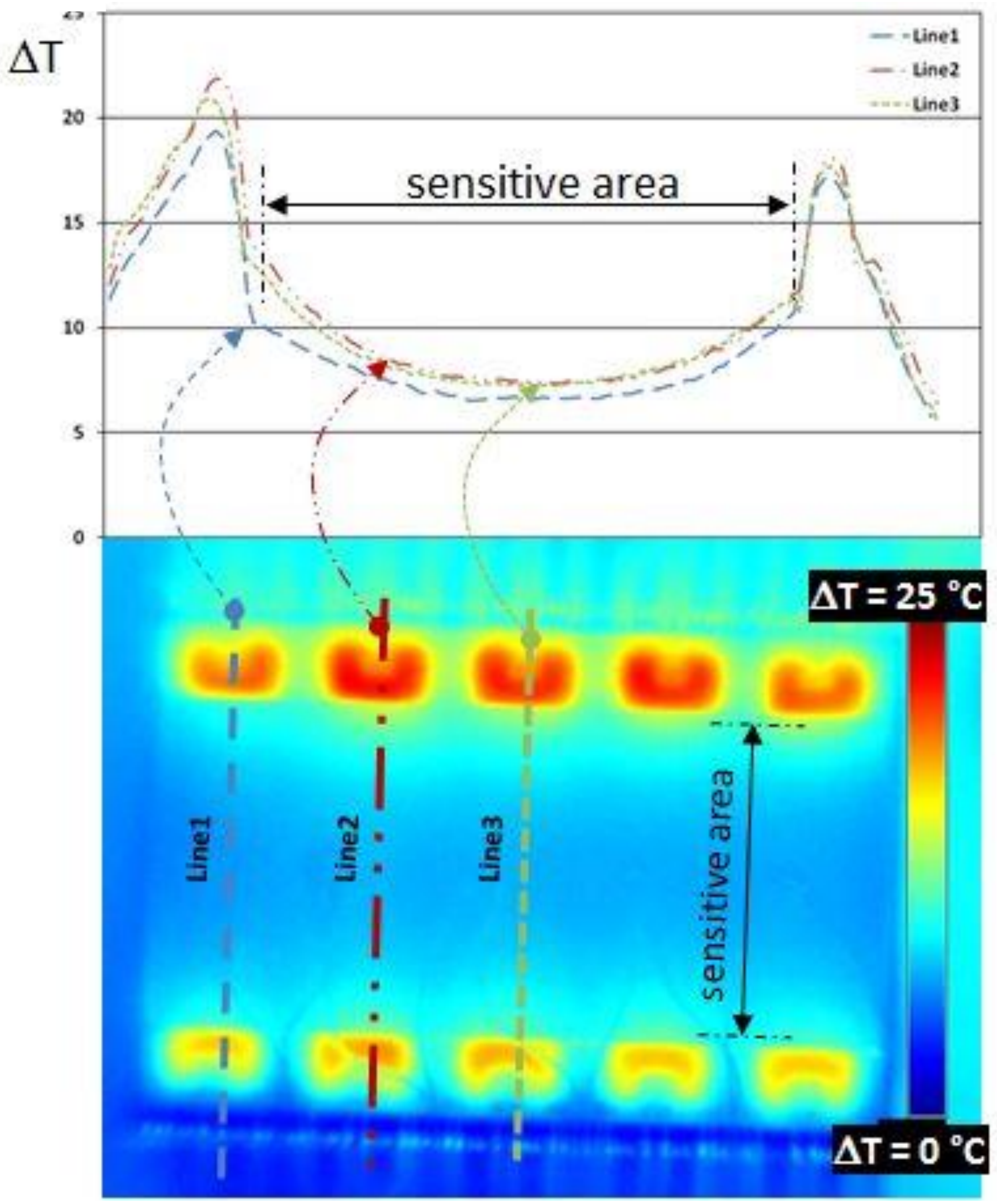
NA62 GTK: first μ-cooled detector





Very first device designed
Liquid cooling (C_6F_{14})
No interface optimization
Tested in vacuum





"ΔT" = (Surface T - Inlet Fluid T)

Worst case scenario:

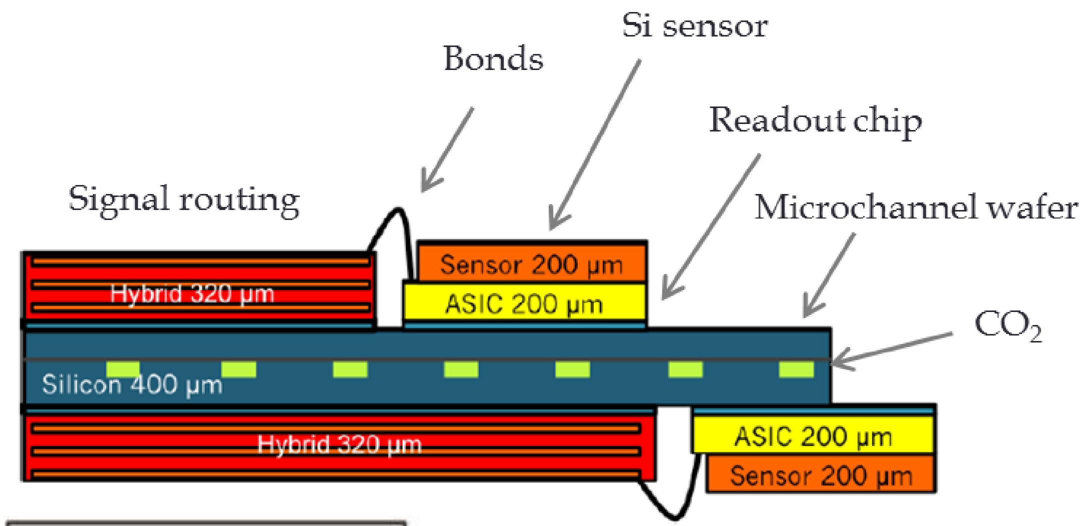
- 38 W on ROC (~5.5 W/cm^2)
- 10 W on Pix Matrix (~ 0.6 W/cm^2)
- 8 g/s liquid C_6F_{14} flow rate

HTC ~ 2500 W/m^{2}K
TFM = 5÷8 [K·cm^2/W]

Highly non-uniform power distribution
Liquid cooling (T fluid increases)

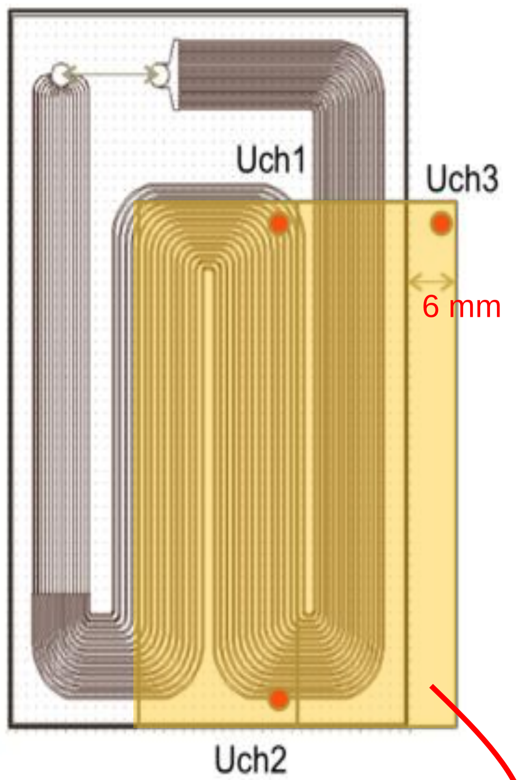
A.Francescon et al: *Application of micro-channel cooling to the local thermal management of detectors electronics for particle physics*,
Microelectronic Journal, Volume 44, Issue 7, July 2013, Pages 612–618

LHCb VELO: μ-cooled CO_2 phase-I upgrade

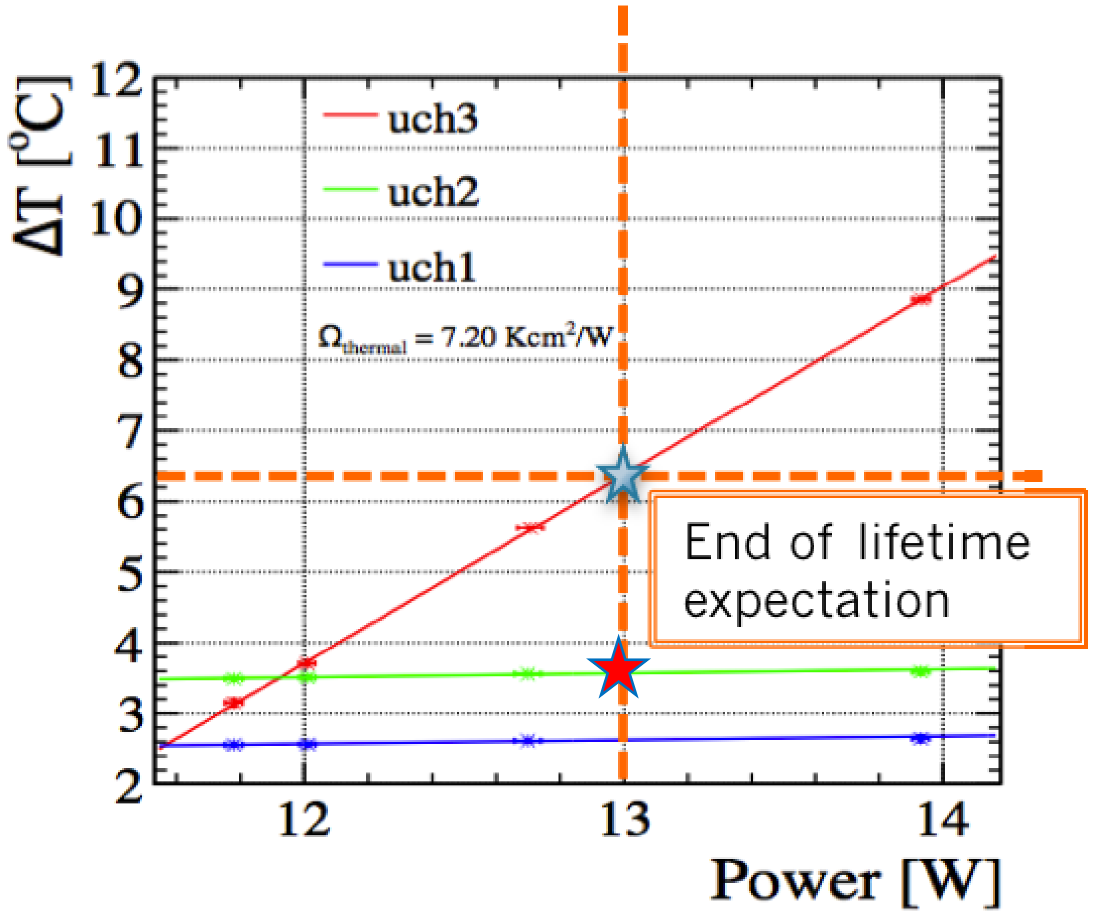


VELO 2018 upgrade:

- **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 evaporative CO_2 !**

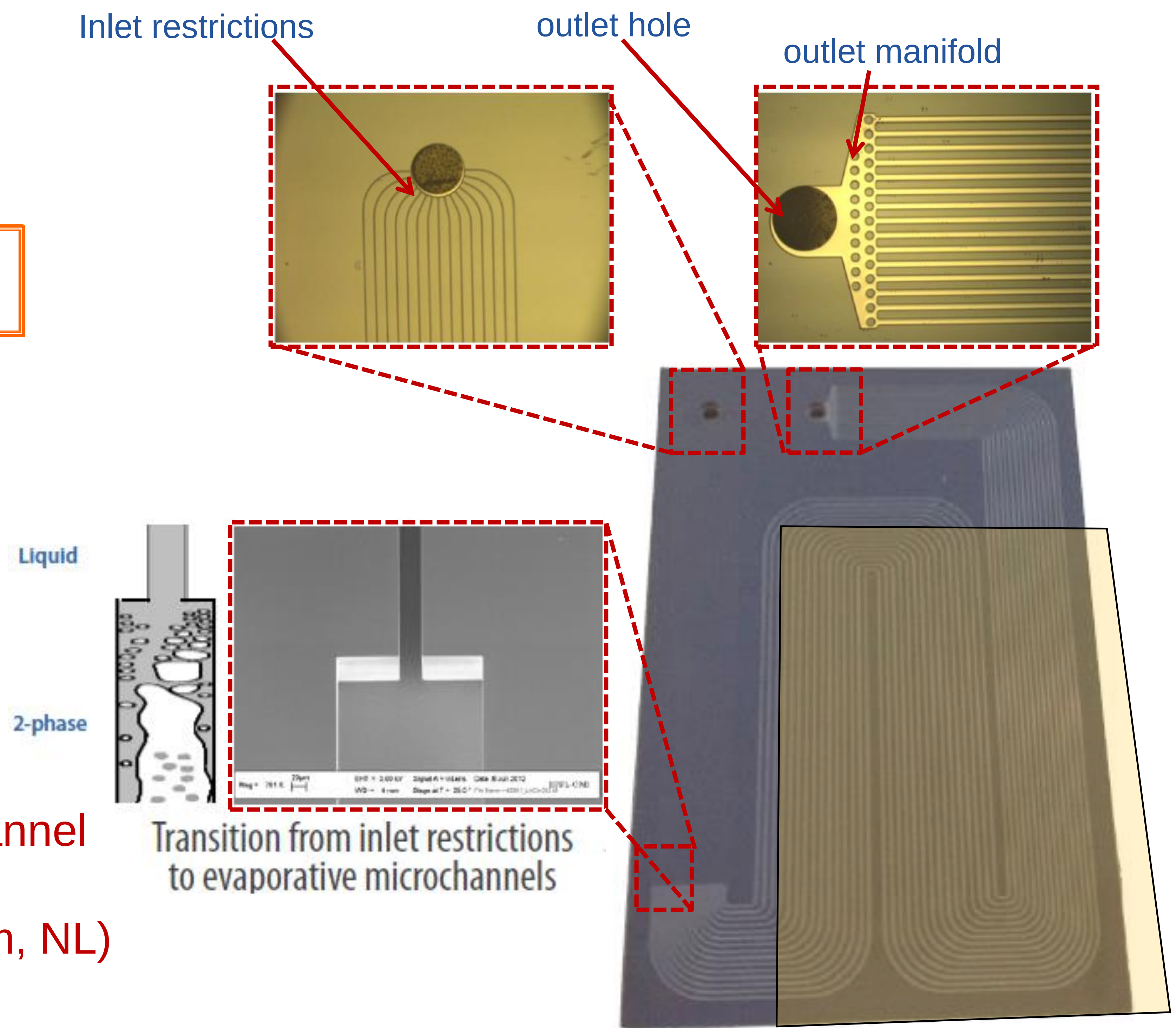


Silicon thermal mock-up for chips and sensor



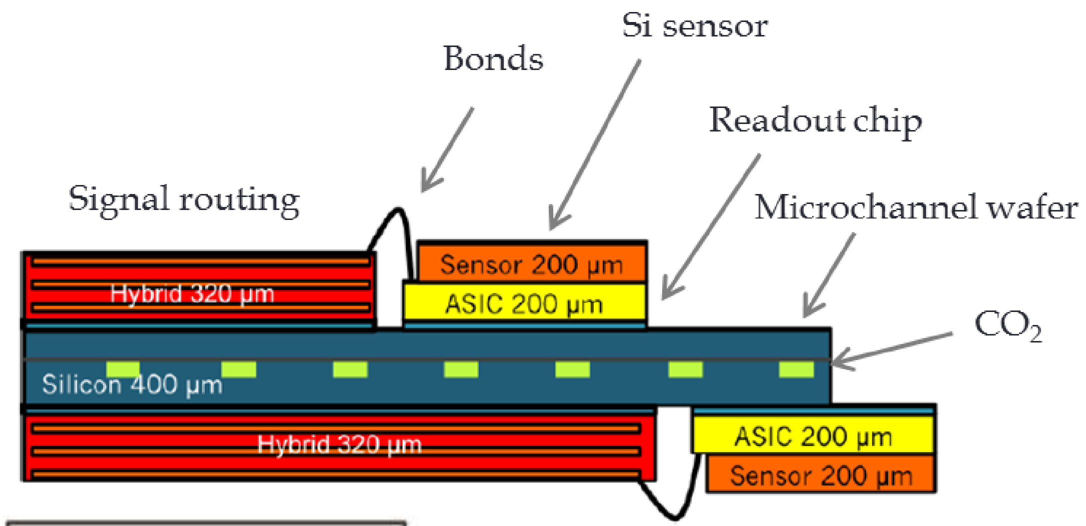
★**TFM = ~3 [K·cm2/W]** (cooled)
☆**TFM = <6 [K·cm2/W]** (cantilevered)

First generation prototype features:



"Progress on the LHCb VELO Evaporative CO2 microchannel cooling" (J. Buytaert et al.)
Forum on Tracking Detector Mechanics 2015 (Amsterdam, NL)
https://indico.cern.ch/event/363327/contribution/29

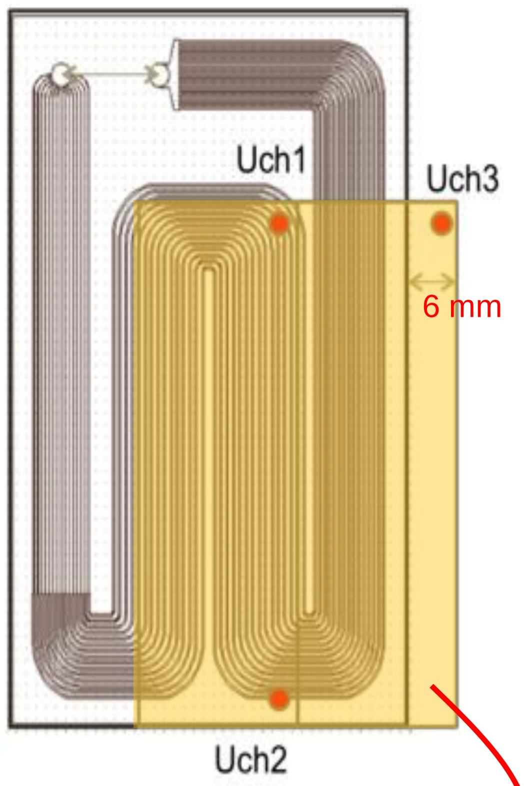
LHCb VELO: μ-cooled CO_2 phase-I upgrade



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**
- **2 rows of 26 modules each**
- **First application of μ-channel cooling with**

First generation



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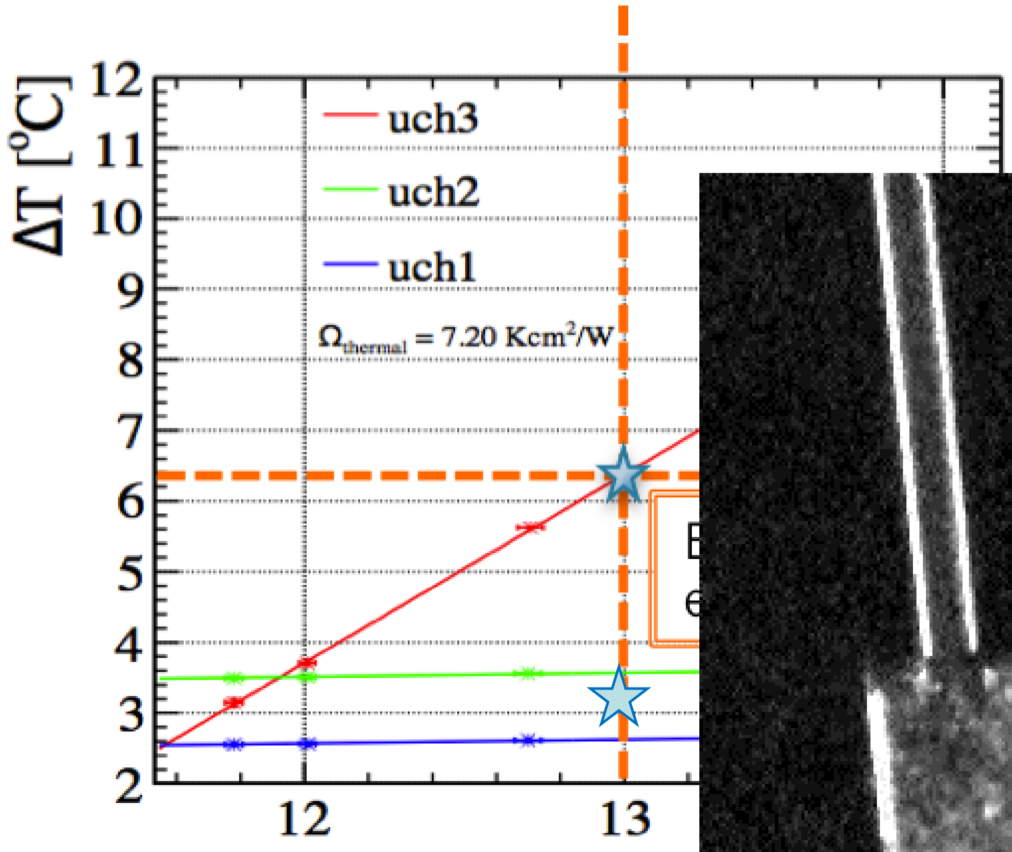
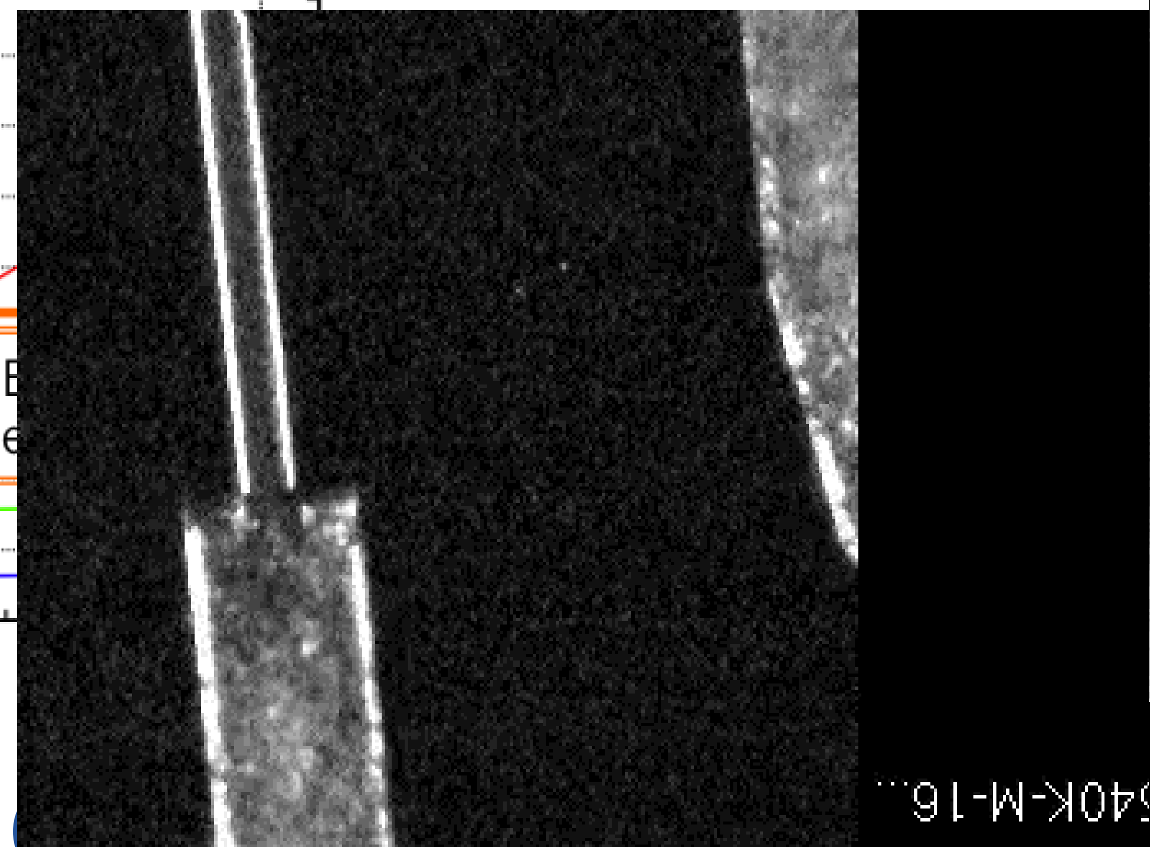
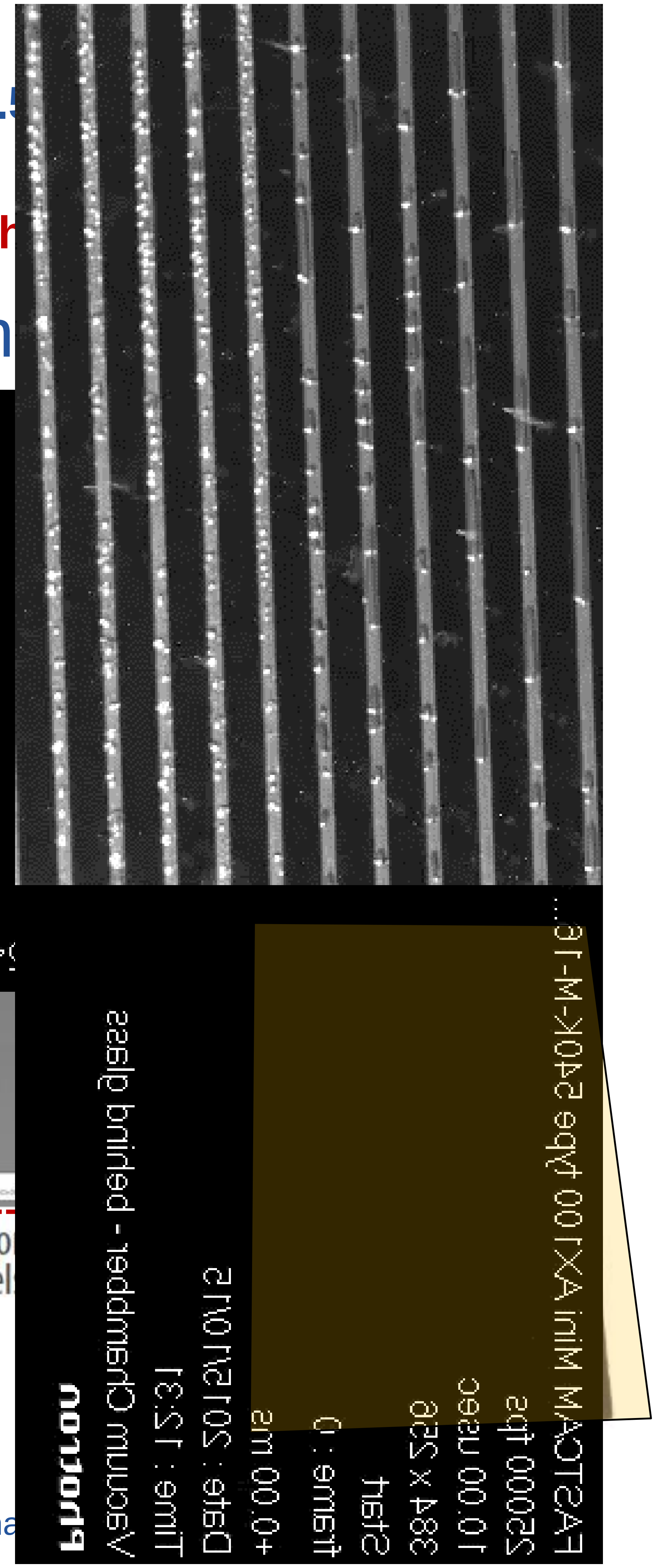
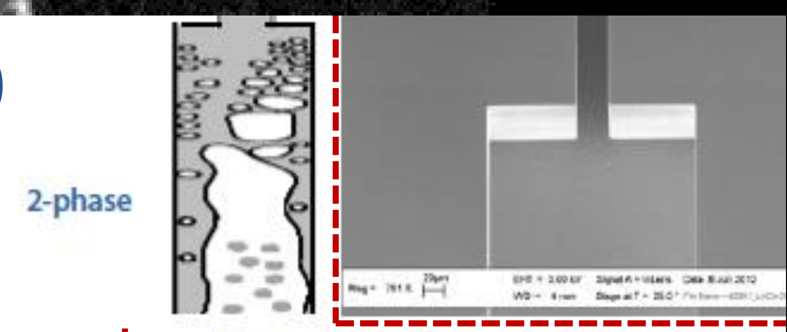






TFM = ~3 [K·cm2/W]

TFM = <6 [K·cm2/W] (cantilevered)



Transition from inlet restrictio
to evaporative microchannel

"Progress on the LHCb VELO Evaporative CO2 microchannel cooling" (J. Buytaert et al.)
Forum on Tracking Detector Mechanics 2015 (Amsterdam, NL)
https://indico.cern.ch/event/363327/contribution/29