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Poster

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

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

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Introduction

- Along with the general mass and volume minimization, the thermal management needs of future silicon detectors are steadily increasing

► **This requires highly effective active cooling in very small channels**

- CO_2 in boiling state has been adopted as preferred refrigerant for the future generations of silicon detectors at the LHC
- However, available data on CO_2 boiling in small channels is too limited – made difficult by the high pressure of CO_2 and often affected by too large measurement uncertainties – to allow for developing reliable predictive models
- To confront these shortcomings a long-term experimental study has been launched with the ambitious objective of developing a deeper understanding of the properties of boiling flows of CO_2 in small channels

Experimental Approach

The properties of evaporative CO_2 are studied within:

1. simple small-diameter **tubular evaporators** (stainless steel, L = 0.2 m)
2. complex **multi-microchannel cooling devices** (silicon-substrate bonded to glass for visualization purposes)

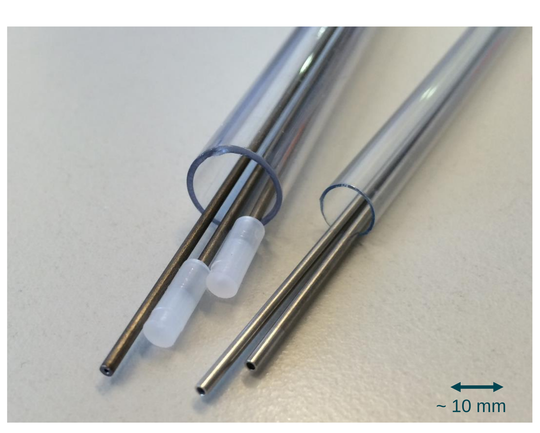


Fig. 1 tubular evaporators

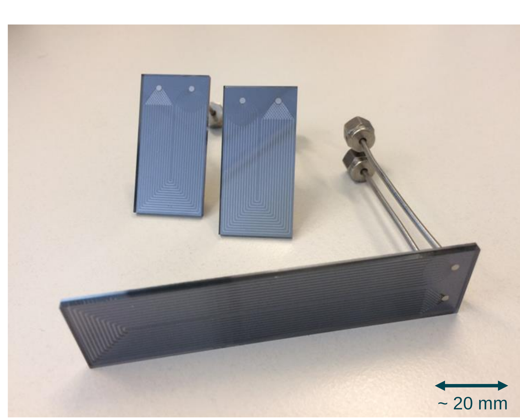
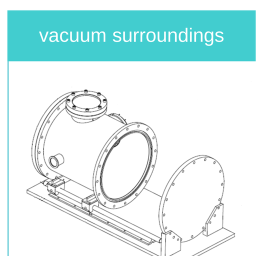
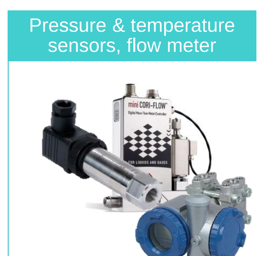
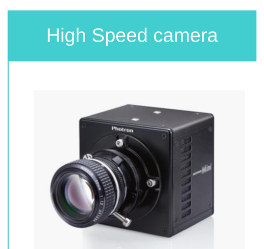


Fig. 2 silicon-embedded multi-micro-channels

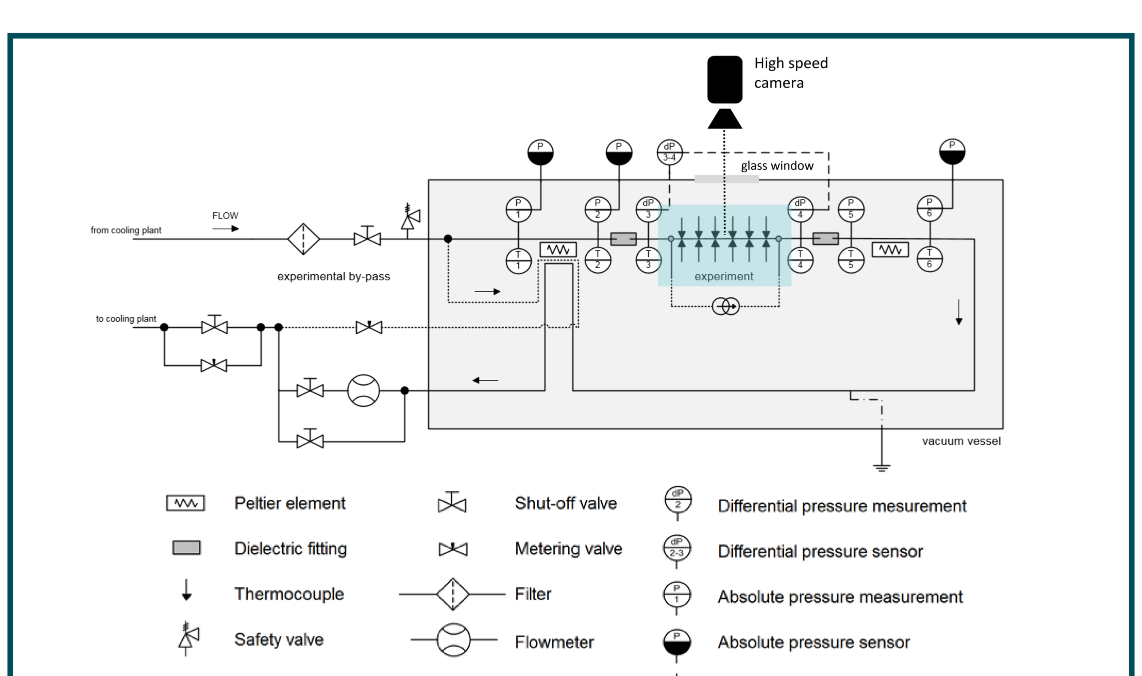
- Both applications are **highly relevant for HEP experiments**
- Results from the **more basic** single-channels can complement the **rather multifaceted** findings from the multi-micro-channels and vice versa
- Thus it is possible to address the need of a deeper understanding of CO_2 boiling properties at mini- and micro-scales at all temperatures of interest on **various levels**

Experimental Setup

A very versatile new test setup was built with following main components:

2-phase CO2	vacuum surroundings	Pressure & temperature sensors, flow meter	High Speed camera
			
Transportable Refrigeration Apparatus for CO_2 Investigation (TRACI)	Vacuum vessel for adiabatic test conditions for more accurate heat transfer measurements	High precision measurements of transfer for flow & heat transfer applications	Visualization of details on bubble dynamics up to 100 000 frames per second (fps)

The schematic layout of the test stand is shown below with the interchangeable experimental section at its core:



Studied Parameters

The test range for the two different detector cooling approaches is for

Tubular evaporators:

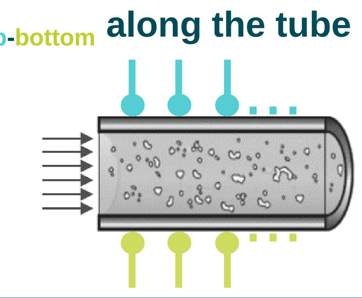
- saturation temperatures (T_{sat}) from +15 to -25°C, mass fluxes from 1200 to 100 kg/m²s and heat fluxes from 5 to 35 kW/m²

Multi-micro-channels:

- saturation temperatures from +15 to -25°C, mass flow rates of 0.1 g/s and 0.3 g/s and surface power densities from 1 to 5 W/cm²

Following parameters are studied with an unprecedented level of accuracy (experimental uncertainty below 10 % ↔ typically ~ 20 %)

Tubular evaporators	Multi-micro-channels
Heat Transfer Coefficient *h*	**Thermal Figure of Merit**
Pressure drop	**Pressure drop**
Δh top-bottom along the tube	**Bubble dynamics in the channels**

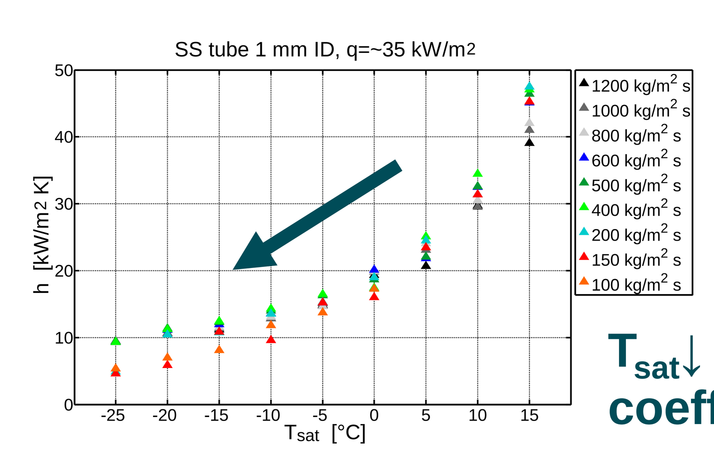


Combination of results leads to new insights on CO_2 boiling in small channels and its dependency on T_{sat}

Parametrical Results

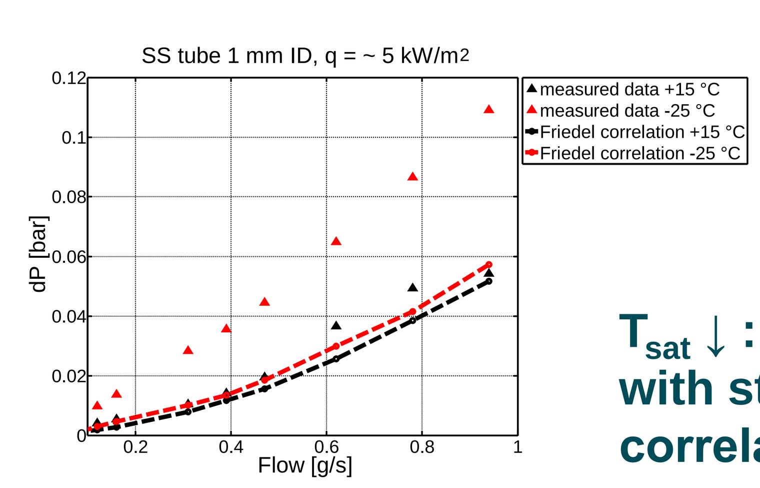
EXAMPLE : Tubular evaporators

1 mm inner diameter (ID) stainless steel tube, L = 0.2 m



T_{sat}↓ : heat transfer coefficient *h*↓

Fig. 3 CO_2 boiling heat transfer coefficient at constant heat flux 35 kW/m² and various T_{sat}

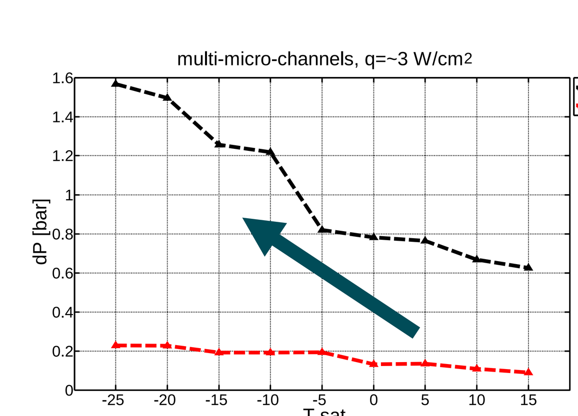


T_{sat} ↓ : predictability with standard correlation ↓

Fig. 4 CO_2 boiling pressure drop at constant heat flux 5 kW/m² and various flow rates

EXAMPLE : multi-micro-channels

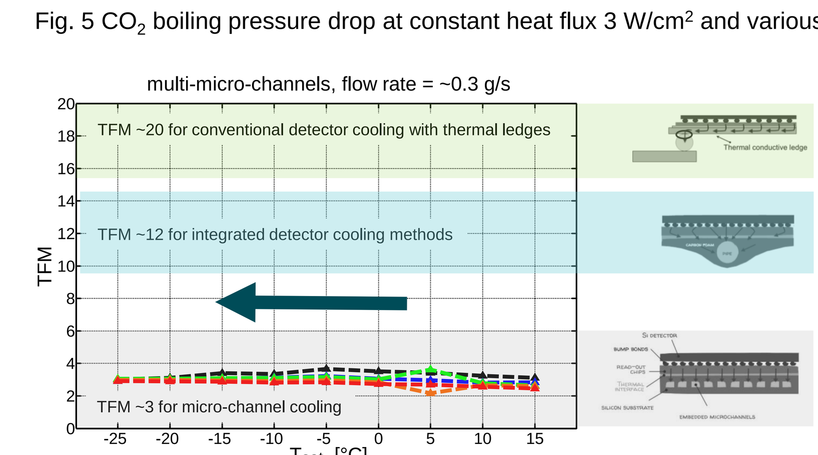
200 µm x 120 µm channels in silicon-substrate bonded to glass



T_{sat}↓ : pressure drop ↑

T_{sat}↓ : pressure drop ↑↑ for highly confined flow

Fig. 5 CO_2 boiling pressure drop at constant heat flux 3 W/cm² and various T_{sat}

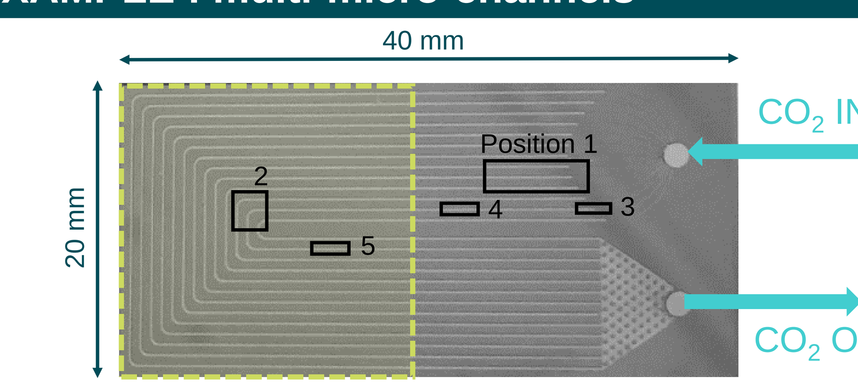


T_{sat}↓ : Thermal Figure of Merit constant →

Fig. 6 CO_2 boiling *Thermal Figure of Merit (TFM)* at constant flow rate 0.3 g/s and various T_{sat}

Visual Results

EXAMPLE : multi-micro-channels



2 x 2 cm² metallized silicon heater glued onto the silicon side simulating a chip footprint (e.g. ATLAS FEI4)
M. Garcia-Sciveres, et al., The FE-I4 pixel readout integrated circuit, Nucl. Instrum. Meth. A636 (2011) S155–S159

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

High speed camera recordings were carried out at the shown positions along the channels for different T_{sat} and examples are given for 3 W/cm² and 0.3 g/s

Position 1 : 13600 fps

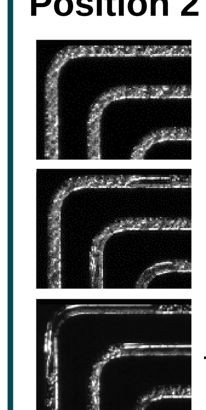
15 °C : bubble size is in the order of microns or less

5 °C : bubble size is in the order of a few tens of microns or less

-25 °C : bubble size is in the order of the channel size

Position 2 : 100000 fps

T_{sat}↓ : general bubble size ↑



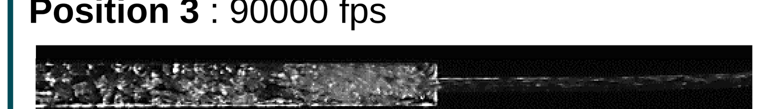
15 °C: uninterrupted flow of small bubbles

5 °C: flow of bubbles with intermittent vapour slugs

-25 °C: vapour slugs and liquid film along walls predominant

Other phenomena found in the studied channels are:

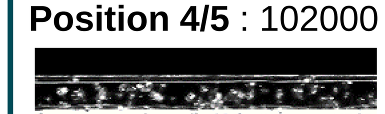
Position 3 : 90000 fps

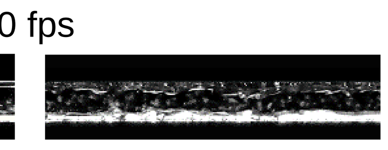


5 °C

Very efficient boiling enhancement by expansion as anticipated by the special design of the inlets of the channels

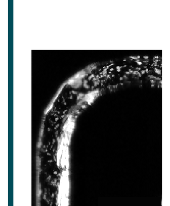
Position 4/5 : 102000 fps





10 °C

Different kinds of film behavior in the channels: homogeneous & smooth (left), inhomogeneous & wavy (right)



Bends trigger a change in flow behaviour:

- incoming bubbles colliding with the bend wall can form a spontaneous gaseous film after the bend
- Very small secondary bubbles are created thus enhancing heat transfer

For more information some videos will be shown on a portable at the poster sessions !

Combined Conclusion

- In general investigations with changing T_{sat} and heat flux showed **shifting trends of the heat transfer coefficient *h***, suggesting a shift of the dominating boiling mechanism from high T_{sat} to low T_{sat}
- Different boiling mechanisms are due to **different bubble dynamics in the channels** which can cause different pressure drop and heat transfer coefficient results
- The Thermal Figure of Merit of the tested micro-channels is ~3 for the entire test range, which is a **factor 4 better** than the best performing conventional detector cooling method
- The qualitative observations from the high-speed visualizations on micro-channels provide a consistent **key of interpretation** of the quantitative measurements

The examples show that T_{sat} greatly affects the boiling properties of CO_2 in small channels and that new advanced models based on this new findings can enhance the design optimization of future mini- and micro-channel evaporators

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