MICROCHANNEL COOLING

Prospectives IN2P3 – GT08
24 January 2020

CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE
CPPM

S. Beurthey
J. Cogan
G. Hallewell
O. Leroy
M. Perrin-Terrin

LAPP
Laboratoire d'Annecy de Physique des Particules

P. Delebecque
S. Jezequel
J. Leveque

LPNHE
PARIS

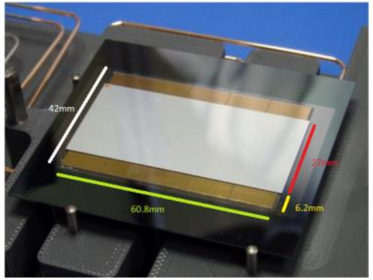
M. Bomben
G. Calderini

OUTLINE

- Thermal management problematic for pixel sensor
- Cooling with Si microchannel
- Silicon microchannel cooling applications
- Aida 2020 ongoing developments
- Silicon microchanel cooling optimization @IN2P3

THERMAL MANAGEMENT PROBLEMATIC FOR PIXEL SENSOR

Future pixel sensors will require more and more cooling



NA62 – GTK sensor

Active elctronic consumption

LHCb : 0.5 W/cm²

LHCb upgrade I (2021) or ITK : ~2 W/cm²

LHCb upgrade II (2034) : ~ 3 - 5 W/cm² (estimation)

Thermal management issues

- Lifespan > 10 years - Availability and reliability : 7/7
- High magnetic field – High radiation

- Material must be minimal
- Sensor T<<0°C
- Coolant T cannot be lowered at will : low TFM

Micro/nano technologies progress

Etching size reduction

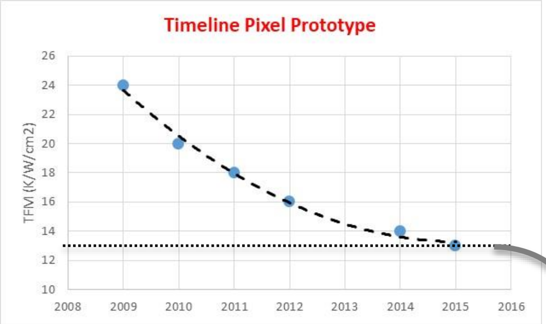
Consumption reduction

Current Trend

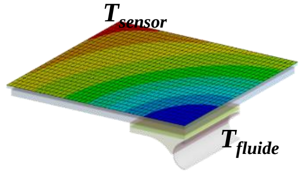
Densification

Time resolved pixel

Consumption increase



TFM for Conductive cooling



$$TFM = \frac{(T_{sensor} - T_{fluide})}{Surface\ power\ density}$$

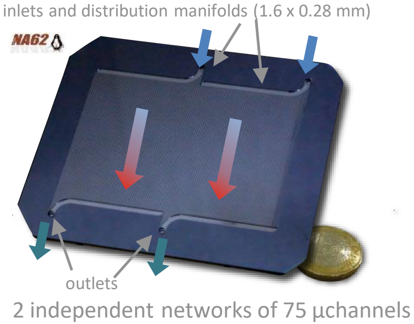
P= 2W/cm² & T_{fluide} = -35 °C

→ T_{sensor} > - 9°C

COOLING WITH SI MICROCHANNEL

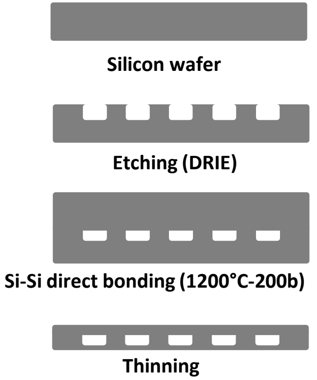
μ-fluidics (microchannel) device as **heat exchanger** for thermal management of heat source

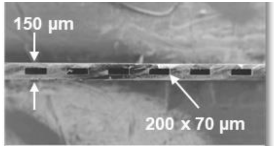
Equivalent Diameter < 1 mm **Single or dual (boiling) phase flow**



Microchannel on NA62-GTK

Microchannel etched on Si wafer



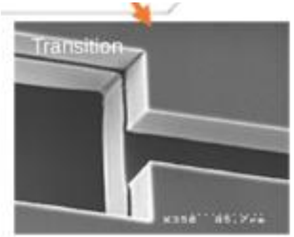


- Locally distributed cooling
- Large thermal exchange surface
- Minimal path of thermal resistances
- Low X_0
- Temperature Homogeneity
- Radiation hard
- Compatible with "HEP fluids"
- No CTE mismatch with Si

Minimizing TFM

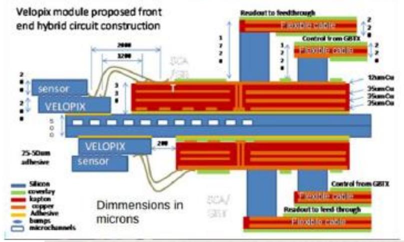
Typically TFM for Si cold plate circulating boiling CO_2 is lower than 3 K.cm²/W

SI MICROCHANNEL COOLING APPLICATIONS

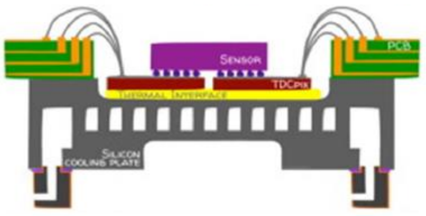


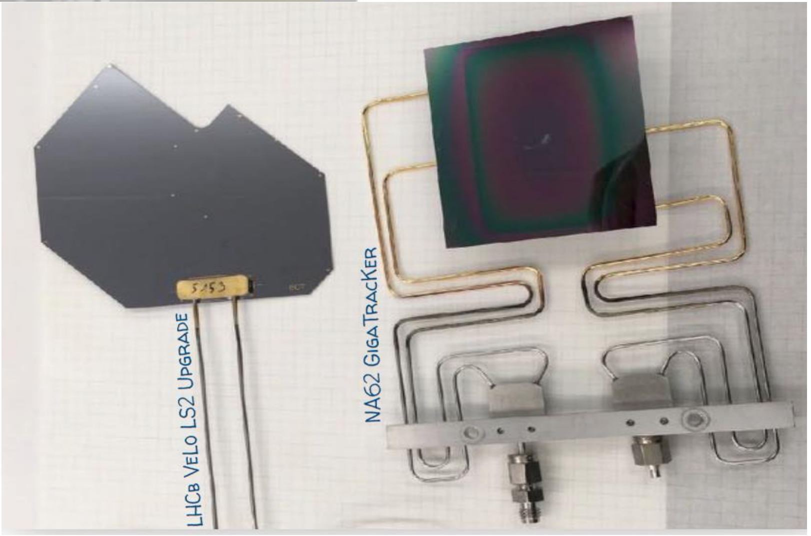
Chanel restriction (LHCb-Velo)

LHCb-Velo (Boiling CO_2)



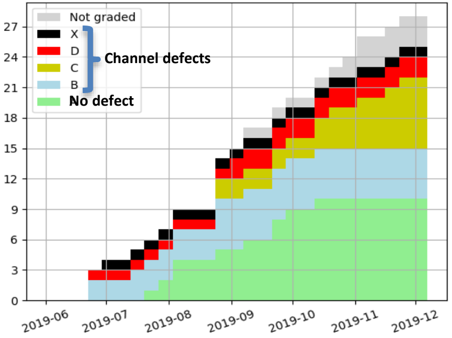
NA62-GTK (Liquid C6F14)





Advantage

- Low TFM (~3Kcm²/W)
- Minimum material budget: very thin coldplate (250-500µm)
- No CTE mismatch with Si sensor
- Channel failure has little impact on cooling



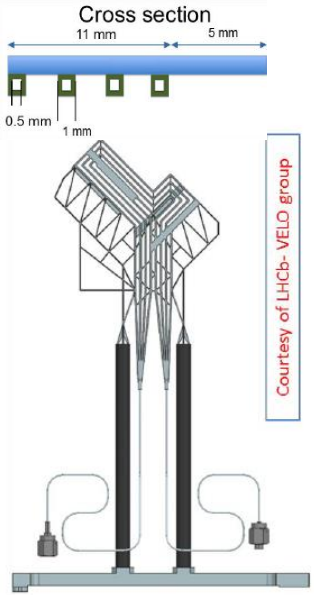
Silicon microchannel production on LHCb

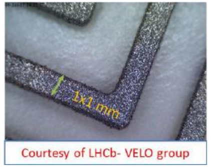
Drawback:

- Expensive process (>120 steps)
- Size limitation
- Few competent subcontactors
- Direct bonding difficult
- Bad prod. Output
- Simulation not enough predictive

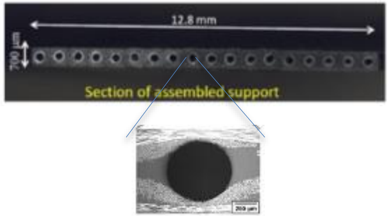
AIDA 2020 ONGOING DEVELOPMENT

Alternative process

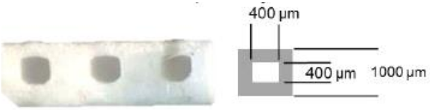




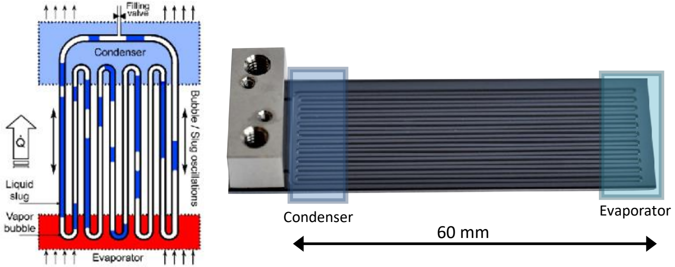
Ti 3D printing
- Low mass
- Cheap
- Easy to integrate



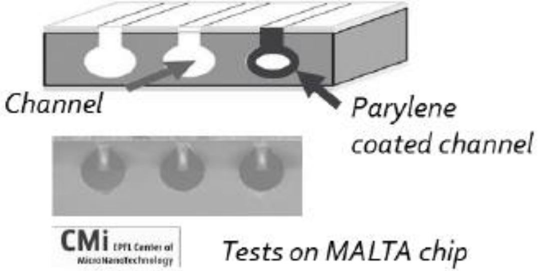
Carbon microvascular
- Ultralight
- Can be very long



Céramic 3D printing
- Lighter than metal
- Flexibility
- CTE compatible



Micro oscillating heat pipe: « caloduc »
- No pump
- Self-contained and self-actuated.
- Eliminate connectors



Microchannel back to sensor
- CMOS Compatible
- Silicon advantage
- No bonding

SILICON MICROCHANEL COOLING OPTIMIZATION @IN2P3

Objectives

- Cost reduction
- Design optimization

→ Kaizen approach instead of technological breakthrough

- Process optimization
  - *Laser etching & cutting*
  - *Direct bonding replaced by anodic bonding coated glass*
- Optimization of the connections
  - *Anodic bonding*
  - *Serialization of cooling plates*

Inexpensive, flexible and fast process

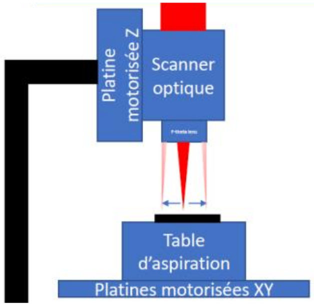
- Design optimization
  - *Predictive Simulation*
  - *Caraterisation : heat engineering*

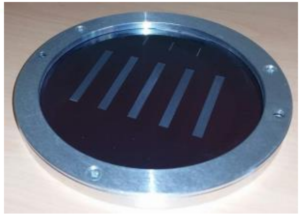
TFM optimization
Material optimization
Fast design

SILICON MICROCHANEL COOLING OPTIMIZATION @CPPM

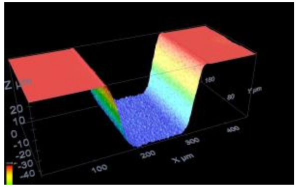
Process optimization :

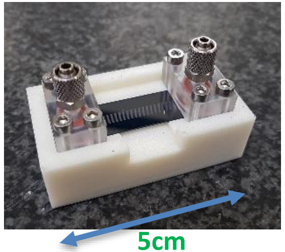
- Laser etching



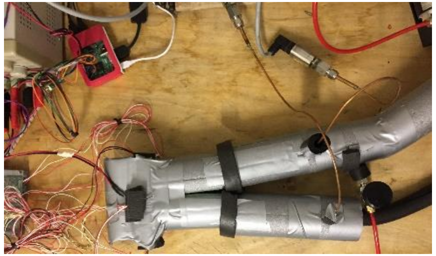


Low cost for a prototype (<1k€)
Fast prototyping and optimization
Adapted to SiC
Complementary to chemical etching



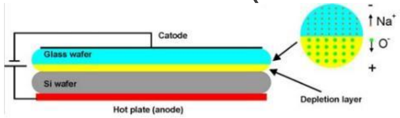


5cm

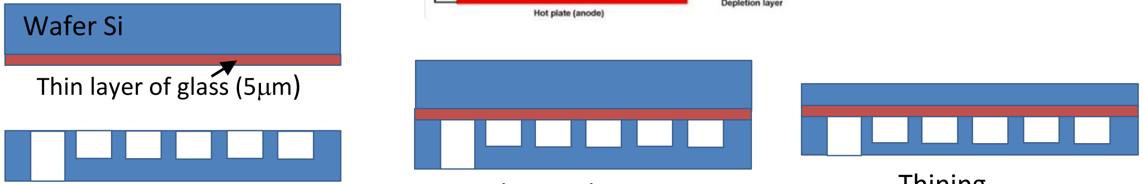


Tests in progress

- Anodic bonding Si wafer coated (electron beam) with 5µm of glass



Glass deposition



Thin layer of glass (5µm)

Etching (DRIE)

Anodic Bonding

Thining

4 inch wafer with a thickness of 500 µm

Low cost (<1k€)
Fast production
Mature technology
Bonding can be done at home
Possibility to do complex structure

Pressure tests 06/2020

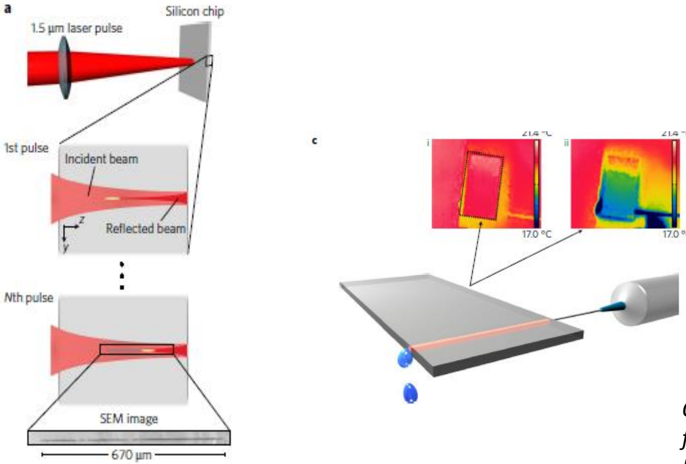
SILICON MICROCHANEL COOLING OPTIMIZATION @CPPM

Process optimization possibilties:

- Anodic bonding of connector on cooling plate → **Cost & time saving**
- Anodic bonding of sensor/electronic on cooling plate → **Time & material saving**

Call for tender in September

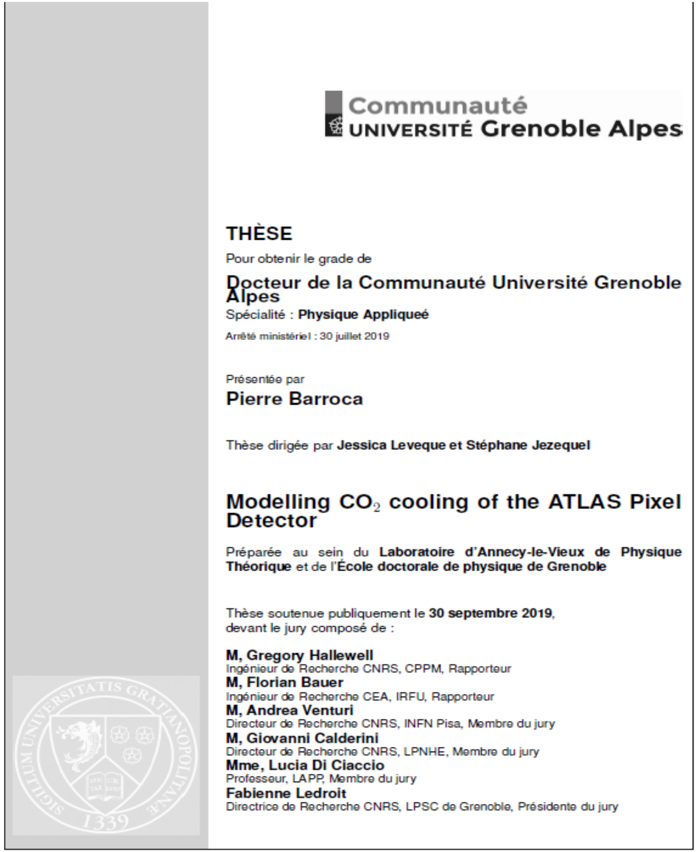
- In chip 3D etching



Thesis in co-tutuelle?

O. Tokel & Al - In-chip microstructures and photonic devices fabricated by nonlinear laser lithography deep inside silicon
Nat. Photon. VOL 11 | OCTOBER 2017 | 639–645 |

LAPP EXPERIENCE FROM CO2 COOLING OF FUTURE ATLAS PIXEL


Communauté UNIVERSITÉ Grenoble Alpes

THÈSE

Pour obtenir le grade de

Docteur de la Communauté Université Grenoble Alpes

Spécialité : **Physique Appliqueé**

Arrêté ministériel : 30 juillet 2019

Présentée par

Pierre Barroca

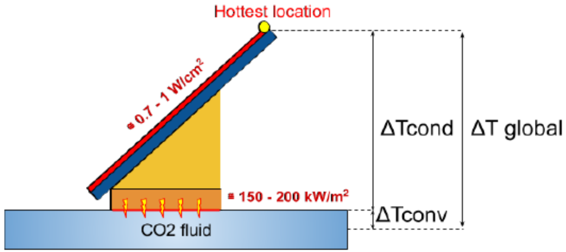
Thèse dirigée par **Jessica Leveque et Stéphane Jezequel**

Modelling CO_2 cooling of the ATLAS Pixel Detector

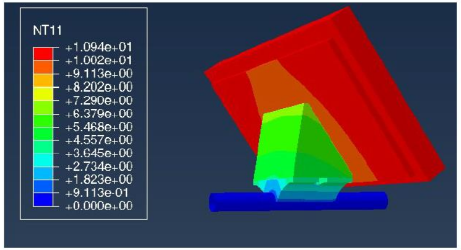
Préparée au sein du **Laboratoire d'Annecy-le-Vieux de Physique Théorique** et de l'**École doctorale de physique de Grenoble**

Thèse soutenue publiquement le **30 septembre 2019**, devant le jury composé de :

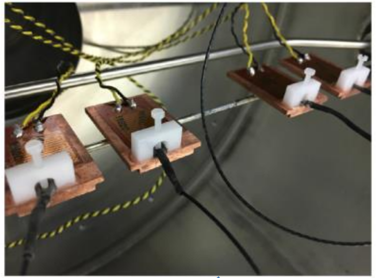
M, Gregory Hallewell
Ingénieur de Recherche CNRS, CPPM, Rapporteur
M, Florian Bauer
Ingénieur de Recherche CEA, IRFU, Rapporteur
M, Andrea Venturi
Directeur de Recherche CNRS, INFN Pisa, Membre du jury
M, Giovanni Calderini
Directeur de Recherche CNRS, LPNHE, Membre du jury
Mme, Lucia Di Ciaccio
Professeur, LAPP, Membre du jury
Fabienne Ledroit
Directrice de Recherche CNRS, LPSC de Grenoble, Présidente du jury

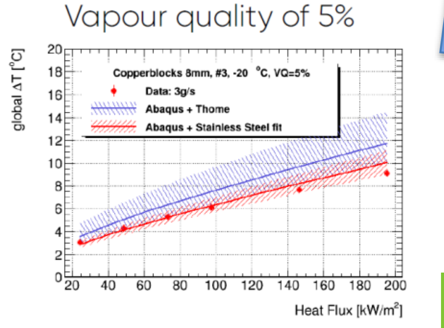


Estimate of ΔT_{cond} with **ABAQUS**



Metallic tube of 2-3 mm diameter





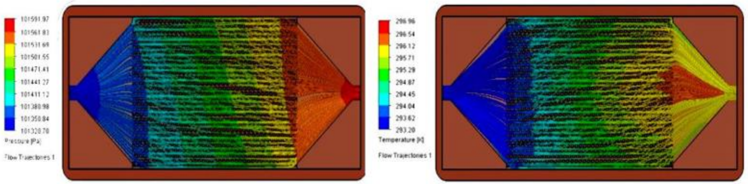
New parametrisation of CO2 heat exchange in High Heat Flux regime

LAPP CONTRIBUTION FOR MICROCHANELS DEVELOPMENTS

Thermo-fluidic di-phasic CO_2 simulation

Current studies : 3D thermal models + 1D fluid models

New studies : 3D thermo-fluidic models (ANSYS FLUENT)



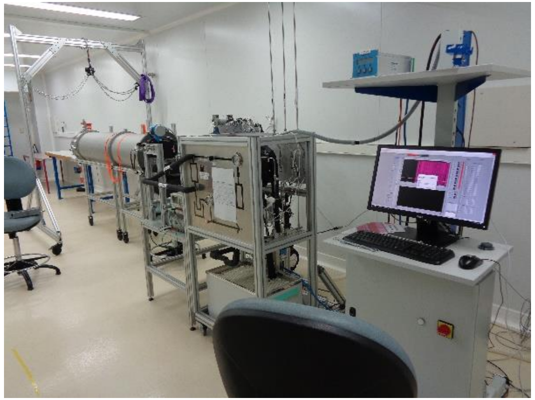
1- Validate the simulation with Pierre Barroca data

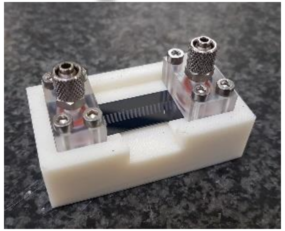
2- Perform simulation + mesurements for critical parameters (roughness, …)

3D simulations seems pretty difficult to manage

Expertise from OPTIFLUIDES company (https://www.optifluides.net/)

Prototype measurement





Publications : New insights on boiling carbon dioxide flow in mini- and micro-channels for optimal silicon detector cooling

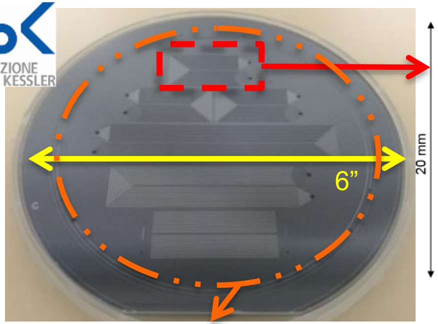
DEPFET pixel detector for future e-e+ experiments

LPNHE EXPERIENCE FROM CO2 COOLING OF FUTURE ATLAS PIXEL

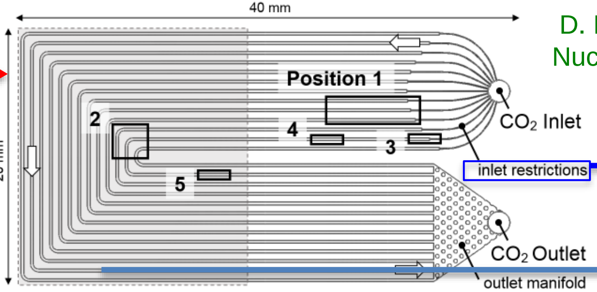
* PI: M. Bomben

Thanks to Reflecs* & Reflecs2* proj. (CNRS-Defi instr. 2014&15) it was possible to:

- Realize prototypes of µ-channels etched in silicon and sealed with pyrex



Round single channel to study 2-phase fluid at high-pressure (50-100 bar) in micro-channels: valuable data to improve simulations



2 x 2 cm² metallized silicon heater glued onto the silicon side simulating a chip footprint

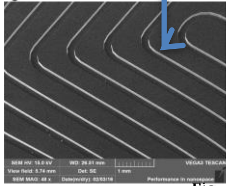
channel size: cross-section 200 µm x 120 µm, length ~ 55 – 80 mm
inlet-restriction size : cross-section 100 µm x 60 µm, length 6 mm

flow direction

Figure 2: Multi-micro-channel layout

D. Hellenschmidt, M. Bomben, G. Calderini et al. Nucl. Instrum. Meth. (2019) 162535.

CO_2 boiling enhanced at restrictions



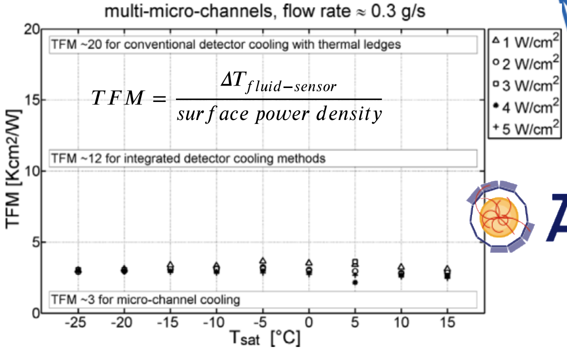
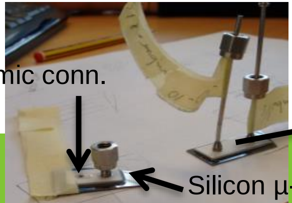
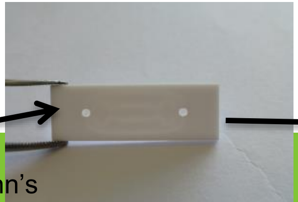
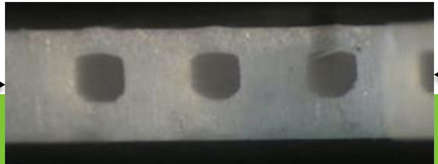


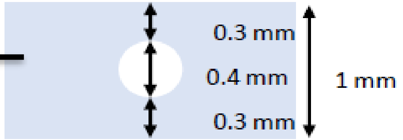
Fig. 6. TFM for boiling CO_2 in multi-micro-channels at constant flow rate ≈ 0.3 g/s and various T_{sat}.

- Connectors in 3D-printed ceramic:



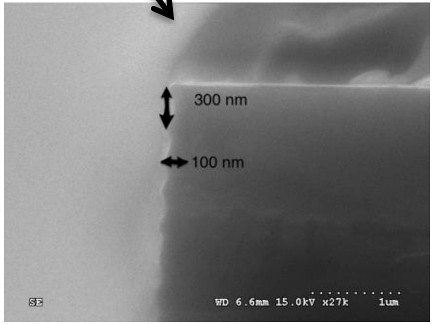






LPNHE CONTRIBUTION FOR MICROCHANELS DEVELOPMENTS

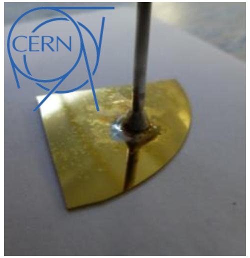
- New production being prepared at C2N (Saclay)
  - Test of different walls rugosity to see the influence on boiling



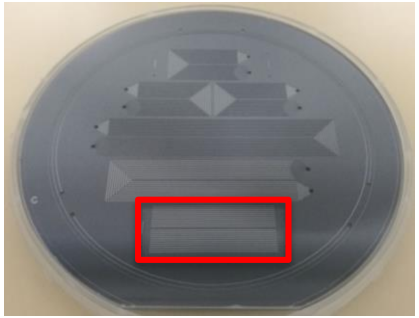
- Continue prototype testing – e.g soldering

AIDA 2020

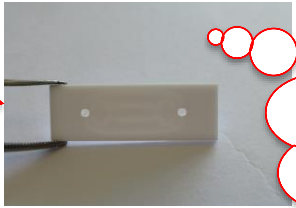
Pressure test → no leak until 600 bar
Leak test with Helium: taux de fuite: 9×10^{-10} mbar l/s



- More work on connectivity among building block samples



“Rallonges” to be inserted somehow between one inlet unit and one outlet one



Using existing ceramic connectors?
To be continued...

CONCLUSIONS

- **Strong interest in microchannel cooling for tracker detectors :**

    - NA62 GTK wishes to use microchannels by anodic bonding in 2021.
    - R&D for LHCb-upgrade II vertex detector - Contribution to framework TDR in 2021 ?
    - FCC, BELLE, AIDA++ …

- **We can play a major role in the development of microchannel if we intensify our efforts**

- **Complementary skills on :**
    - LAPP: simulation, tests
    - CPPM: process
    - LPNHE: connectors, tests

- **Industrial transfer potential (computers, biology, space, microreactors, etc.)**