Microchannel CO_2 cooling project

A review of the PhD Thesis of Maxime Vacher:

« Study of CO_2 evaporation in micro-channels for next generation of silicon detectors : experimental and numerical approaches»

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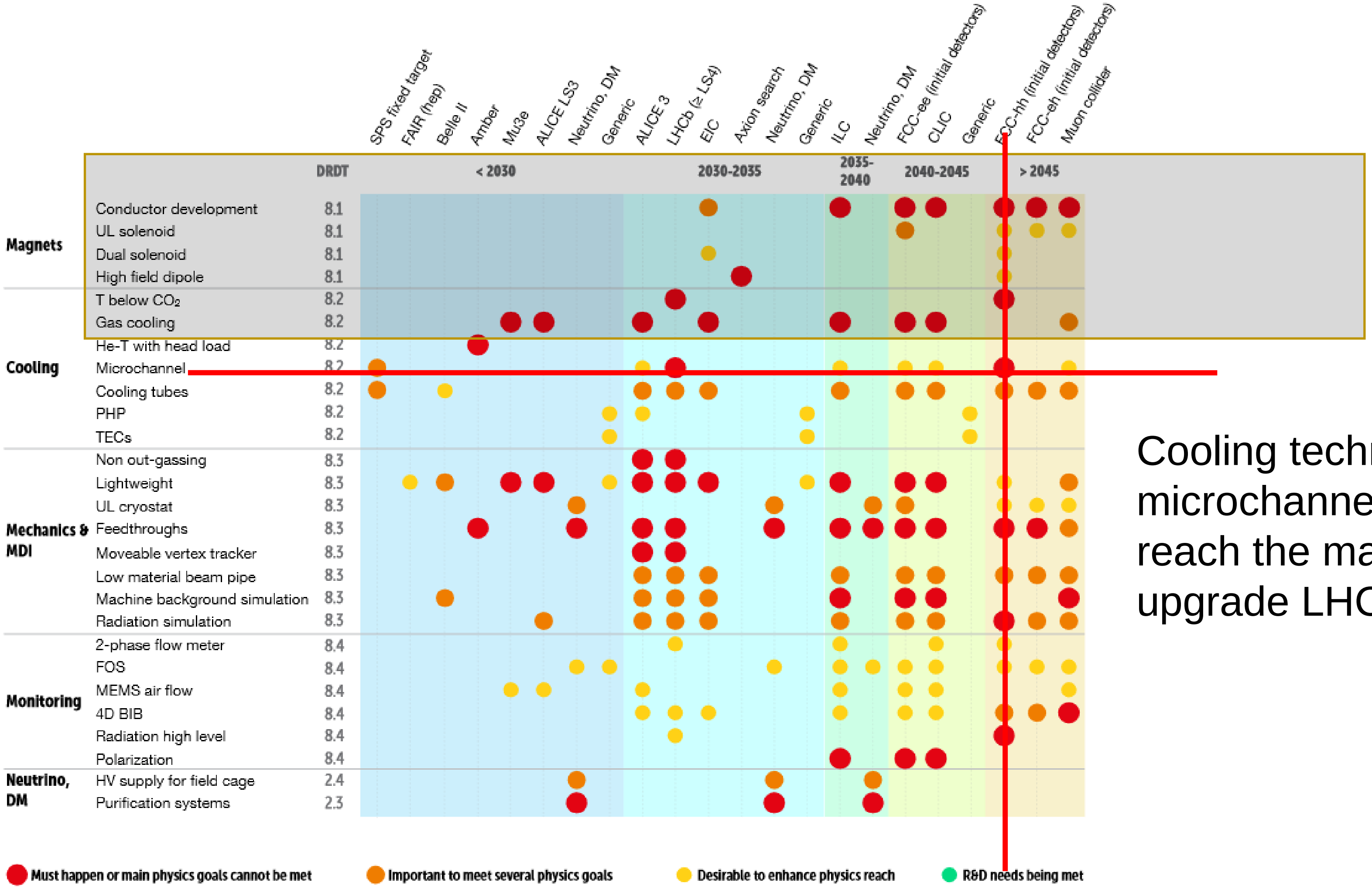
I. Motivation
II. Project organisation
III. Sample micro-fabrication and flow visualisation
IV. Experimental and image treatment results
V. Direct numerical simulations
VI. Conclusion and perspectives

THE 2021 ECFA DETECTOR RESEARCH AND DEVELOPMENT ROADMAP

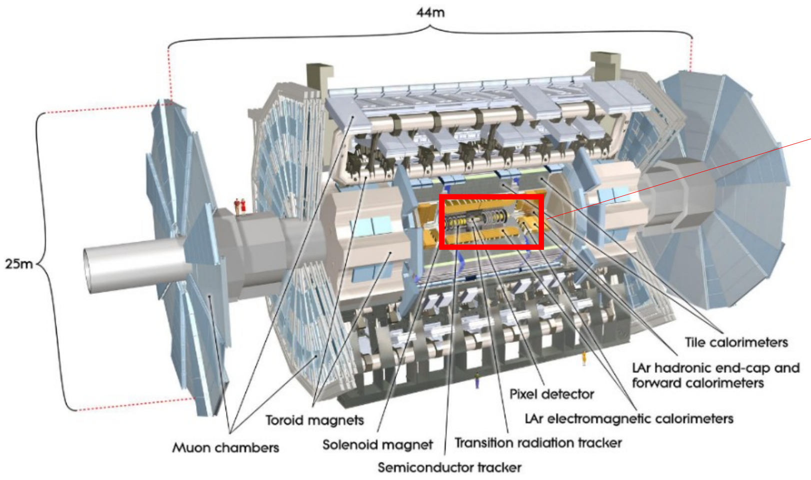
The European Committee for Future Accelerators Detector - R&D Roadmap Process Group



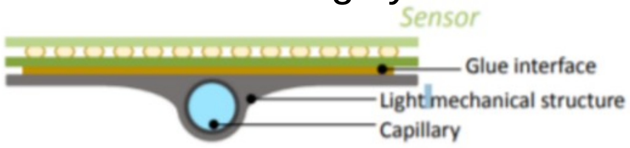
Cooling technic development using microchannels is one of the promising way to reach the main physics goal for FCC-hh and upgrade LHCb

Motivation : Pixel sensor cooling system

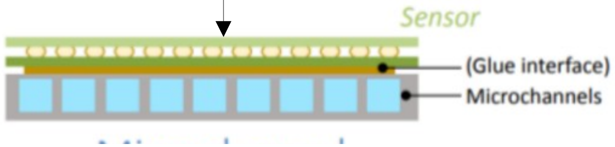
Internal structure of ATLAS experiement (LHC)



Pixel sensor CO2 cooling system



LHC 2029 : Single mini-channel 2.5mm



Next generation : Multi micro-channels 0.2mm

The main constraints for PIXEL sensor next generation cooling system:

- Sensor size : 2x2cm
- Cooling strategy : boilling CO2 in microchannels directly in the sensor silicon matrix
- Cooling temperature -45°C < Tsat < 10°C and power >1 W/cm² (10 kW/m²)
- Low temperature difference between the fluid and the silicon matrix
- Homogeneous cooling with no dry out at the wall = maximale vapour quality of Xmax<40 %
- Microchannels = reduction of the material budget = lower mass and volume of the cooling system

Previous works : AIDA-2020 project shows this solution interessting

Need of complementary studies

Need of flow visualisation and simulation tools

Project organisation :

R&T IN2P3 - 5 Labs involved, not only IN2P3

Stéphan Beurthey
Julien Cogan
Mathieu Perrin-Terrin

Stéphane Jézéquel
Roman Kossakowski

Pierre Delebecque*
Physicist 1

Damien Colombet

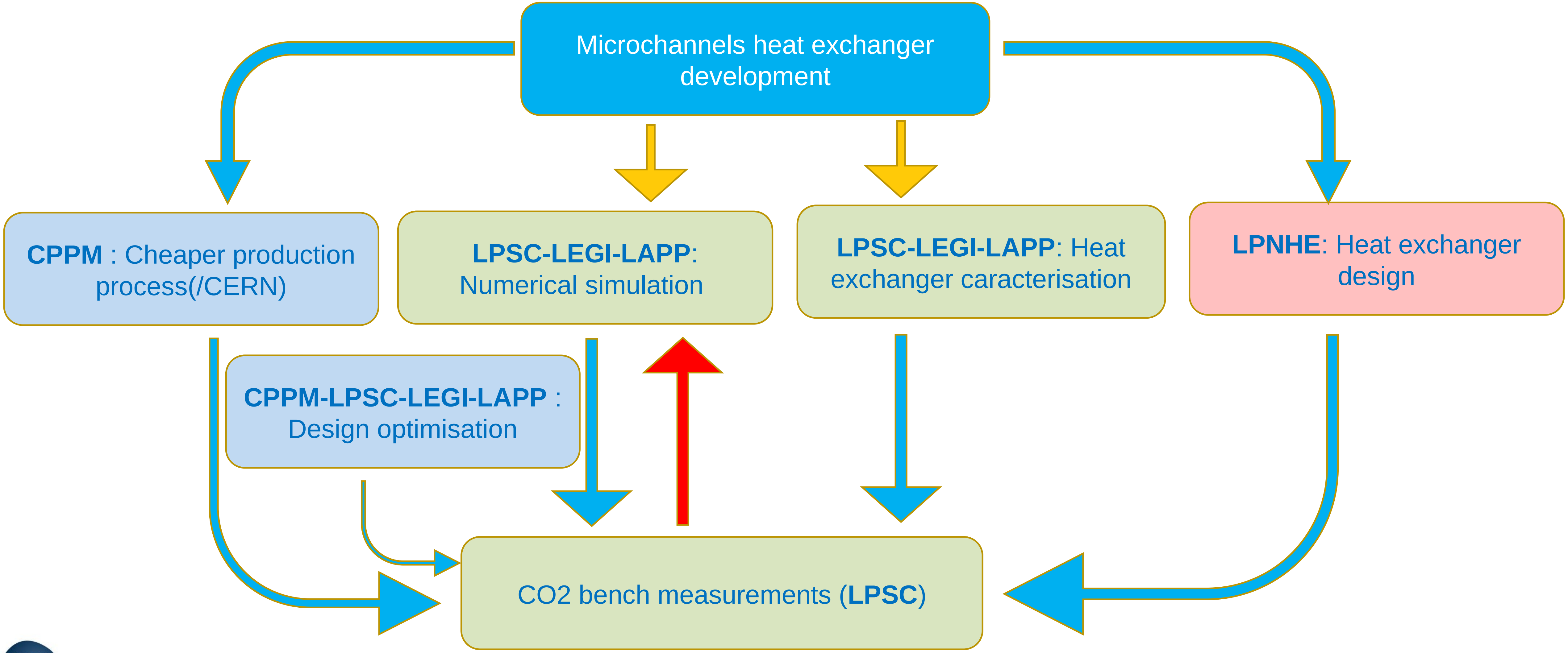
PhD students : Maxime Vacher → Clément Lassagne

Giovanni Calderini
Francesco Crescioli
Yahya Khwaira

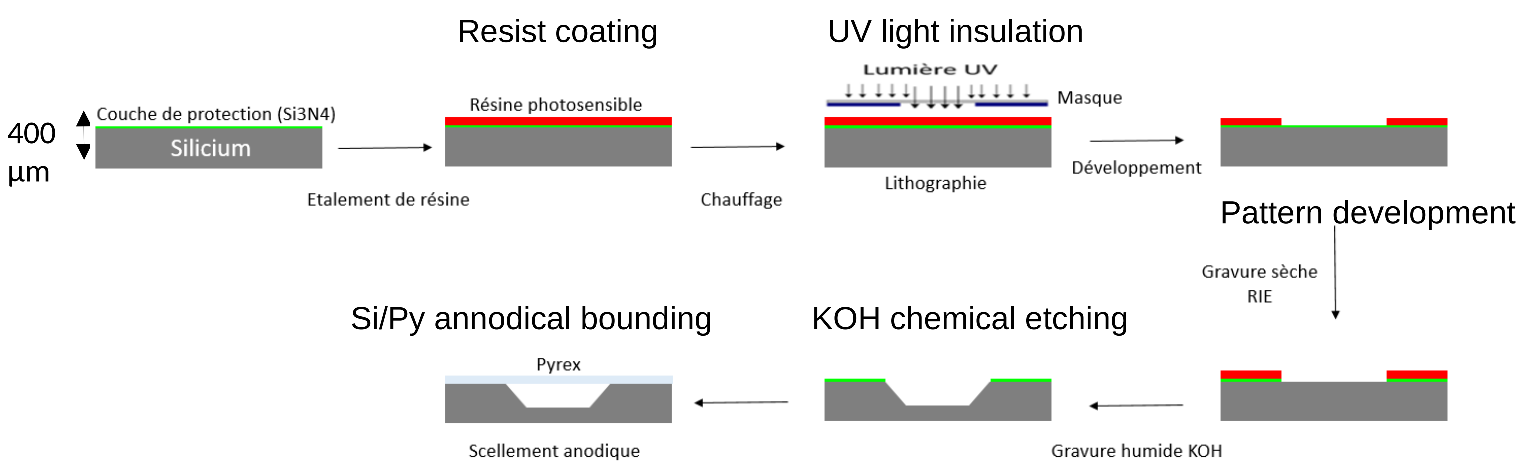
* Project leader

Project organisation :

Scientific and technical activities



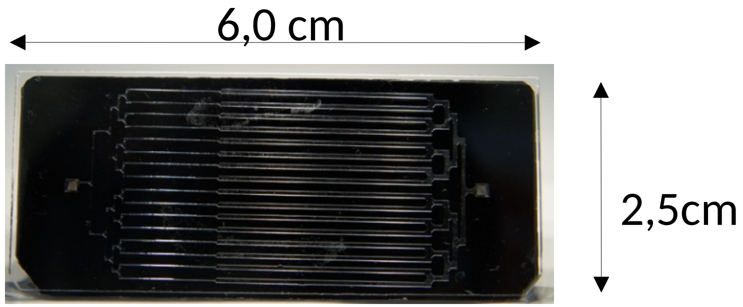
Fabrication of multi microchannels evaporator into a silicon wafer (e ~ 400 µm, D ~ 3 in)

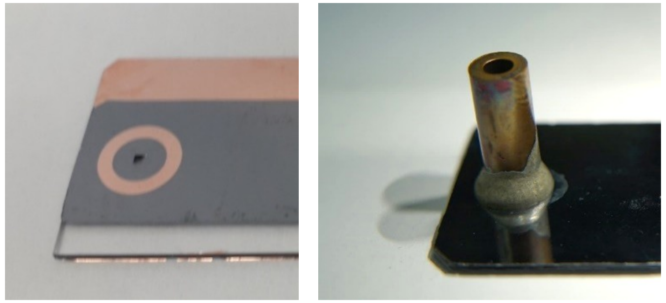


Commercial connection with glue Pmax<20bar

5 days

~40 steps

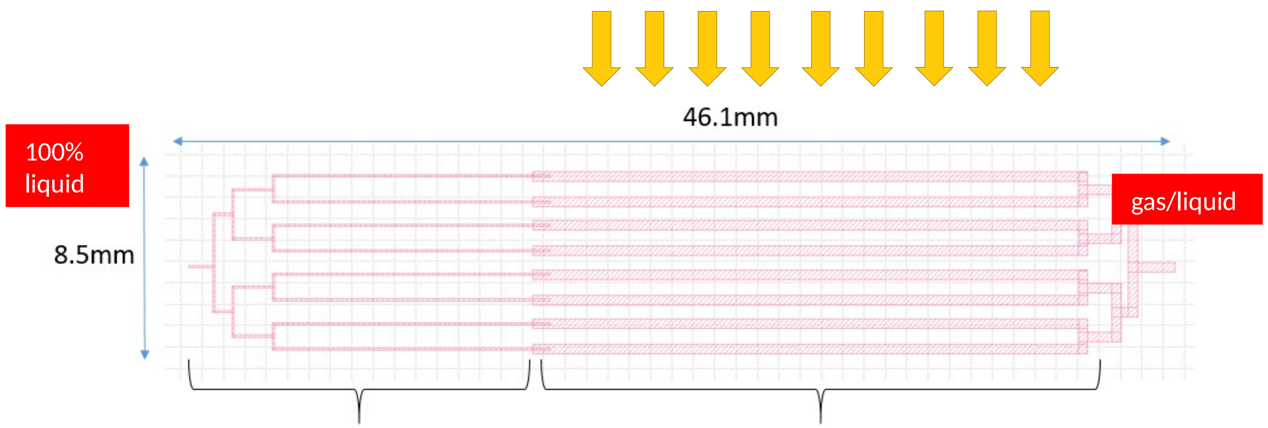




Home-made connection with tin soldering Pmax=70bar

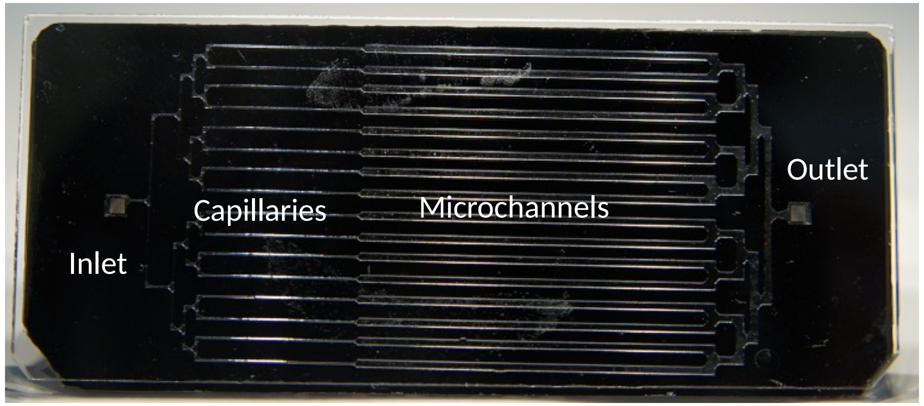
IN2P3 Les deux infinis

Sample design and equipment

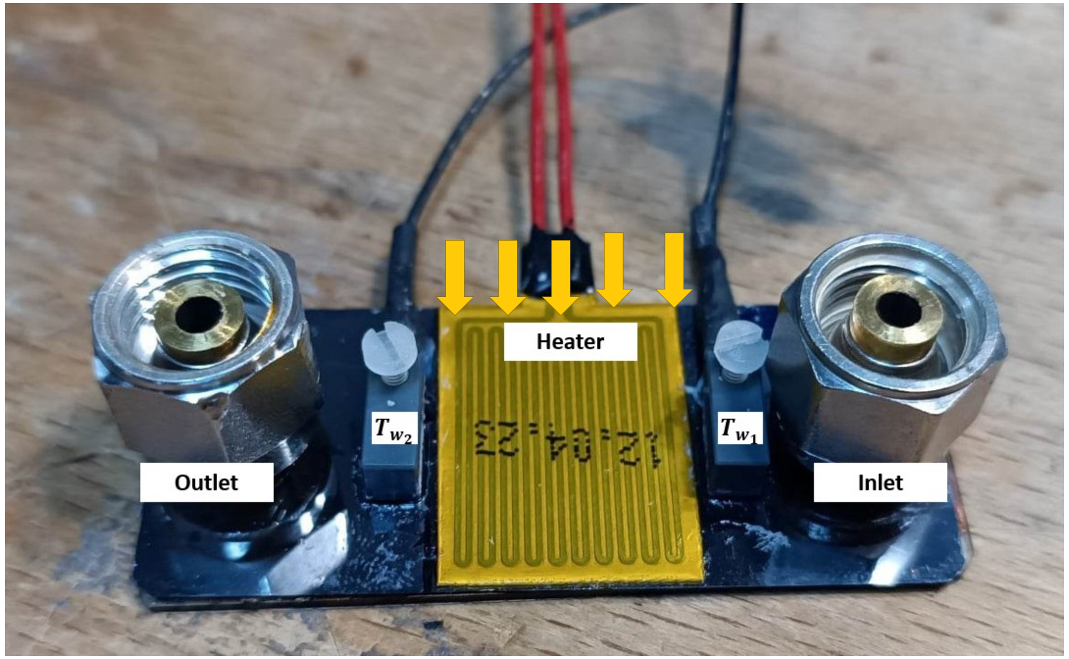


Pressure decrease
= bubble generation

Bubble growth
= silicon cooling



Front view



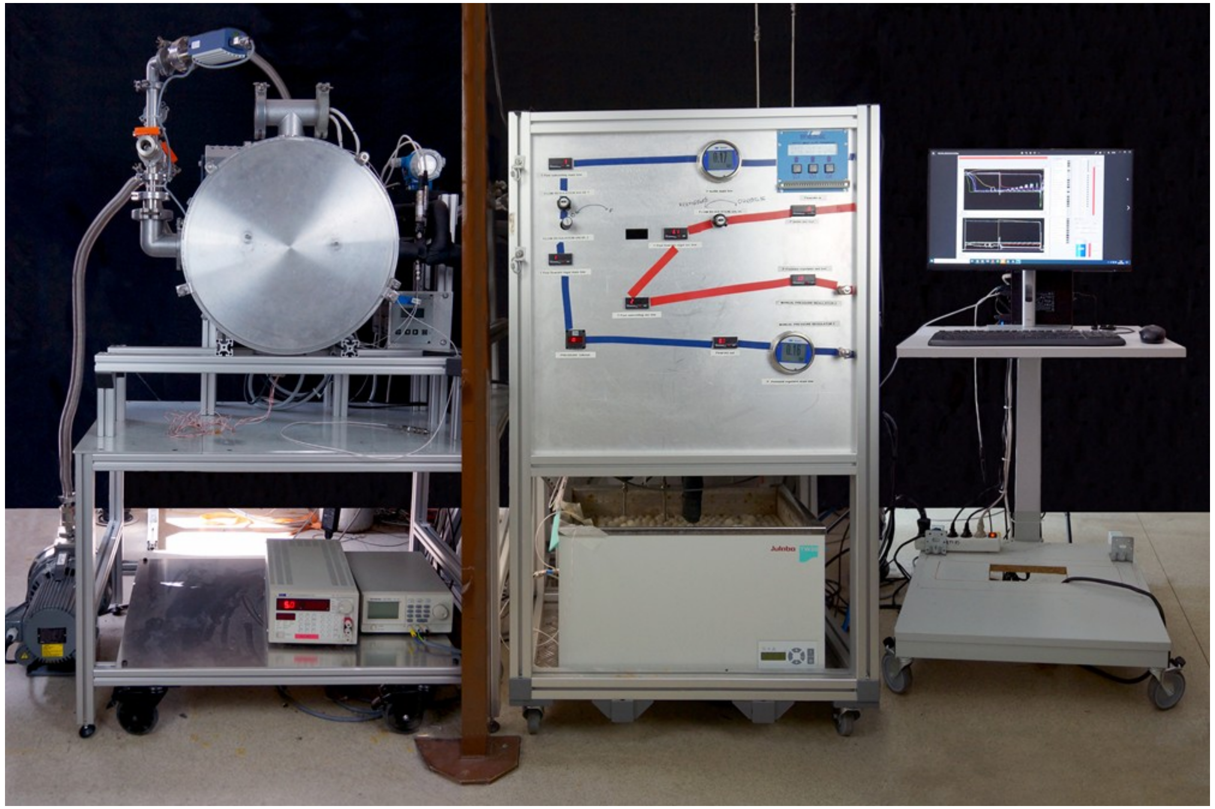
Back view

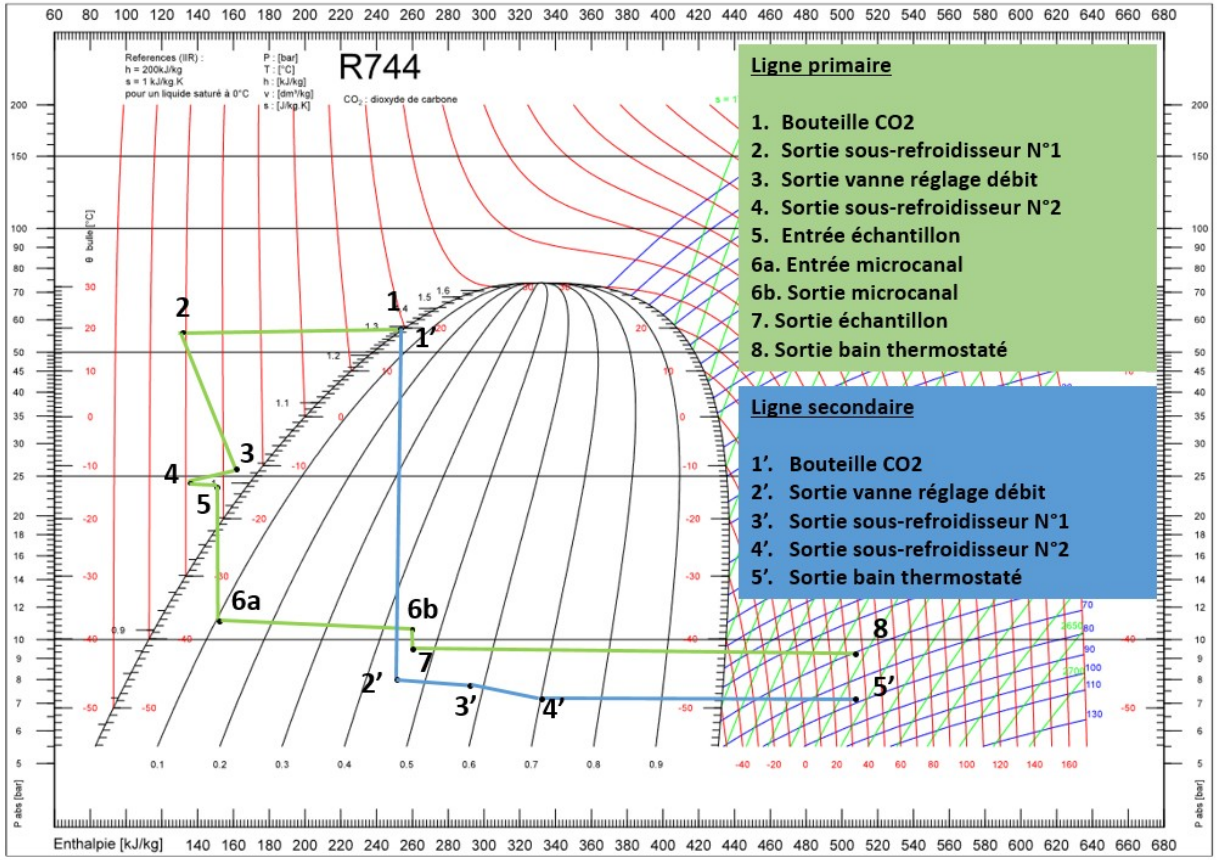
Heat transfer coefficient $h=P_{th} / S / (T_w-T_{sat})$

Nusselt number $Nu=h\, D_h / \lambda_L$

Experimental installation

P.Barroca 2016-2019: cooling efficiency CO2 boiling flow Dh=2.5 mm titan pipe
M.Vacher 2021-2024: cooling efficiency CO2 boiling flow Dh=200 µm silicon chip



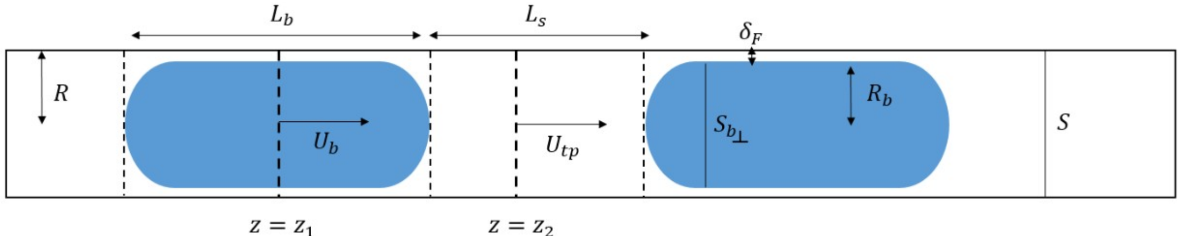


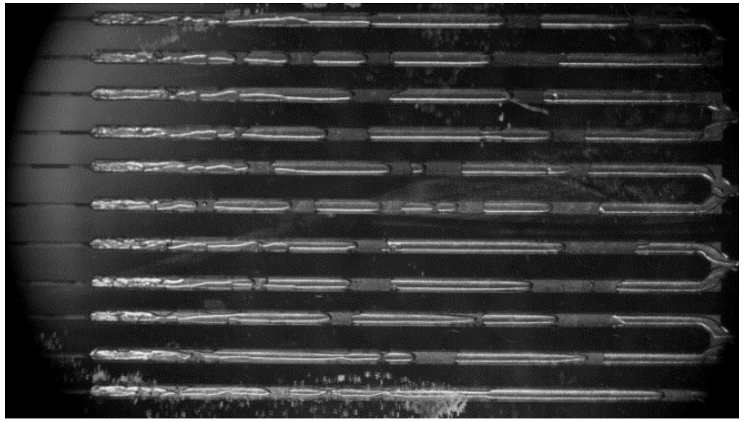
- Open loop system with two lines and 2 subcoolers for managing low flow rate (<1g/s) with the constraint of being 100 % liquid at the sample inlet
- Operating cooling temperature : Tsat = -35°C

Flow visualisation

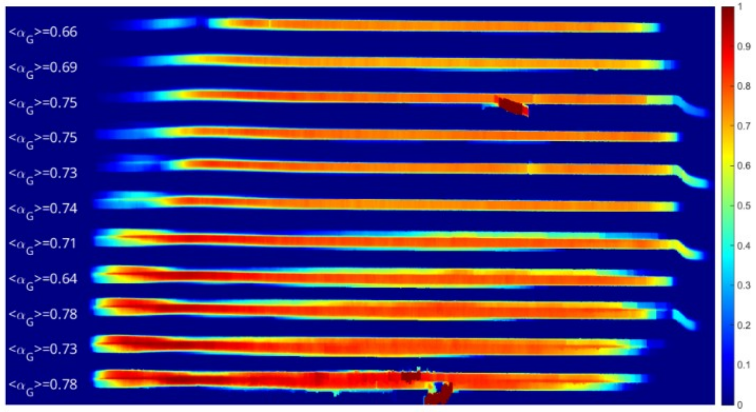
High speed camera + binocular + Lighting

• Bubble length	Lb
• Liquid slug length	Ls
• Bubble velocity	Ub
• Bubble frequency	fb
• Bubble growth rate	dLb/dt
• Gas volume fraction	$\alpha = V_V/(V_V+V_L)$
• Vapour quality = gas mass fraction	$X = m_V/(m_V+m_L)$





Raw image



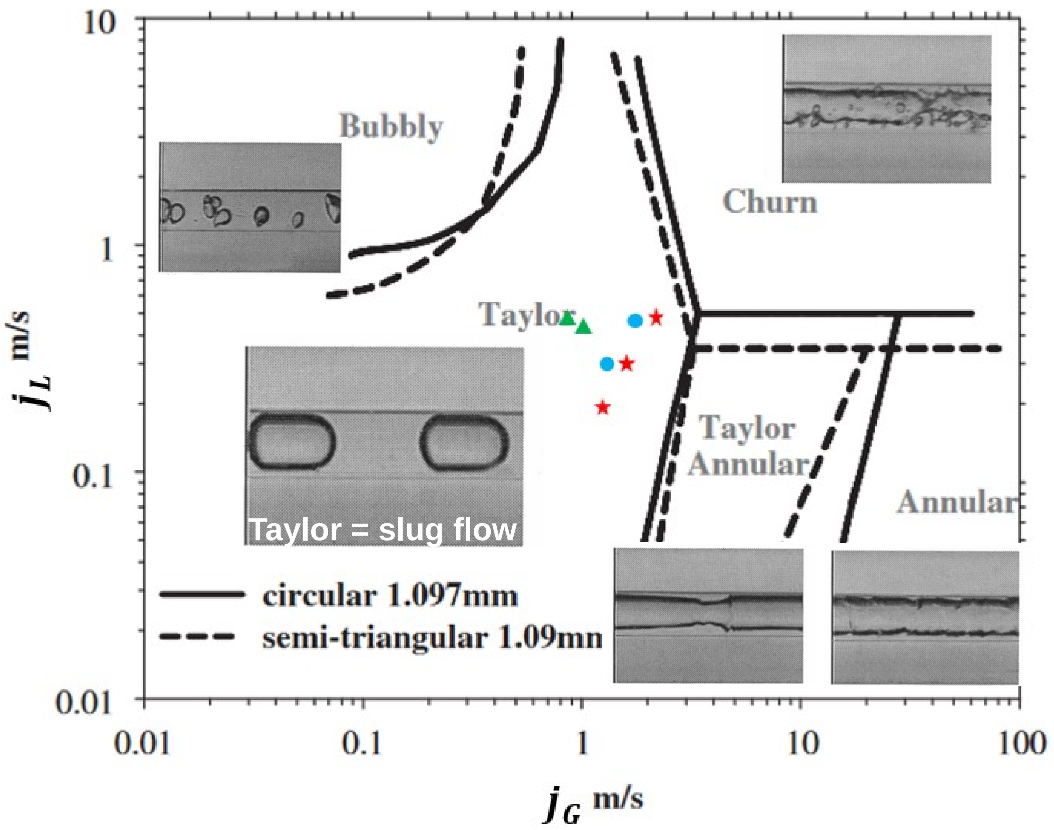
Gaz volume fraction field

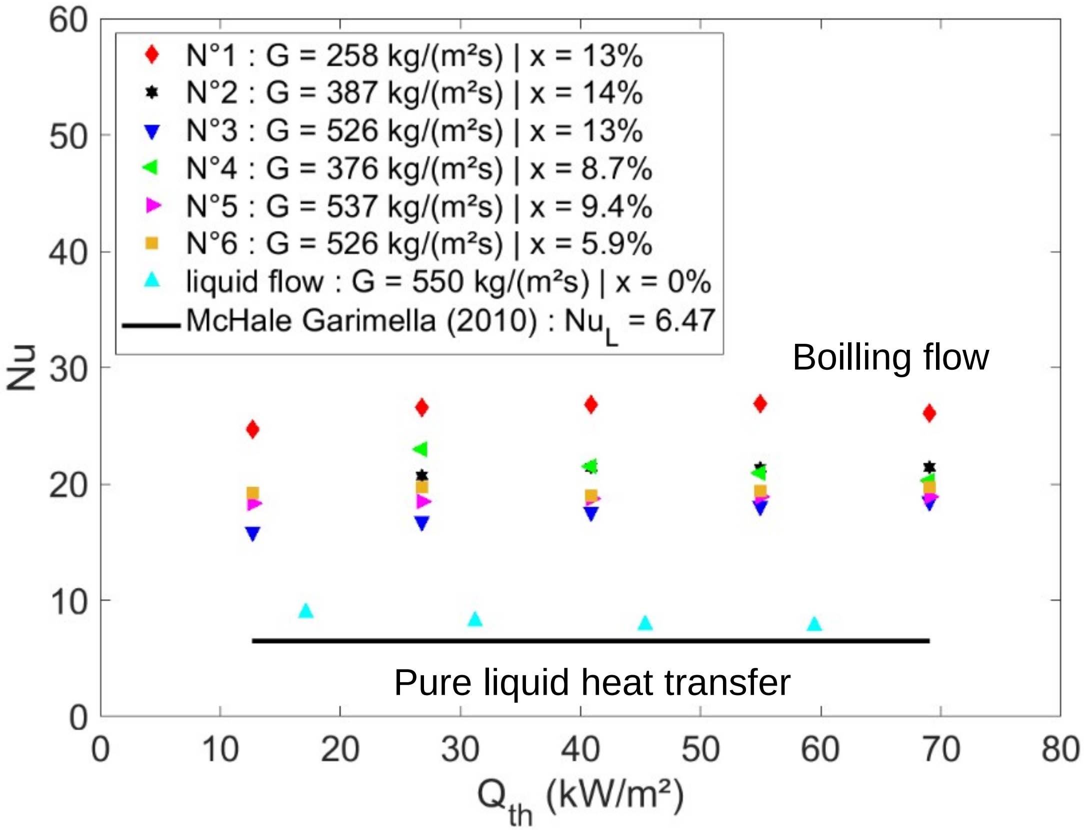
CNRS IN2P3 Les deux infinis

Bubble contour detection (slow down x100)

See the movies

Experimental flow regime and heat transfer



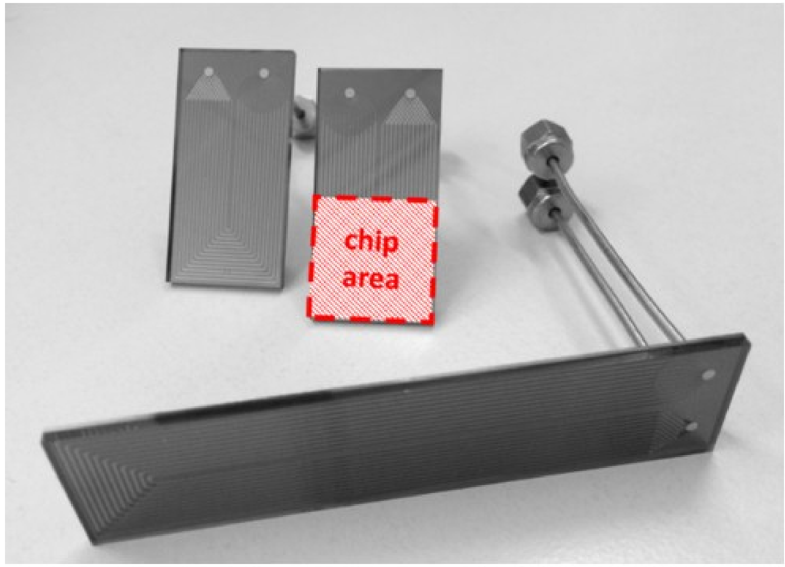


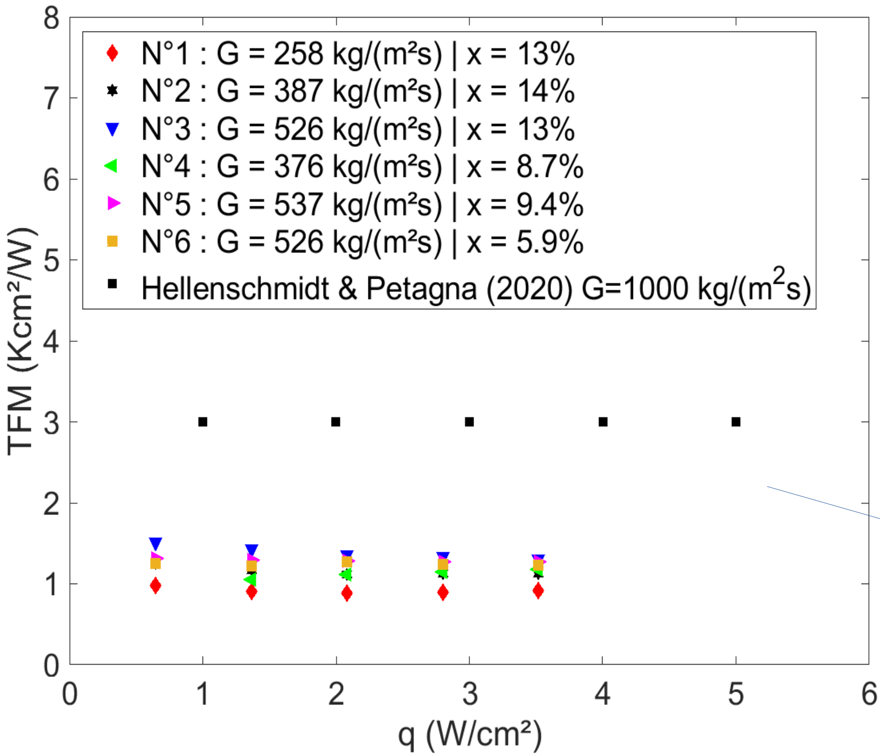
- Flow regimes are found to be consistent with prediction given by the flow map of Triplet(1999) + slug flow dominate
- As expected heat transfer with evaproation is more efficient than with 100% liquid flow
- Measurement of heat transfert (Nusselt number) is as expected independant of Qth

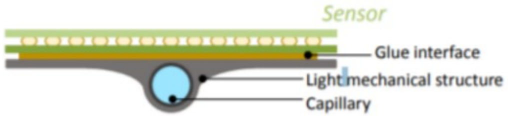
But is found to decrease with the flow velocity

- Solid/Liquid temperature difference is estimated through the « Thermal Figure of Merit »
- Our results confirm CERN's results: no effect of heat flux on TFM
- Proposed chip design « LEGI-LAPP » = same TFM values

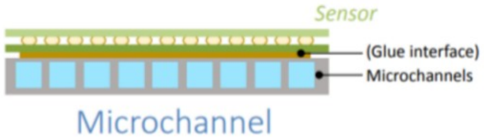
$$TFM = (T_w - T_L)/(P_{th}/S_h)$$







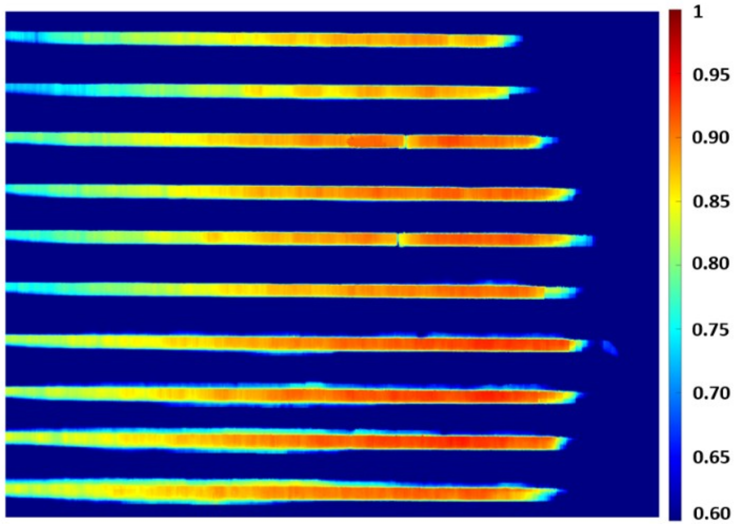
Single mini-channel 2.5mm
→ TFM ~ 12 Kcm2/W



Multi micro-channels 0.2mm
→ TFM < 3 Kcm2/W

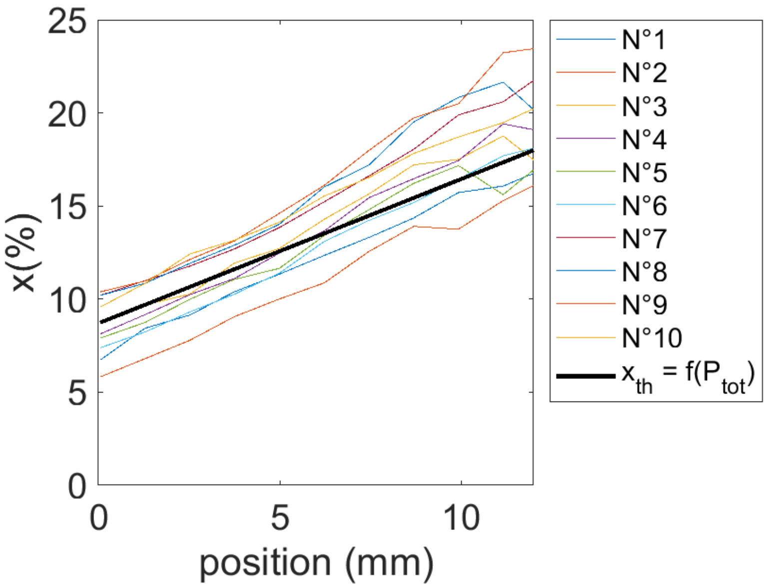
Image traitement –vapour gas fraction, quality and bubble length

Homogeneous flow rate, flow regime and gas fraction field for Xin>8 %

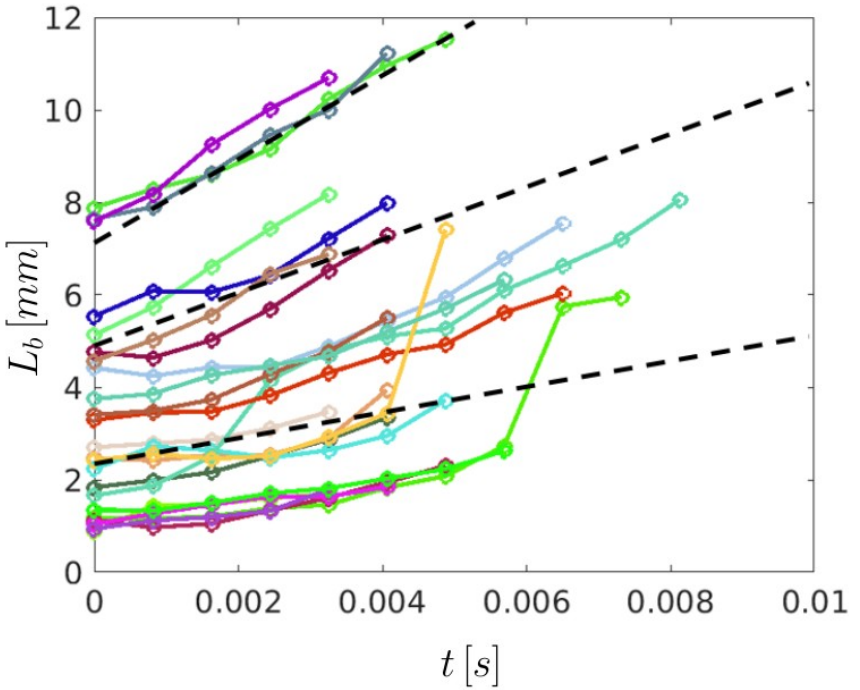


Theoretical vapour quality variation
= consistent with the thermal balance

Xmax=25 % <40 % no dry out



Theoretical bubble growth rate
= proposition of a new model linking heat flux and bubble dynamics



$$L_b(t) = L_{b-ini}\,(1 + \gamma t)$$

$$\gamma = \frac{Q_b P_b}{L_{vap}\rho_G S}$$

$$Q_b = \frac{P_{tot}}{< n_b >< S_b > N}$$

Direct numerical simulation of heat transfer in the slug flow regime

Numerical conditions very close to the experiment

Same fluid (CO_2), temperature (-35°C), hydraulic diameter

But in 2D axisymetric (circular tube) and no evaporation

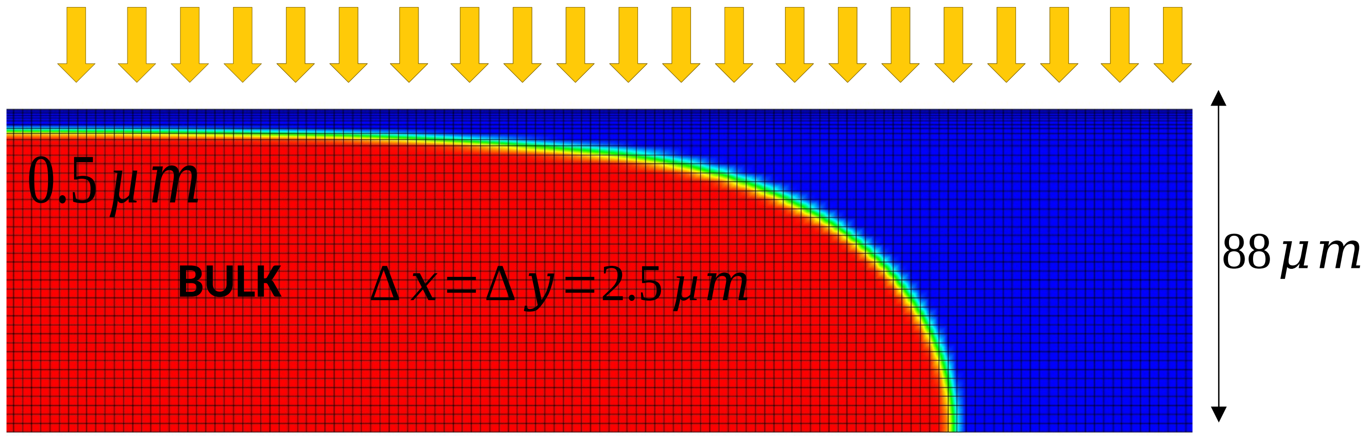
Similar heat transfer steps than in boiling flow

- A heat flux is imposed at the wall that heats the liquid

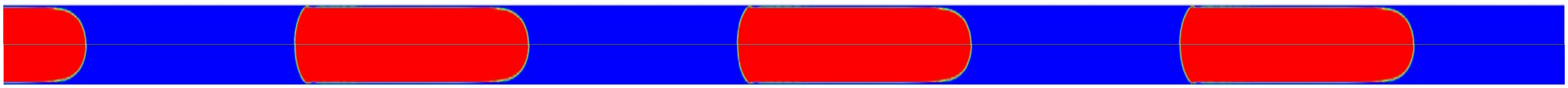
- Then, the liquid is cooled down by the bubbles

because the bubbles are set at saturation temperature

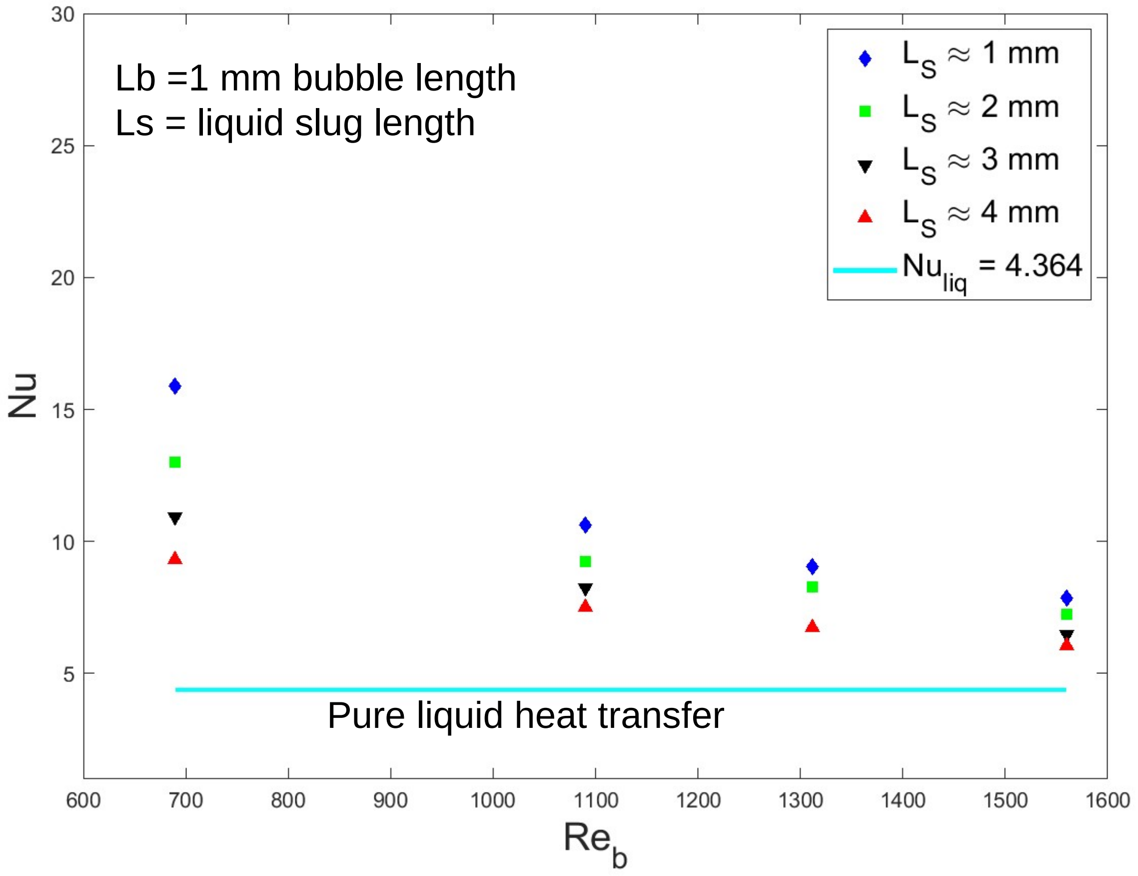
(TG=Tsat, thermodynamic equilibrium)



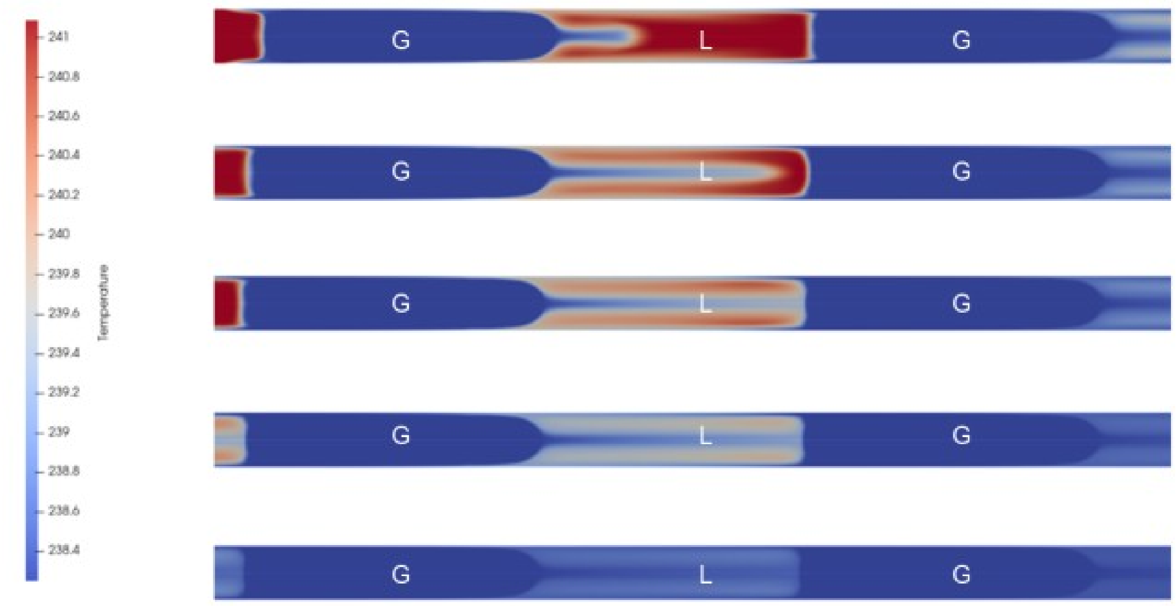
Gas volume fraction field with the mesh



Heat transfer results with heated wall



Reynolds number $Re_b = U_b D_h \rho_L / \mu_L$



- Again, as expected, heat transfer more efficient than pure liquid flow
- **Simulations confirm the decrease of Nu with flow velocity (Re) as observed experimentally** + effect of Ls is found
- Due to the increase of the liquid thickness ? decreasing normal wall temperature gradient = complementary analysis needed
- Experimental Nusselt number 2 to 3 times > numerical one because no evaporation is considered

I. Sample micro-fabrication
II. Flow visualisation
III. Experimental results
III. Image traitement
IV. Direct numerical simulations
IV. Conclusion and perspectives

Conclusion

Experimental study

- Fabrication silicon/Pyrex multi-channels chip with low hydraulic diameter (<200µm) and pressure resistant (70 bar)
- Characterisation of thermal performance (h, Nu) with flow visualisations on a 16 channels chip @ Tsat=-35°C

→ The predominant flow regime = slug flow because of confinement + in agreement with Triplett flow map

→ Thermal performance close to CERN's chip (TFM<3K cm2/W) + no dry out (X <40%)

+ homogeneous flow repartition + cooling power of 3 W/cm² = design suitable for Pyxel sensors

→ Observation of a decrease of heat transfer efficiency (Nu) with the flow velocity

Numerical study

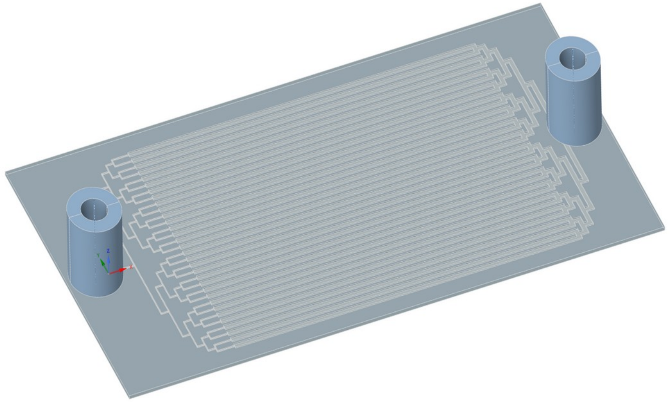
- Direct numerical simulations of 2D slug flow with VOF method without phase change (just wall heating)

→ From litterature data = validation of pressure losses, bubble slip velocity and adiapatic heat transfer efficiency (Nu)

→ Simulations confirm the decrease of the Nusselt number with the flow velocity

→ This results from the increase of the liquid film thickness but also from the mixing in the liquid slug = need more analysis

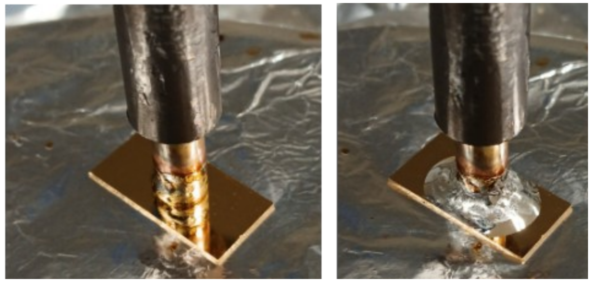
Experimental approach (New thesis : Clément Lassagne)



- Fabrication of new samples (32 channels instead of 16)

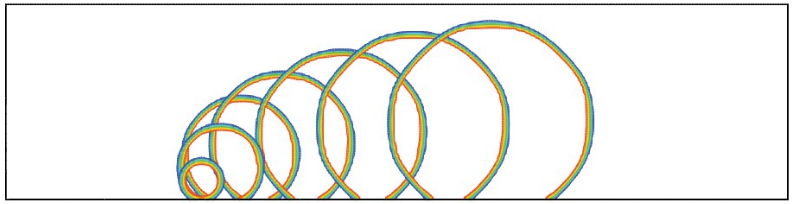
to decrease flow velocity = more stable flow regime (lower Reynolds number)

- Investigate évaporation at higher temperatures (>-25°C) since more documented
- Micro-fabrication of temperature sensors directly at the sample wall for more accuracy
- Improve the process of connection tin soldering (50 % success currently)



Numerical simulation approach

- To identify a new correlation to describe heat transfer in slug flow regime without phase change
- To add phase change with an evaporation model



Nichita & Thome 2010

Thanks for your attention