Detector cooling R&D with multi-micro-channels:
lessons learned & open issues

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Presentation outline

Definition and advantages of micro-channel cooling

→ Multi-micro-channel detector cooling R&D with Silicon-substrate cold plates:

- first generation channel layouts, design necessities and experimental setup
- **Problem**: unknown channel contamination after experimental testing
- **Explanation**: hydrodynamic erosion in micro-channels
- **Solution**: Proposal of a parametrical map for safe cold plate operation
- Conclusion & **lessons learned**
- Outlook & **open issues**

Definition and advantages of micro-channel cooling

micro-channel cooling =

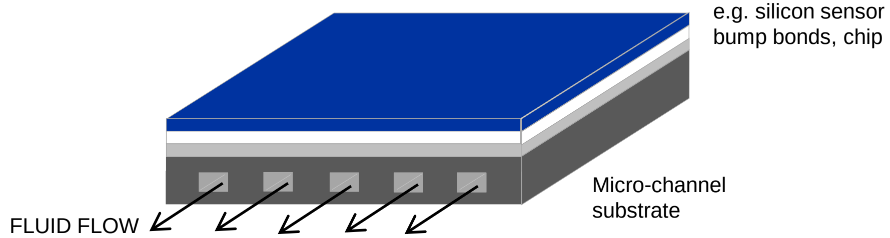
- Network of submillimeter-sized channels embedded into a thin, planar substrate to form a micro-fluidic heat exchanger within which a certain coolant is circulated (cold plate)
- many channel materials, manufacturing techniques, geometries and working fluids possible

→ Herein discussed:

- **Silicon** (Si) **substrate cold plates** manufactured with micro-electromechanical systems (MEMS) techniques
- **Carbon dioxide** (CO_2) as working fluid
- Examples from EP-DT-FS + collaborating institutes (≠ LHCb devices)

Advantages of Si-substrate cold plates for the detector cooling community =

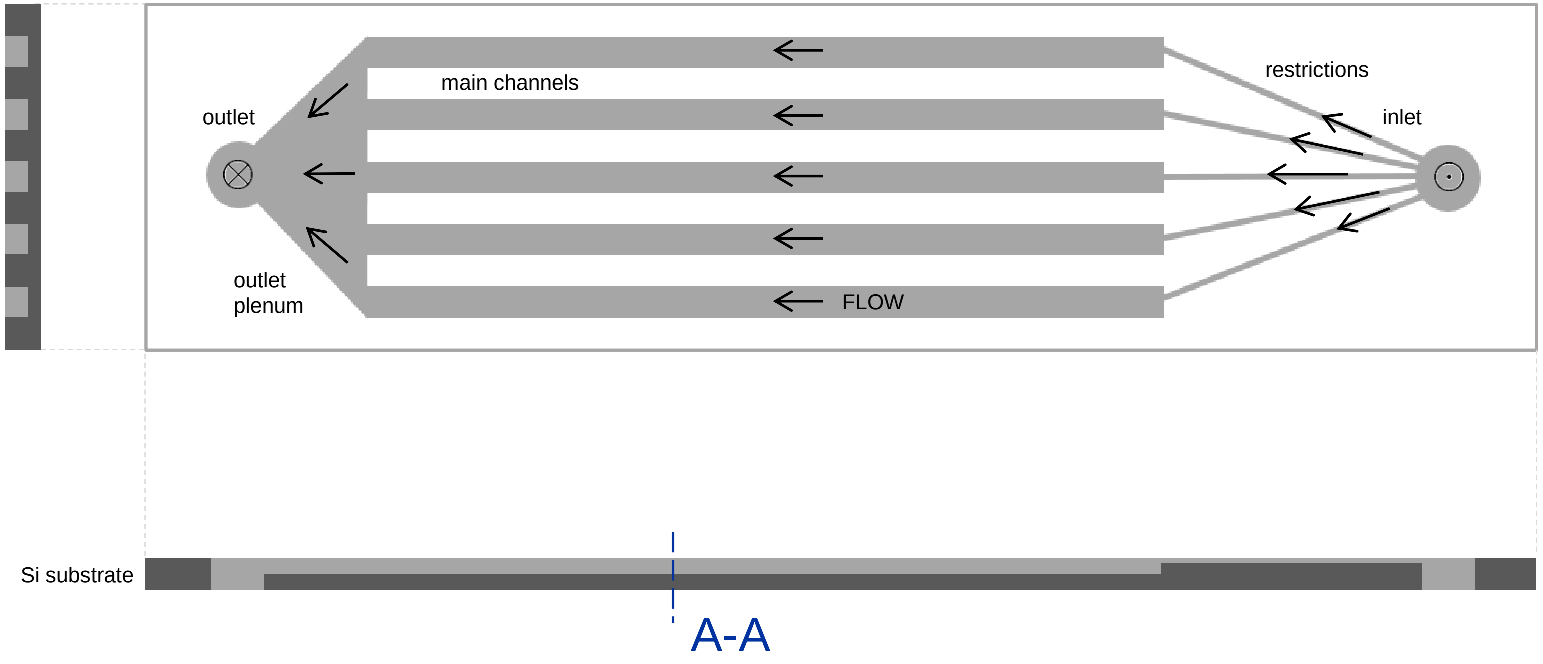
- reduction of material
- direct planar contact with the sensor surface
- minimized thermal resistances
- reduced mismatch in thermal expansion coefficients
- large heat transfer surface involved
- homogeneous temperature distribution across sensor surface

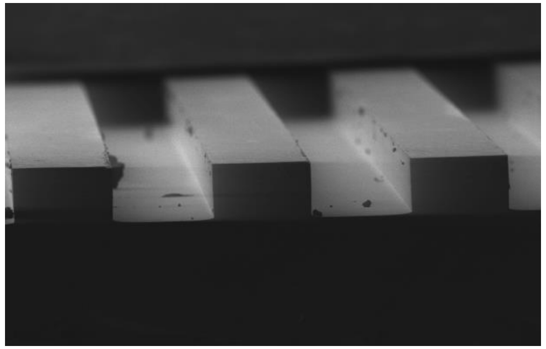


Schematic multi micro-channel detector cooling

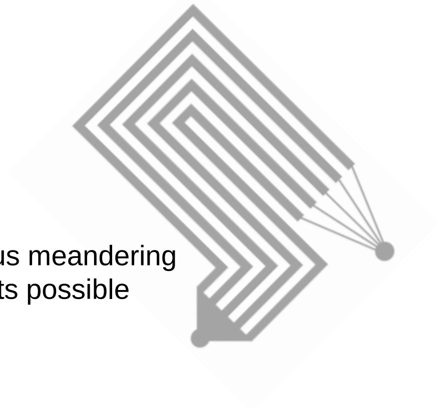
Generic channel layout for boiling flows

Multi-micro-channel cold plates produced with MEMS techniques: etching





A-A: micro-channels etched into Si substrate

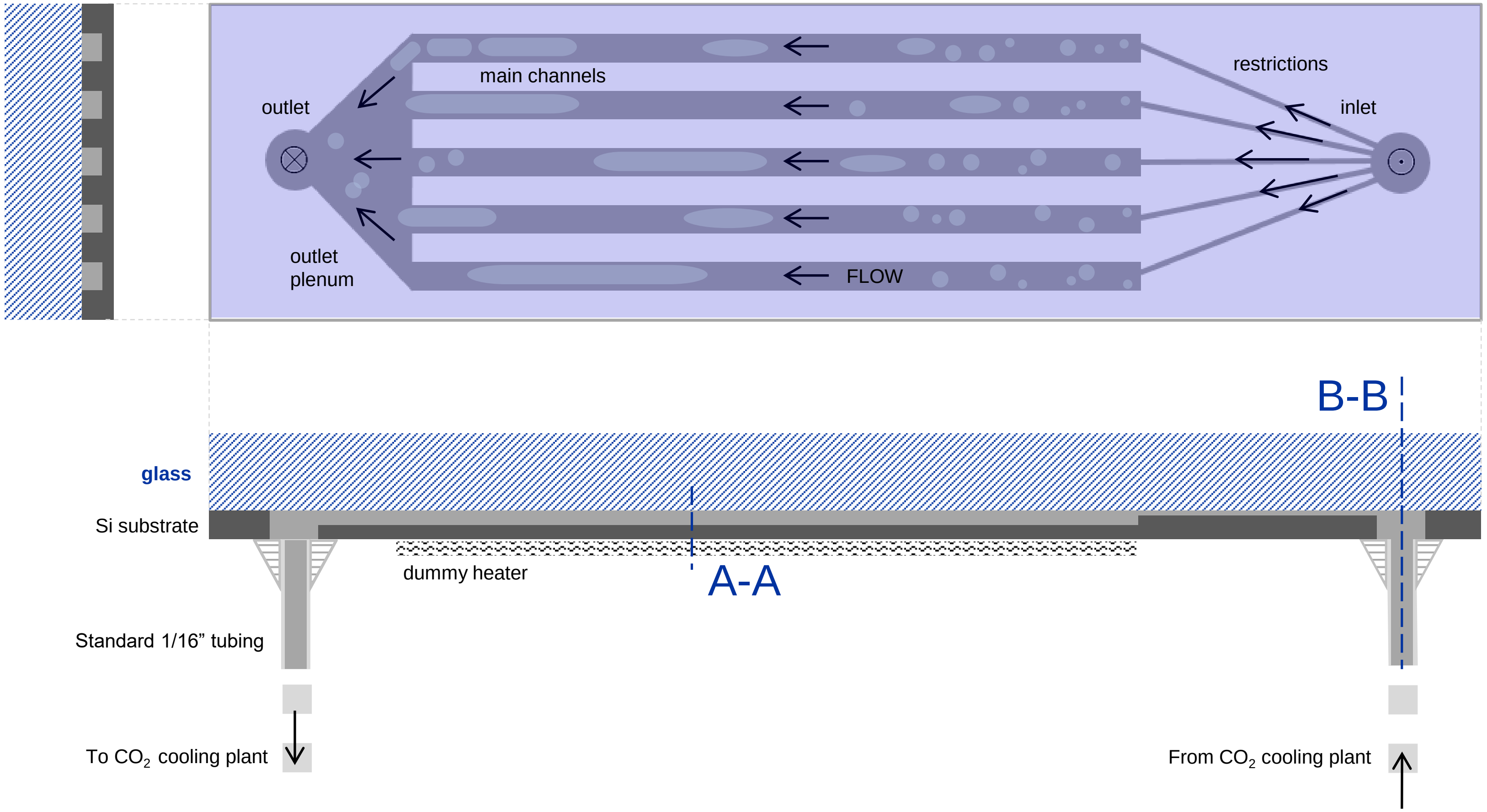


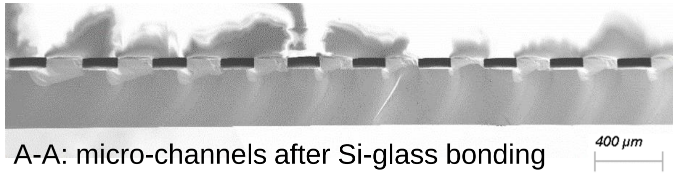
various meandering
layouts possible

Generic channel layout for boiling flows

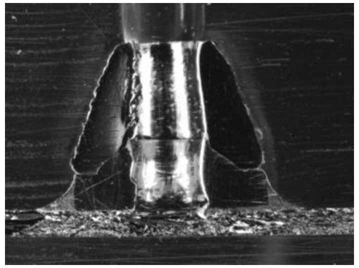
Multi-micro-channel cold plates produced with MEMS techniques: bonding: Si-Si / Si-glass

R&D version for flow visualisation: Si channel substrate bonded to Borofloat (glass) wafer





A-A: micro-channels after Si-glass bonding

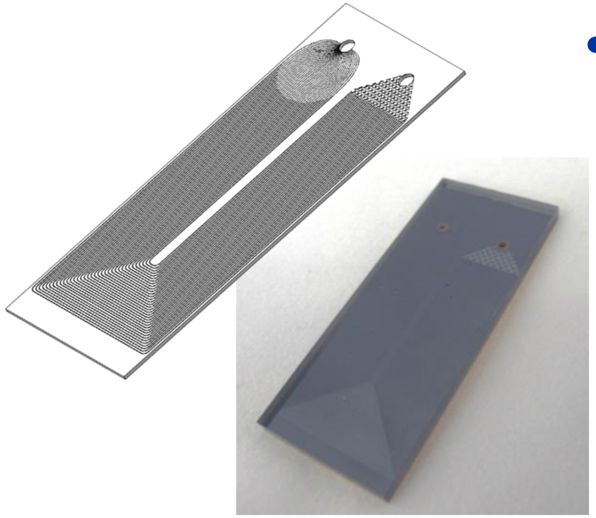


B-B: hydraulic inter-connection: soldered variant

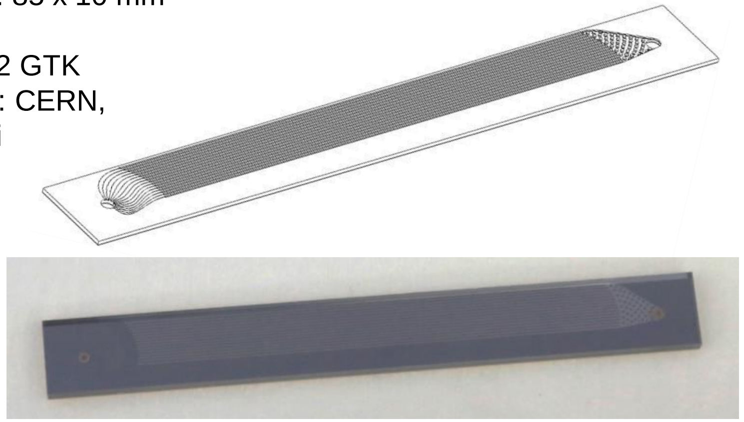
Example: Resulting R&D device

Actual channel layouts for boiling flows (1st generation)

ATLAS
overall dimension 45 x 20 mm
year: ~ 2012
intended for: ATLAS FEI4
institutes involved: CERN, University of Manchester, CSEM, EPFL Cmi

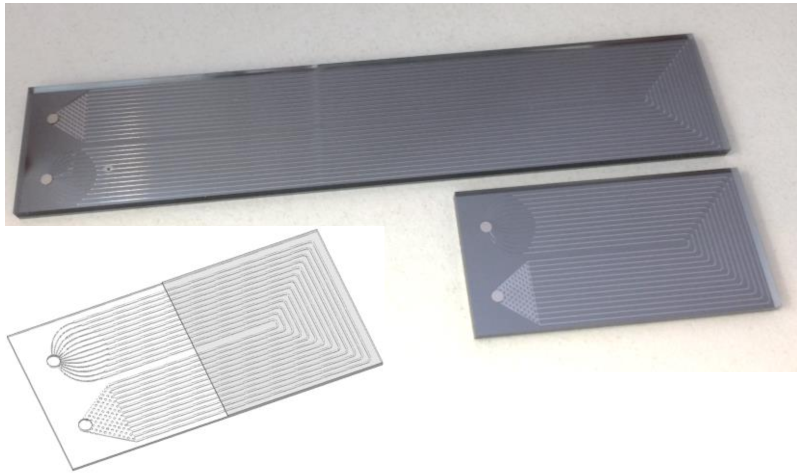


FRAME4
overall dimension: 85 x 10 mm
year: ~ 2012
intended for: NA62 GTK
institutes involved: CERN, CSEM, EPFL Cmi



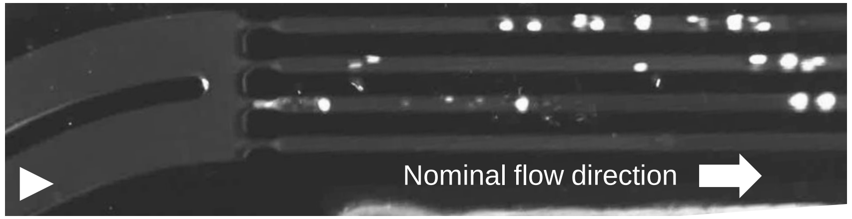
Multi-micro-channel cooling R&D with Si-glass devices and evaporative CO_2
(without connectors)

REFLECS
overall dimensions: 20 x 40 mm, 20 x 80 mm, 20 x 100 mm
year: ~ 2014
intended for: generic 20 x 20 mm chips
institutes involved: CERN, FBK, LPNHE



Detailed channel design for boiling flows

↔ inappropriate restriction design allowing back flow and flow oscillations (video)

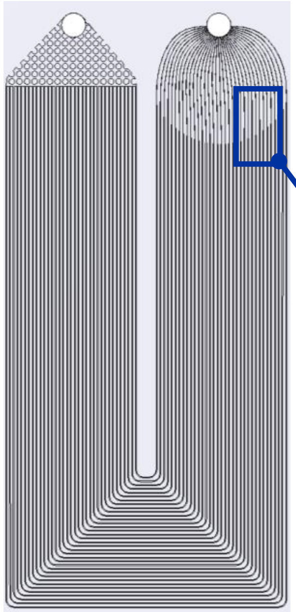


Appropriate inlet restrictions/capillaries:

1) Crucial requirement: for a correct functionality without flow instabilities during two-phase flow and flow boiling which otherwise would induce severe pressure fluctuations and local hot spots

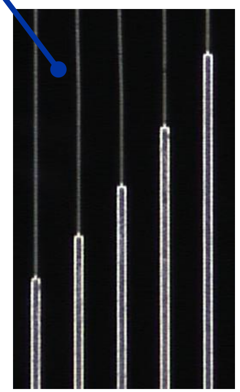
2) Preferred side effect: Fluid-dynamic backward-facing step can trigger boiling onset due to recirculation areas causing low pressure zones in the near-wall region

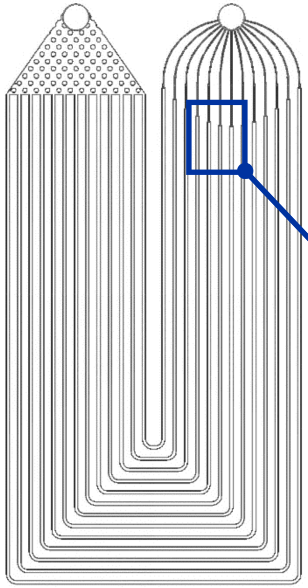
↔ At this stage a complete analytical fluid dynamical evaluation was omitted and the technological manufacturing aspects were prioritised



ATLAS

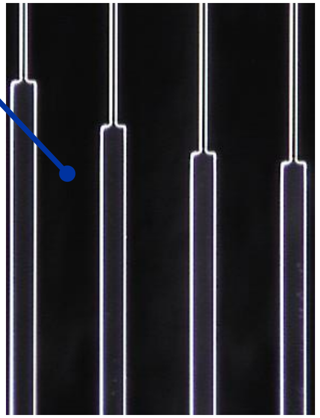
No. channels	35
$W_{restriction}$	10 µm
$H_{restriction}$	190 µm
$W_{main\ channel}$	50 µm
$H_{main\ channel}$	190 µm

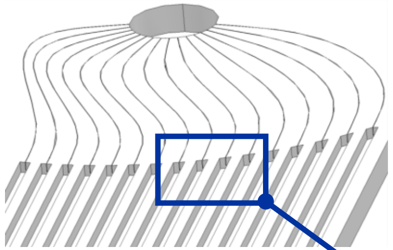




REFLECS

No. channels	13
$W_{restriction}$	60 µm
$H_{restriction}$	120 µm
$W_{main\ channel}$	20 µm
$H_{main\ channel}$	120 µm

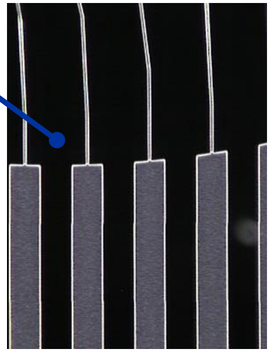




FRAME4

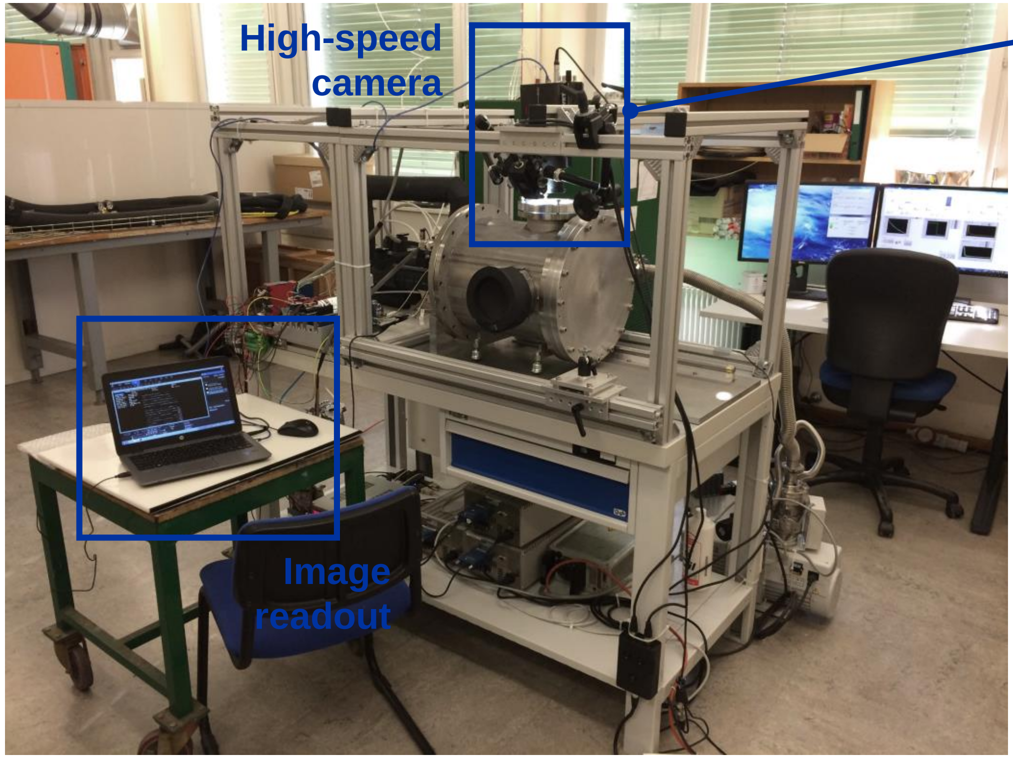
No. channels	16
$W_{restriction}$	20 µm
$H_{restriction}$	200 µm
$W_{main\ channel}$	200 µm
$H_{main\ channel}$	200 µm

(documented version!)

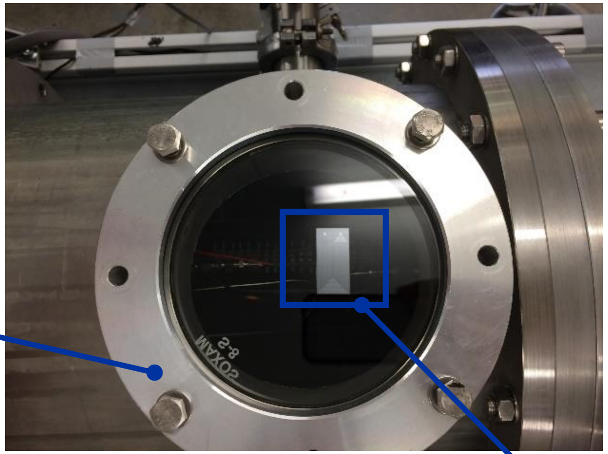


Experimental setup for detector cooling R&D with mini- and micro-scale carbon dioxide evaporators at CERN

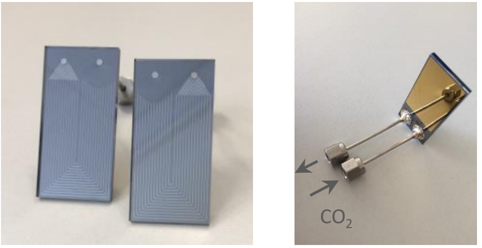
= Centerpiece of our studies, described in http://cds.cern.ch/record/2748428
= Extended version for flow visualisation: + Photron Fastcam Mini AX + software



High-speed camera with LED lights



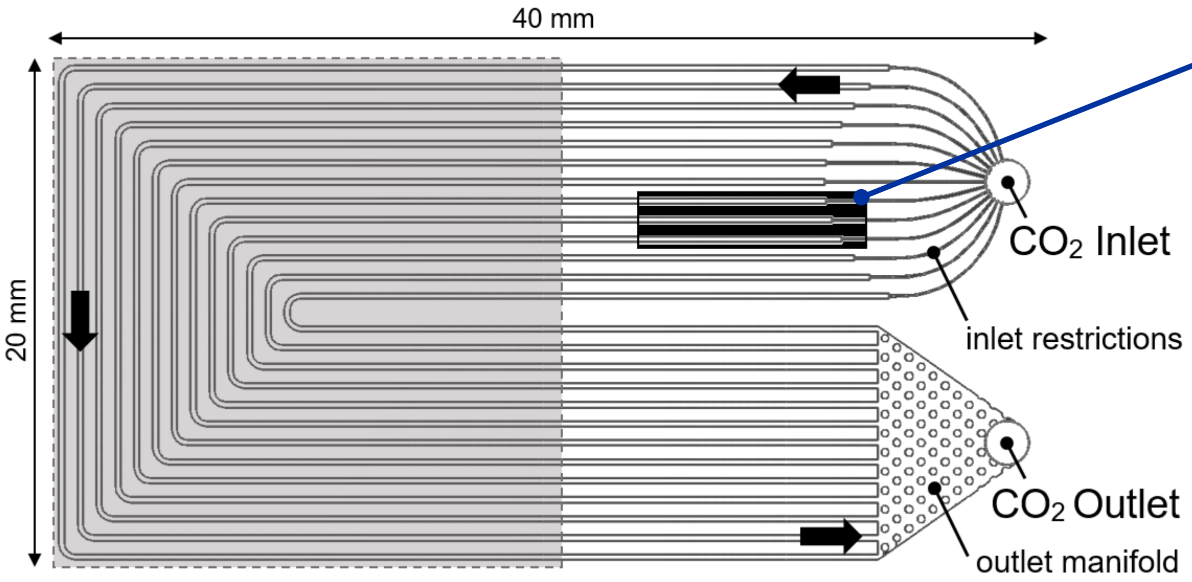
REFLECS micro-channel cold plate mounted inside vacuum vessel

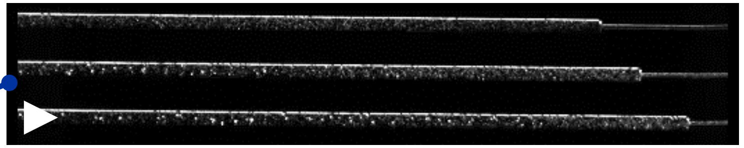


→ REFLECS multi-micro-channels were being studied under flow and recorded with the high-speed camera

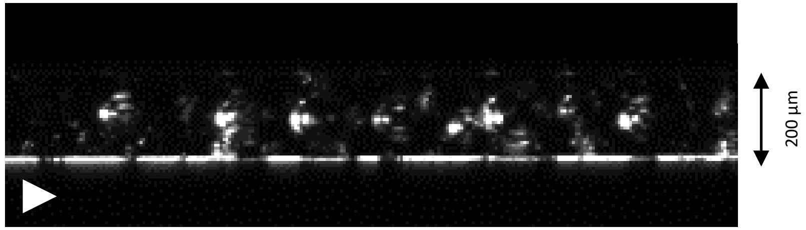
→ **REFLECS image analysis**

REFLECS image analysis





inlet with backward-facing step
13600 fps (video)



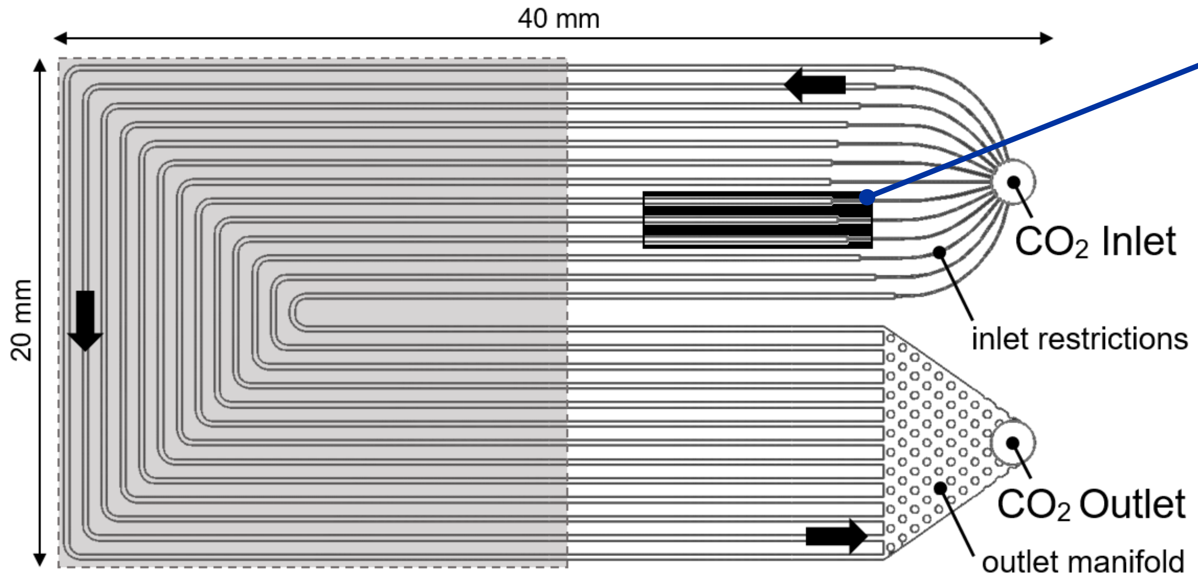
main channel, detail
102000 fps (video)

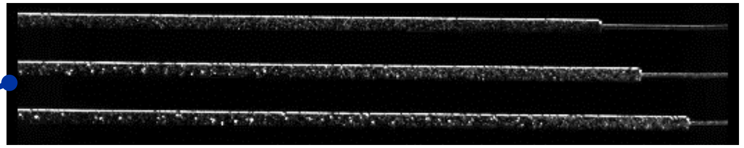
2 x 2 cm^2 metallized silicon heater glued onto the silicon side simulating a chip footprint

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

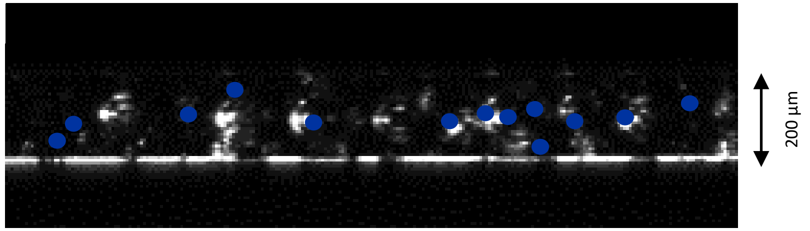
flow direction

REFLECS image analysis





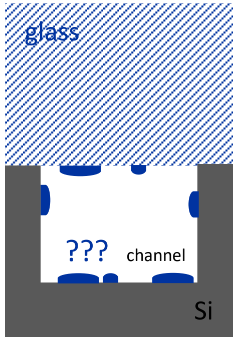
inlet with backward-facing step



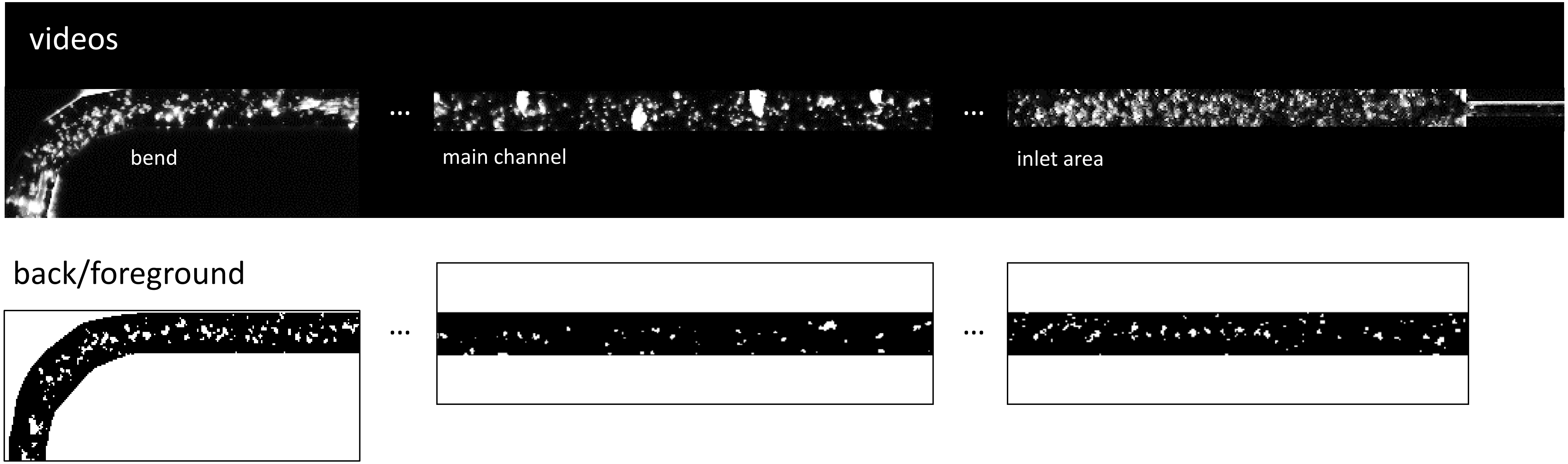
main channel, detail

- 2 x 2 cm² metallized silicon heater glued onto the silicon side simulating a chip footprint
- channel: cross-section 200 µm x 120 µm, length ~ 55 – 80 mm
- inlet-restriction: cross-section 60 µm x 120 µm, length 6 mm
- flow direction

Problem:
Some contamination was found inside the channels which appears as back- and foreground in the images and videos
→ glass and Si side (and probably walls)



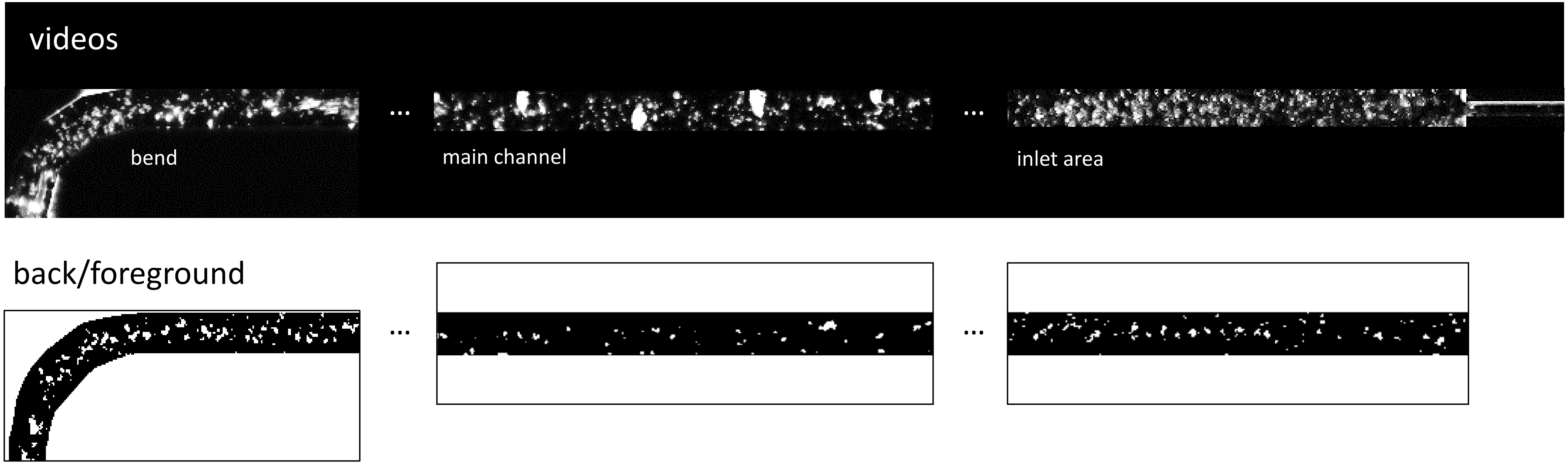
REFLECS image analysis



Examples: inlet, main channel, bend

- High-speed videos with ~ 3000 frames or more
- Applying certain thresholds and summation of all pre-processed images reveals stationary contamination

REFLECS image analysis



Examples: inlet, main channel, bend

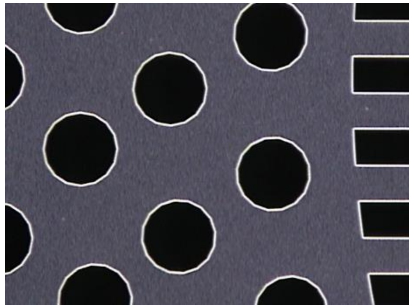
- High-speed videos with ~ 3000 frames or more
- Applying certain thresholds and summation of all pre-processed images reveals stationary contamination

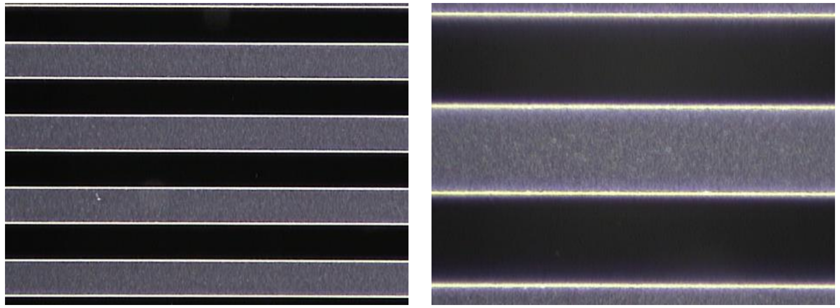
At that point remembering that the FRAME4 device tested in 2012 (G. Romagnoli) and sent to Twente University for further testing (A. Koutoulaki) in 2016 was reportedly “dirty” upon arrival
→ possibly the same contamination?
→ **delayed device analysis on FRAME4 device**

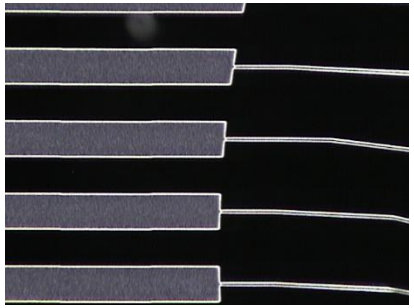
FRAME4 device analysis

→ analysis reveals severe “contamination” of the channel internals after testing with fluid flow

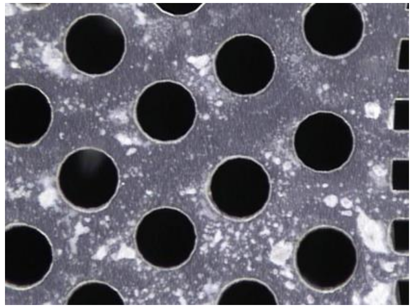
“**before**” = untested device



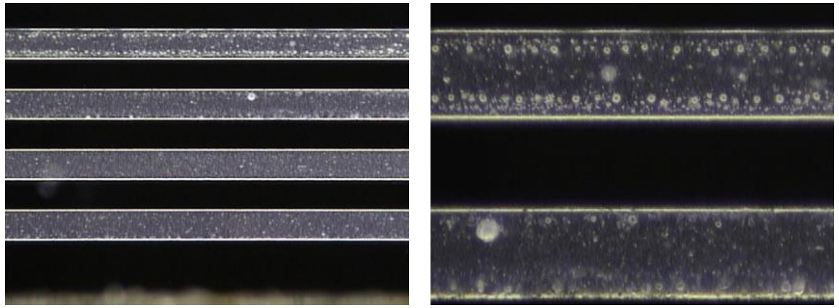




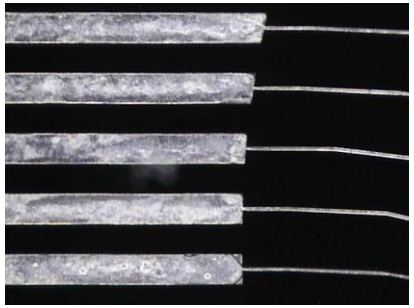
“**after**” = tested device (note: no flow, no fluid inside)



outlet manifold



main channels

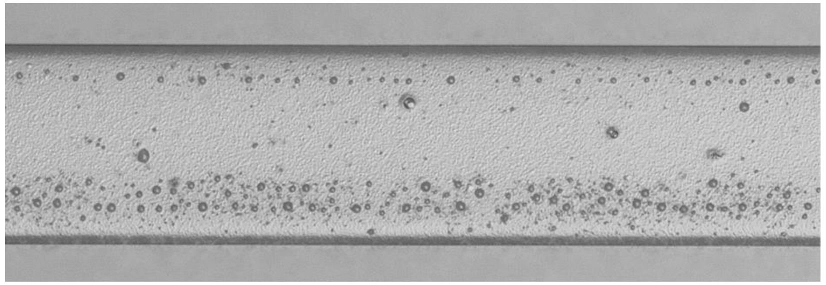


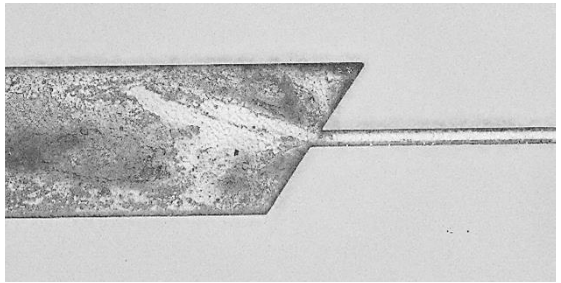
inlet with backward-facing step

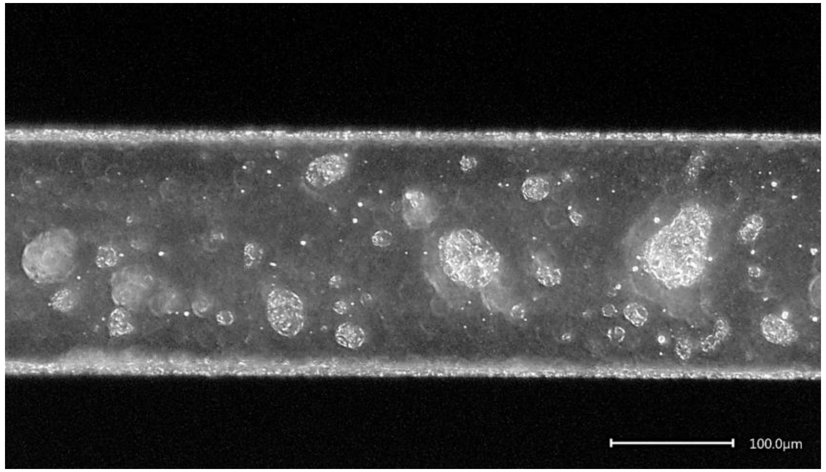
FRAME4 device analysis

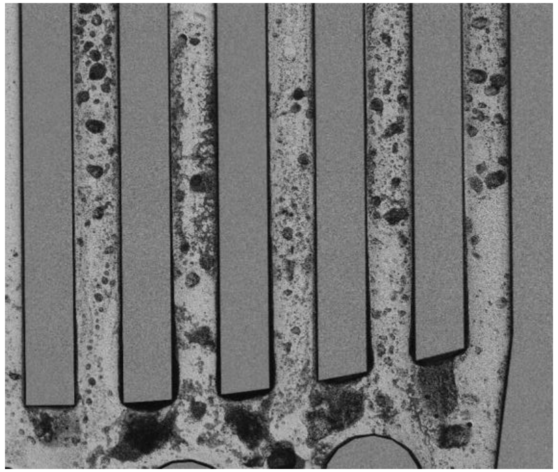
→ further analysis reveals patterns similar to pitting damage found in “literature”

→ **CAVITATION induced local, crater-like EROSION may be the cause of the “contamination”**









Damaged channels: our case

⇔

literature

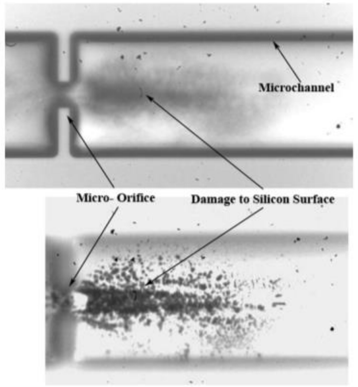


FIG. 22. Pitting/damage is apparent on the silicon surface. (a) Image taken by focusing on the top/Pyrex layer; and (b) picture taken after focusing the camera on the bottom silicon surface, which shows the formation of pits on the silicon floor.

[1]

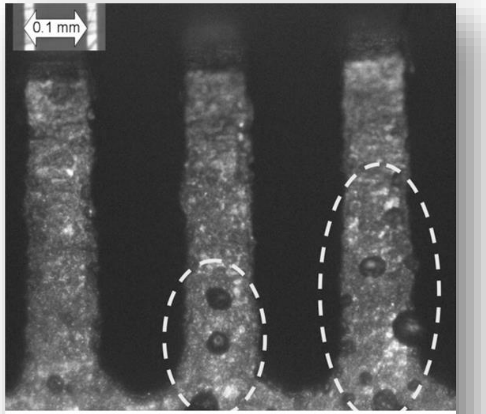


Fig. 14 Damage at straight-channel outlet

[2]

FRAME4 device analysis

→ further analysis to confirm erosion damage

- Confirmation of eroded “craters” required
- non-trivial due to small dimensions, layered and indirect optical access (outer glass, inner glass, inner Si) and no possibility to remove the glass

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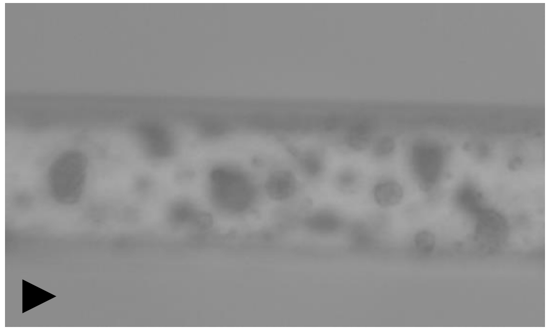
Optical microscope (Keyence 7000, K. Buchanan CERN, EN-MME)

1) Change of focus in order to differentiate the glass and Si side



1) Change of focus from Si to glass side (video)

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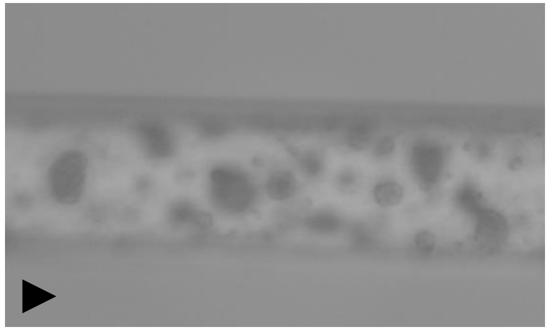
2) Rendered pseudo-SEM images



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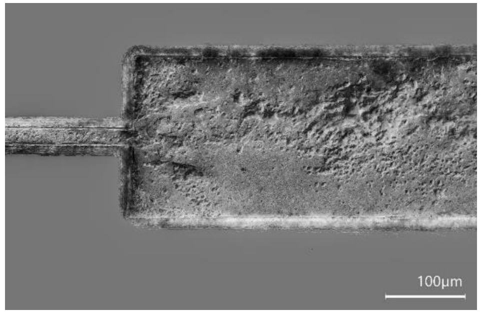

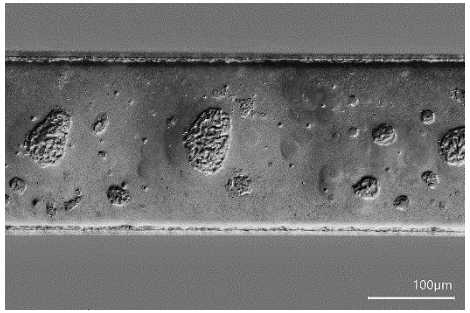

2) Pseudo-SEM images: i) focus on Si side ii) focus on glass side

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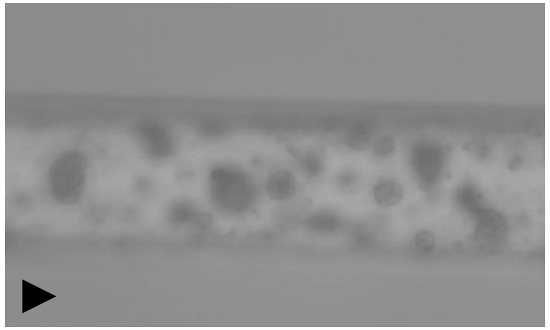

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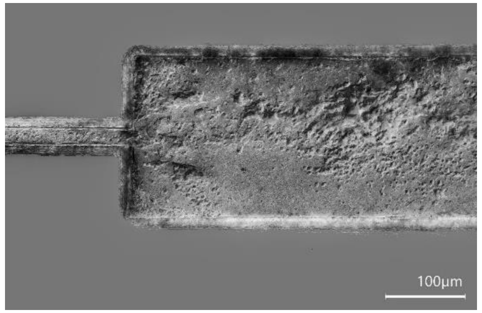

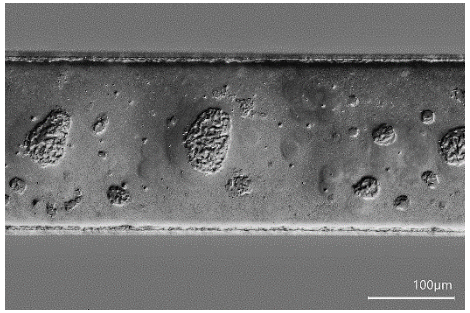

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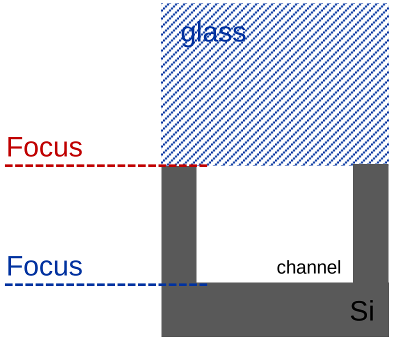
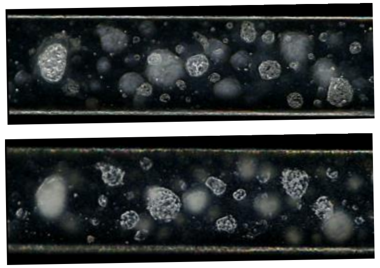


Keyence MME

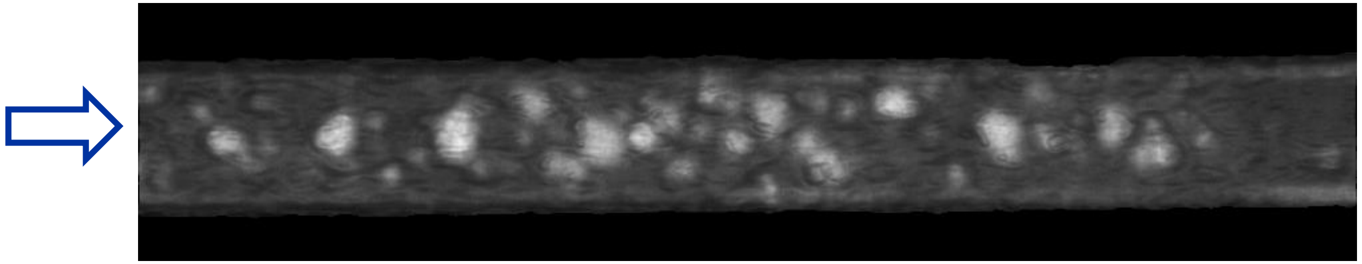
Focus on glass

Focus on Si



Contamination cluster chosen and observed at different foci reveals its location

Keyence EP-DT



Same contamination cluster

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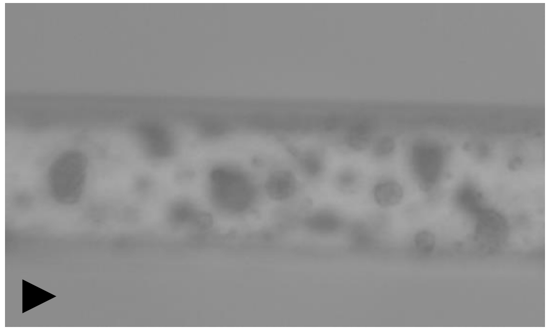

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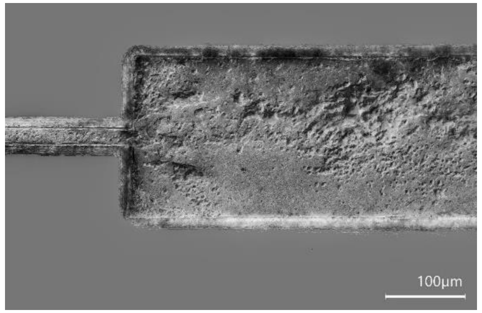

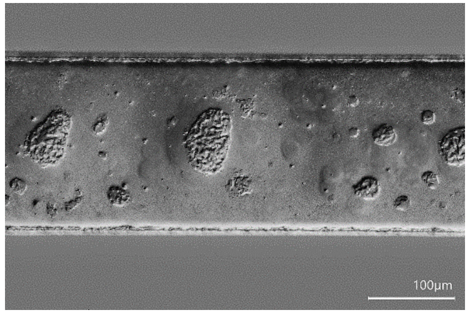

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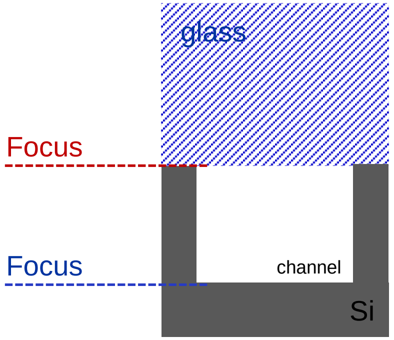
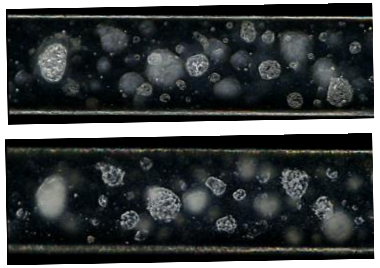


Focus on glass

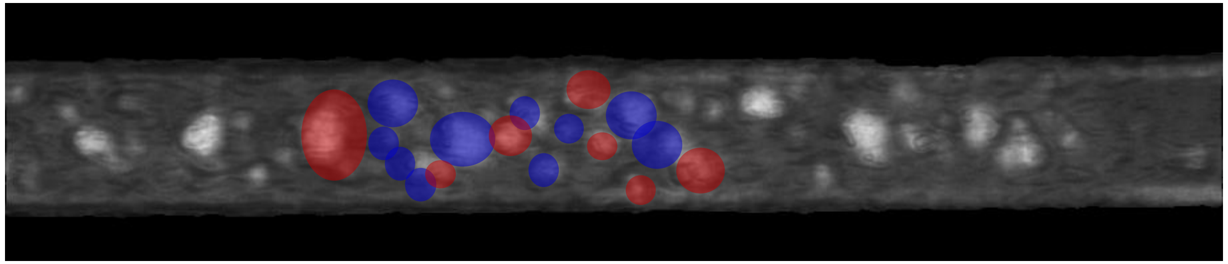
Focus on Si

Keyence MME



Contamination cluster chosen and observed at different foci reveals its location

Keyence EP-DT

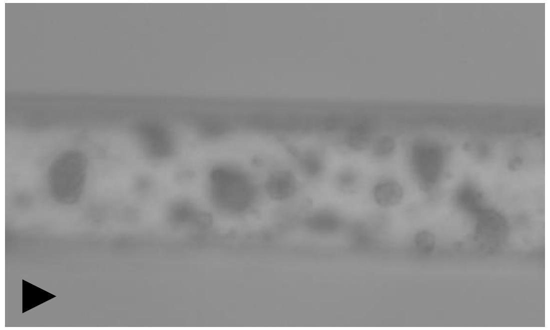


Same contamination cluster marked with location

FRAME4 device analysis

→ further analysis to confirm erosion damage

- Confirmation of eroded "craters" required
- non-trivial due to small dimensions, layered and indirect optical access (outer glass, inner glass, inner Si) and no possibility to remove the glass



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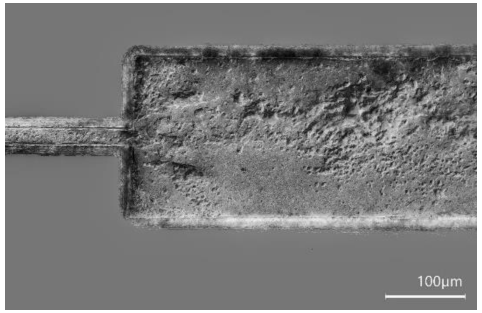

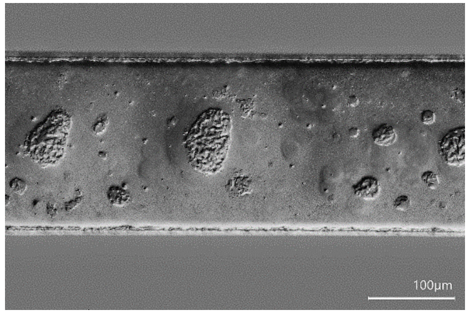

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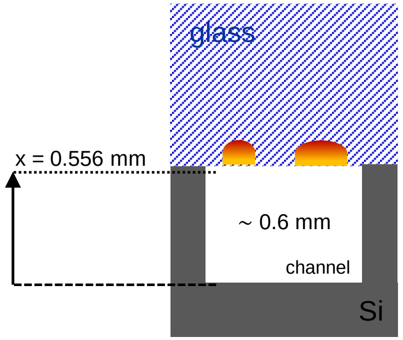

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Focus on Si

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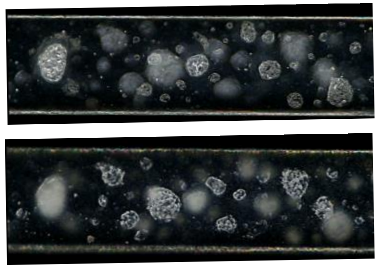
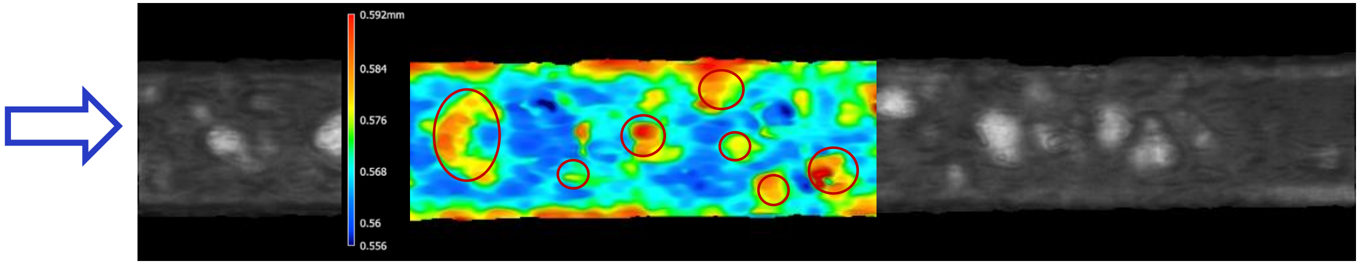


Contamination cluster chosen and observed at different foci reveals its location

Keyence EP-DT measure mode: **glass side**



→ craters on glass side show up as red elevations (+)

FRAME4 device analysis

→ further analysis to confirm erosion damage

- Confirmation of eroded “craters” required
- non-trivial due to small dimensions, layered and indirect optical access (outer glass, inner glass, inner Si) and no possibility to remove the glass

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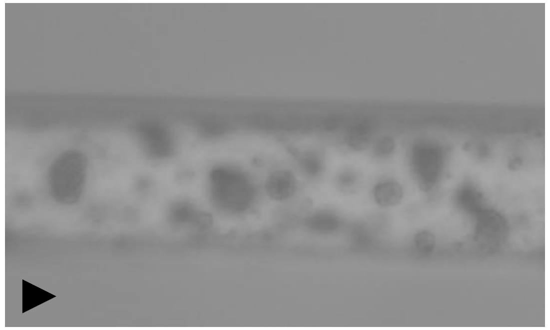

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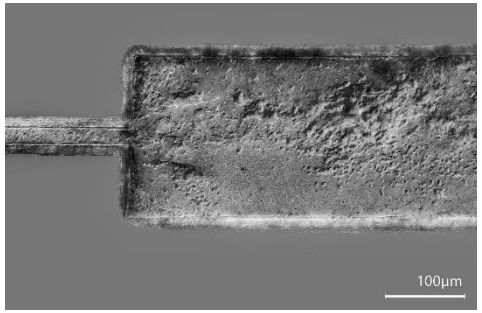

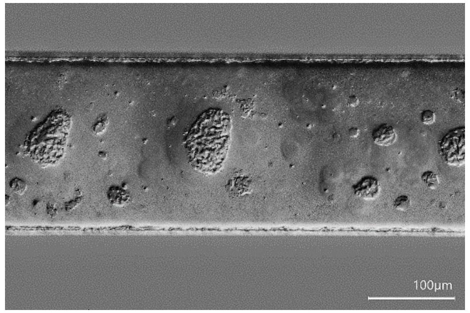

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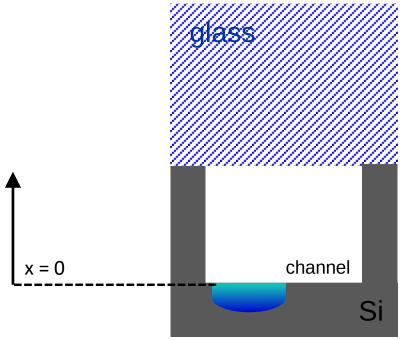
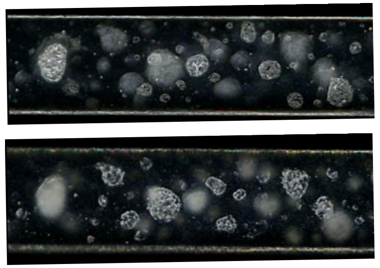


Keyence MME

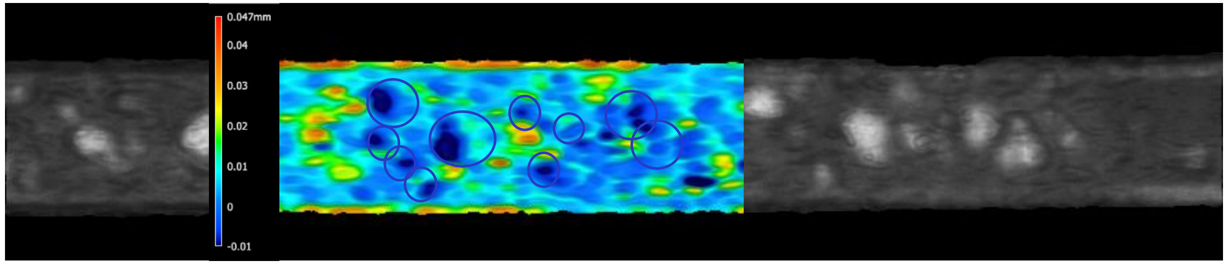
Focus on glass

Focus on Si



Contamination cluster chosen and observed at different foci reveals its location

Keyence EP-DT measure mode: **Silicon side**



→ craters on Si side show up as blue indentations (-)
red elevations still slightly visible, since they are obscuring the direct access

FRAME4 device analysis

→ further analysis to confirm erosion damage

- Confirmation of eroded "craters" required
- non-trivial due to small dimensions, layered and indirect optical access (outer glass, inner glass, inner Si) and no possibility to remove the glass

Optical microscope (Keyence 7000, K. Buchanan CERN, EN-MME)

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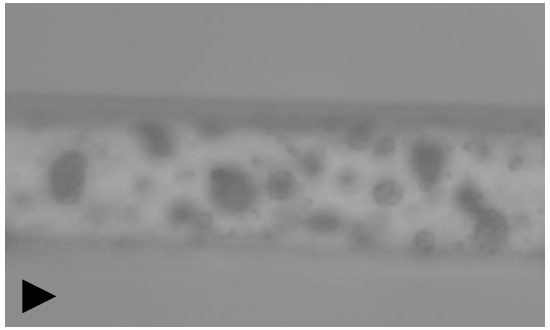

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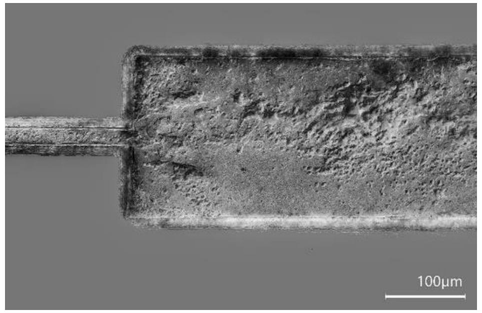

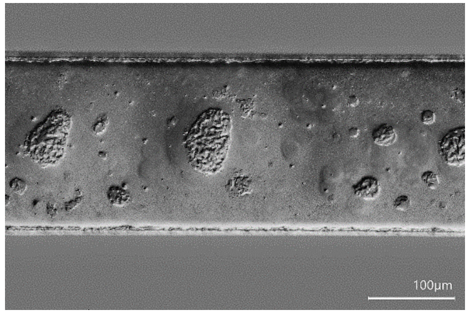

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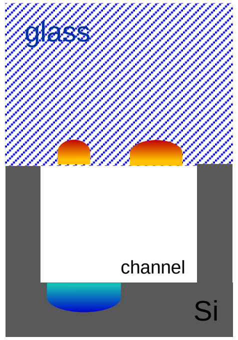

Focus on glass

Focus on Si

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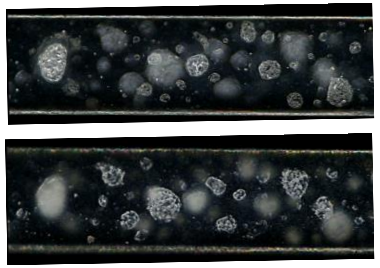

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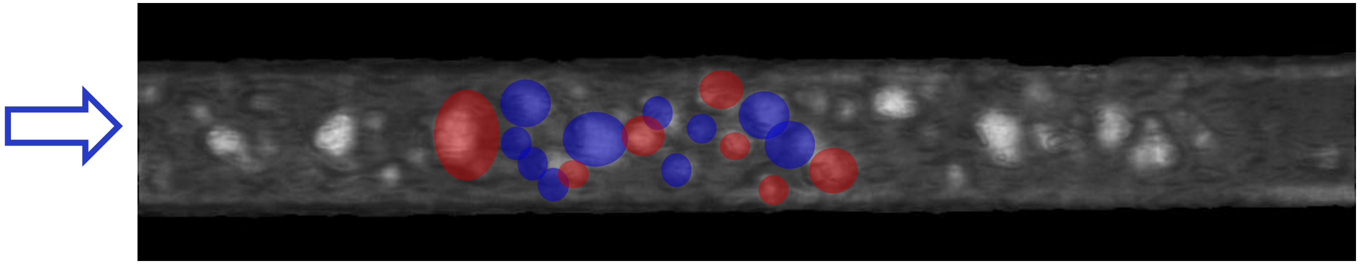


→ Proof of existence of local, crater-like erosion on both channel sides

Explanation: Erosion damage

How can fluid flow damage (erode) a surface in relatively short time ?

→ hydrodynamic cavitation damage
→ flash boiling/ flashing damage
→ fast and highly erosive (solid) particles in the flow

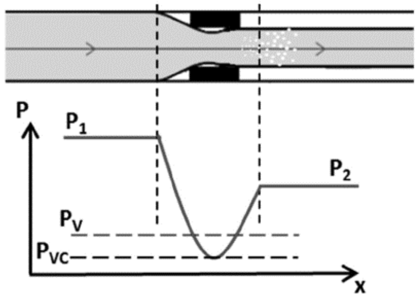
Hydro-mechanic machinery damaged by hydrodynamic cavitation

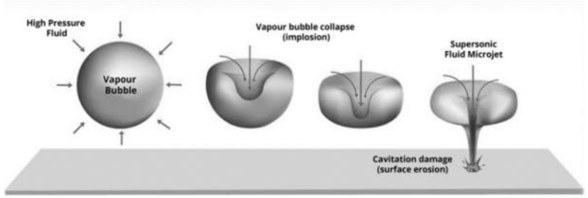
Cavitation vs. flashing damage

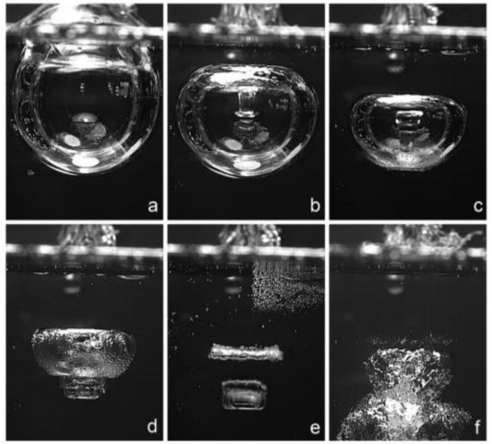
- Both are the result of related, but rather different thermo-dynamical processes
- at a fluid flow restriction (control valves, orifice, venturi tube etc.) the pressure drops suddenly and may drop below the vapour pressure of the liquid and liquid-vapour phase change occurs: formation of bubbles
- downstream, the flow passage expands and **partial pressure recovery** occurs as the flow velocity decreases
- Then …

cavitation occurs …

- if the local pressure recovers to above P_{vapour}
- the vapour bubbles will suddenly collapse and implode
- the implosion induces high-speed fluid micro-jets, shock waves and noise



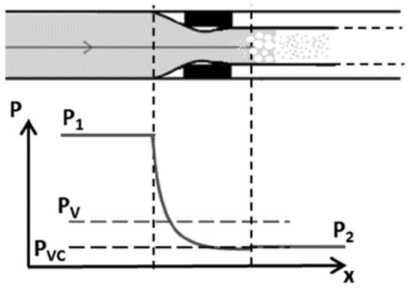




Bubble collapse: schematic and real life [3]

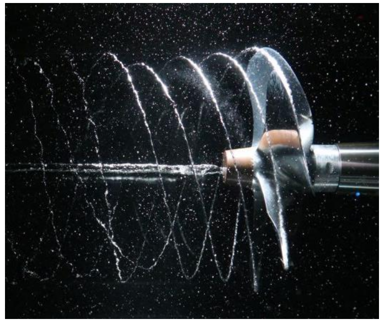
Flash boiling/ flashing occurs …

- if the local pressure does not recover to above P_{vapour}
- the vapour bubbles remain part of two-phase flow
- Fast bubbles may impinge on surface and create damage



→ Cavitation and its related damage is being studied and can be quantified, flashing not so much

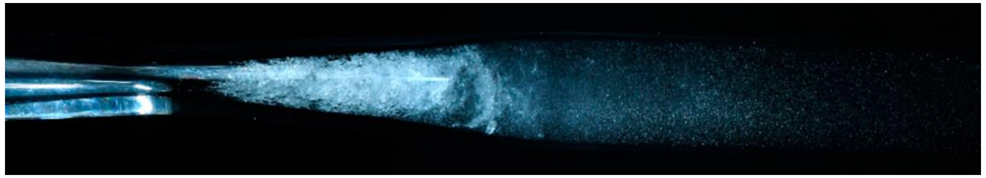
Cavitation – a very short overview



Cavitation induced by propeller [4]

cavitation – studied

- external flow (propellers, impellers, projectiles/submarines or hydro-foils)
- internal flow: e.g. studies on orifices and venturis
- the pressure evolution is monitored before/after the restrictive device: $P_{upstream}$ and $P_{downstream}$
- pressure ports are implemented accordingly
- also for micro-scale devices



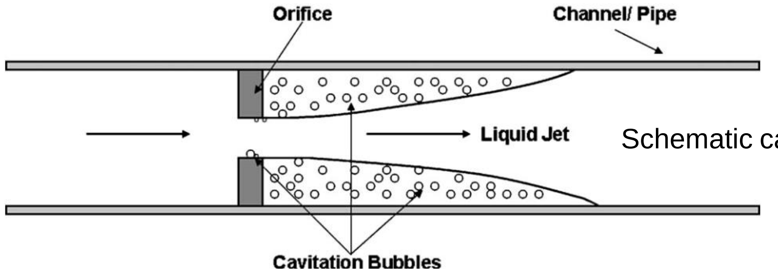
Cavitation induced inside venturi tube [5]

cavitation – quantified

With those pressure measurements one can calculate the

- Cavitation number
  - the smaller the more aggressive the form of cavitation
  - experimentally the exit pressure is lowered to lower σ until flow choking occurs
  - Mostly under constant fluid properties
  - downstream pressure P_2: ideally measured directly at throat exit, but various locations in literature (10s x D_h downstream)

$$\sigma = \frac{P_2 - P_v}{\frac{1}{2}\rho v^2}$$



Schematic cavitation [1]

- Cavitation index

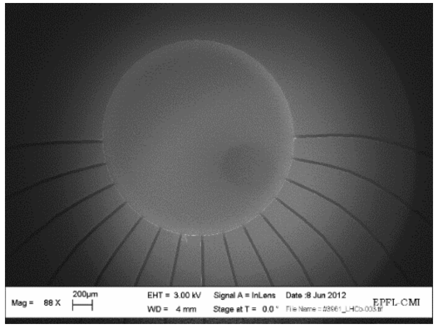
$$C = \frac{P_1 - P_v}{P_1 - P_2}$$

$C \geq 2.0$	No cavitation is occurring
$1.7 \leq C \leq 2.0$	No cavitation control required
$1.5 \leq C \leq 1.7$	Some cavitation control required
$1.0 \leq C \leq 1.5$	Potential for severe cavitation
$C \leq 1.0$	Flashing is occurring

Safety range of the cavitation index [6]

and relate it to an existing “safety range”

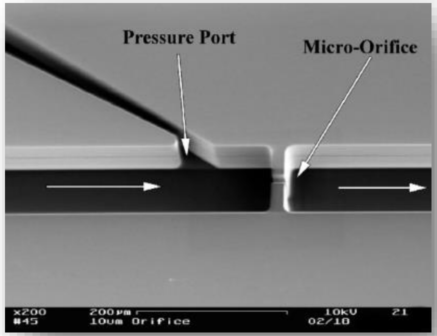
Cavitation – difference between EP-DT devices and devices studied in literature



Considering only the inlet geometry of *one* restriction
- Clearly no orifice or venturi geometry
- No pressure ports before and after restriction to estimate the cavitation potential

+ In addition
- multi-channels instead of single-channel
- No inlet plenum *per se*
- Unique inlet geometry, hence even less clear picture of upstream pressure

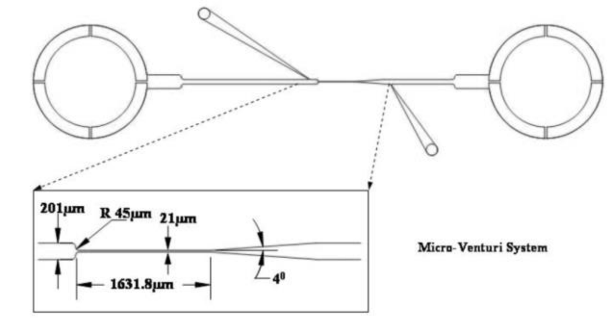
+ Furthermore, for the same device
- length of the multiple restrictions varies (FRAME4)
- outlet geometry varies among the multiple restrictions (FRAME4)
- directional change varies among the multiple restrictions (FRAME4, REFLECS, ATLAS)



↔ **From literature**
micro-orifice with pressure ports for cavitation studies [7]

= direct measurements missing
= rather complex layout to study any fundamental flow behaviour
= note: technological manufacturing aspects of earliest final cold plates was prioritised

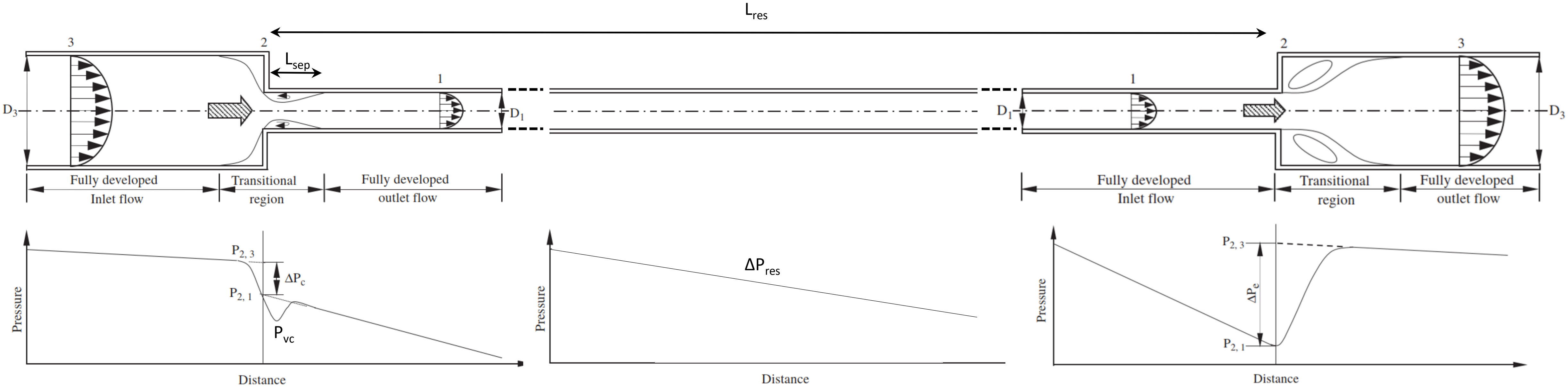
→ Cavitation number cannot be calculated in a meaningful way
→ Other means to estimate the cavitation potential required



↔ **From literature:**
cavitation susceptibility meter (CSM) with pressure ports [8]

Estimation of the cavitation potential of our devices

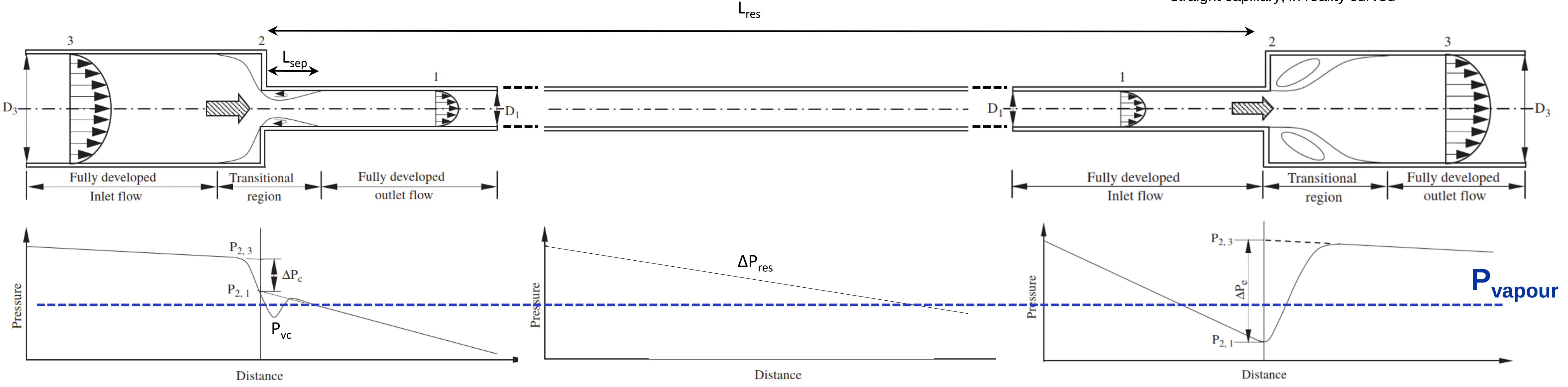
→ by means of the theoretical pressure evolution along one restrictive inlet section
→ analytical combination of flow contraction and expansion with capillary in between



Estimation of the cavitation potential of our devices

→ by means of the theoretical pressure evolution along one restrictive inlet section
→ analytical combination of flow contraction and expansion with capillary in between
→ **evaluation of theoretical bulk static pressure in relation to the local vapour pressure**

Assumptions:
- macro-scale textbook formulations for duct flow used
- actual complex inlet geometry simplified to simple textbook contraction
- sub-cooled single-phase flow at inlet
- no meta-stability effect accounted for
- development of vena contracta and flow separation at contraction
- isenthalpic pressure drop
- even distribution of the flow into n channels
- straight capillary; in reality curved



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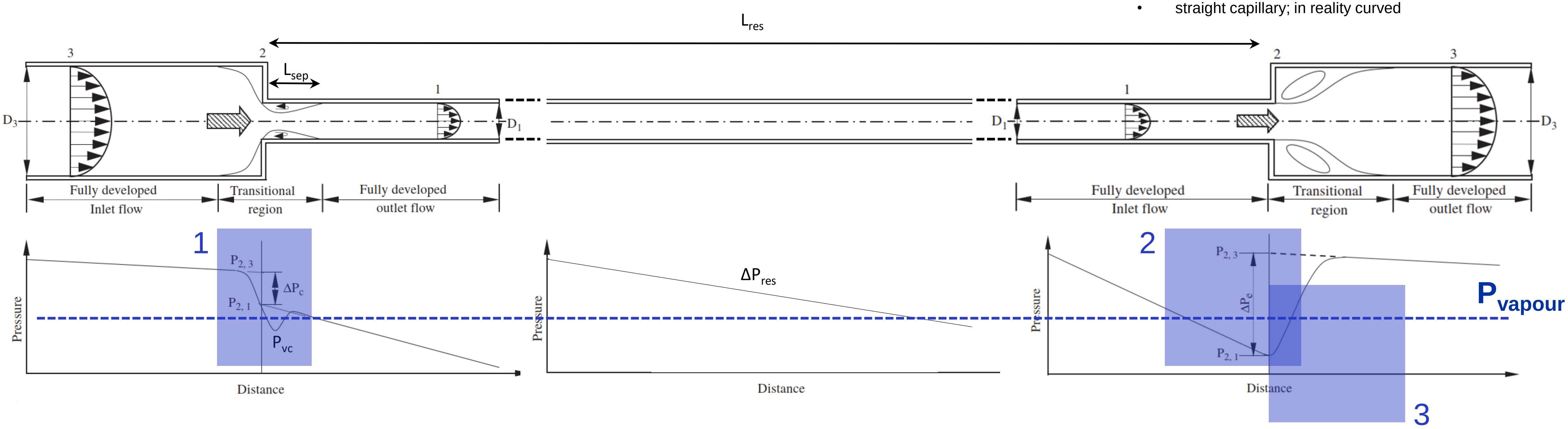
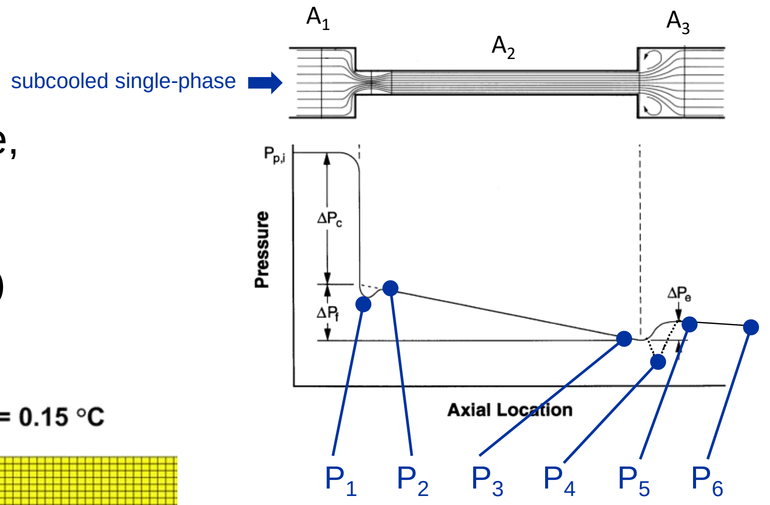


Using very basic criterion: sudden ΔP below vapour pressure + recovery = possibility of formation and collapse of bubbles
= 3 theoretical locations

1 sudden pressure reduction due to flow separation and vena contracta → bubble formation → collapse after flow reattachment
2 low system pressure in core flow at the end of the restriction → bubble formation → collapse after expansion
3 sudden very low pressure due to recirculation area at the walls → bubble formation → collapse upon re-entry into core flow
= theoretical danger zones

Estimation of the cavitation potential of our devices

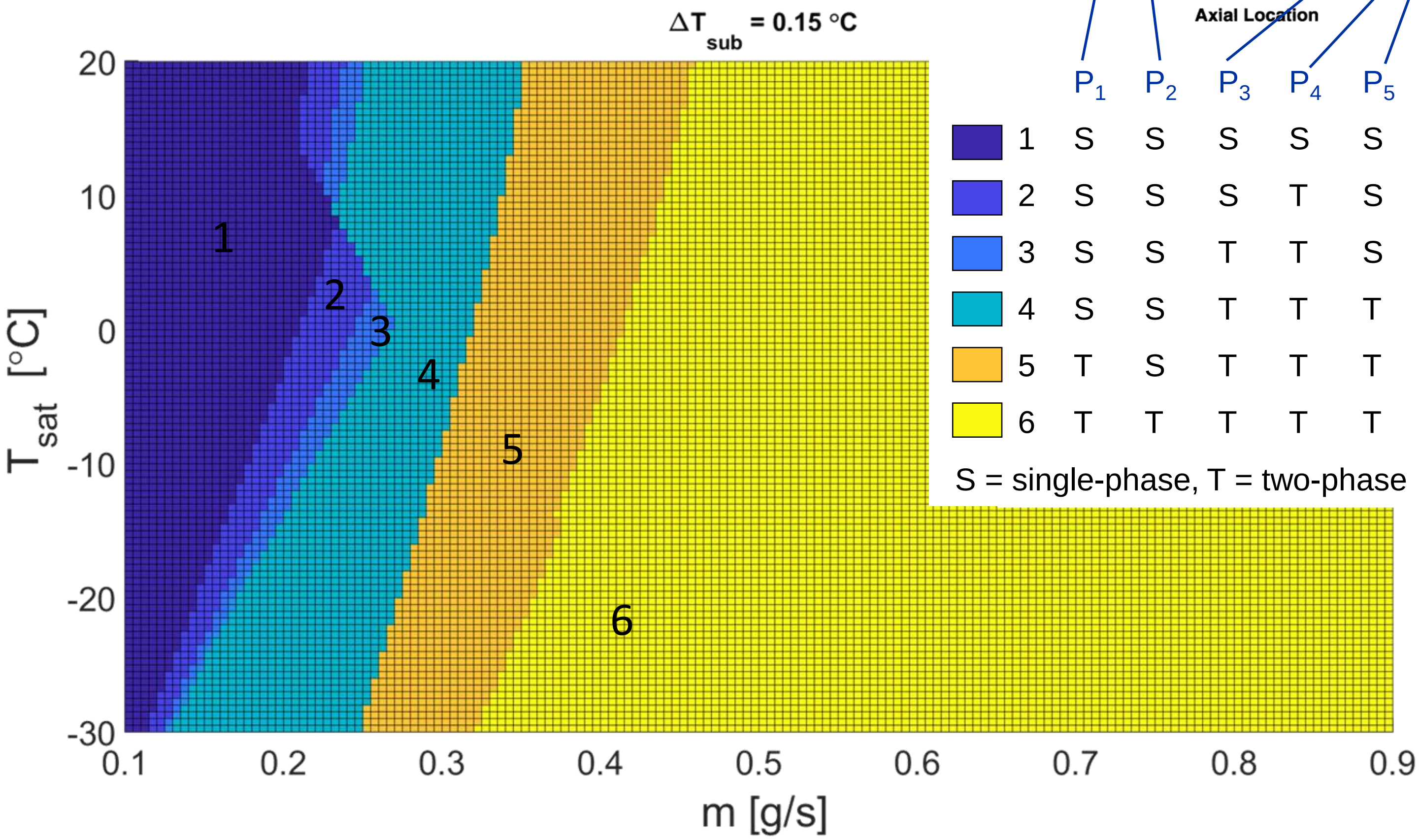


→ the combination of *fluid properties* and *working parameters* (sub-cooling level, flow rate, T_{sat}) within a fixed geometry

- influences the outcome of this analysis
- however those were chosen rather randomly so far for the actual experiments (within reason)

→ creation of a parametrical map

- in function of total flow rate and T_{sat}
- fixed sub-cooling level, fixed geometry
- example: REFLECS @ 0.15°C sub-cooling



	P_1	P_2	P_3	P_4	P_5	P_6
1	S	S	S	S	S	S
2	S	S	S	T	S	S
3	S	S	T	T	S	S
4	S	S	T	T	T	T
5	T	S	T	T	T	T
6	T	T	T	T	T	T

S = single-phase, T = two-phase

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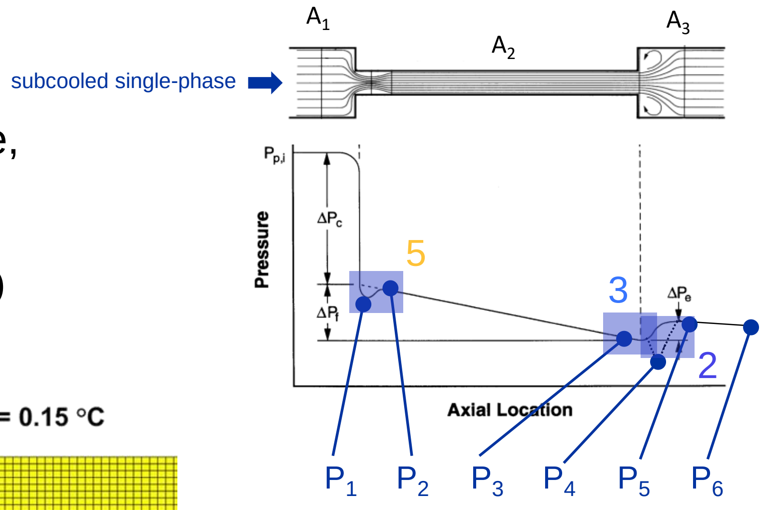

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- in function of total flow rate and T_{sat}
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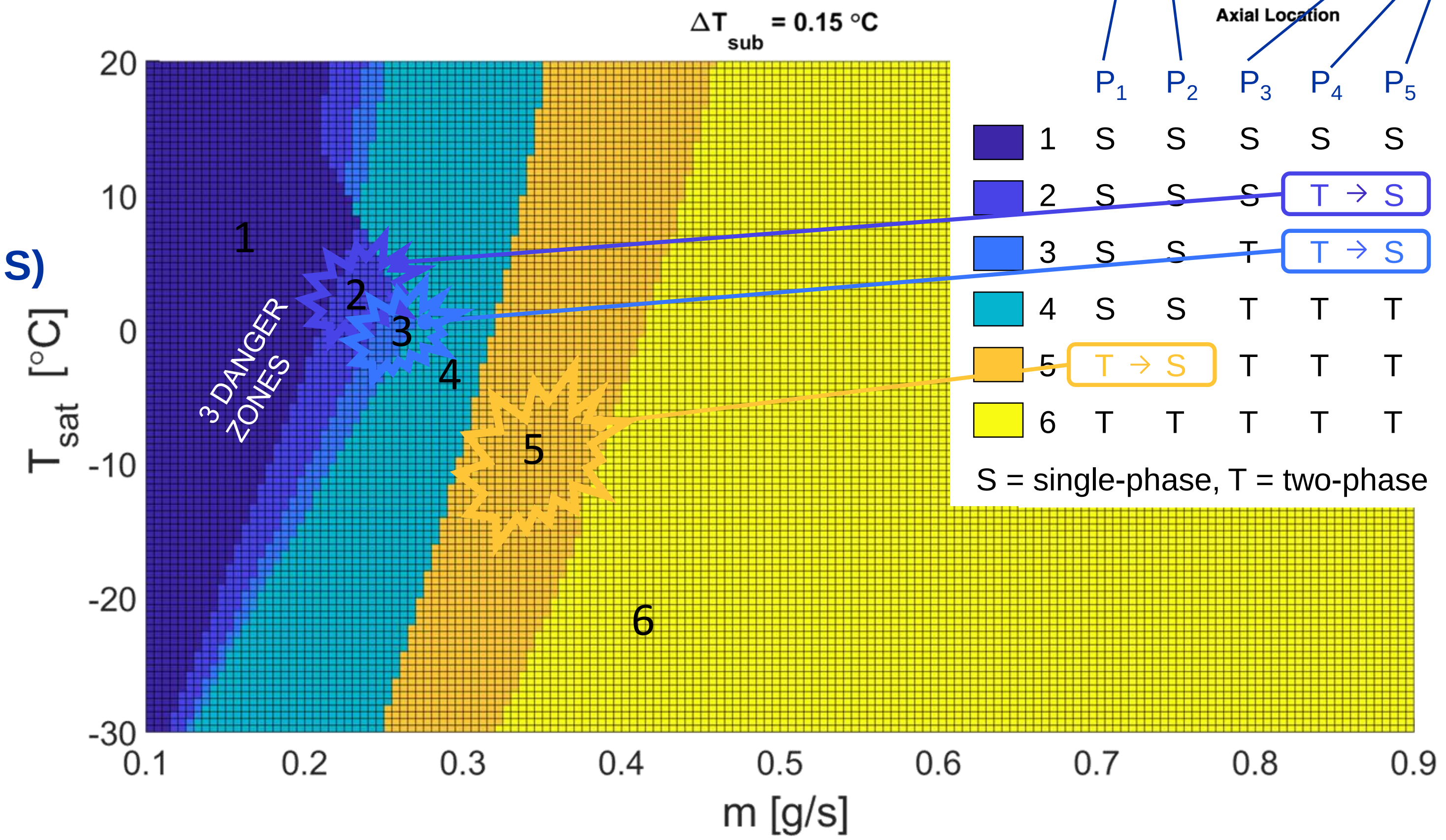
- example: REFLECS @ 0.15°C sub-cooling

→ indication of 3 theoretical danger zones using basic criterion mentioned before (T → S)



	P_1	P_2	P_3	P_4	P_5	P_6
1	S	S	S	S	S	S
2	S	S	S	T → S		S
3	S	S	T	T → S		S
4	S	S	T	T	T	T
5	T → S		T	T	T	T
6	T	T	T	T	T	T

S = single-phase, T = two-phase

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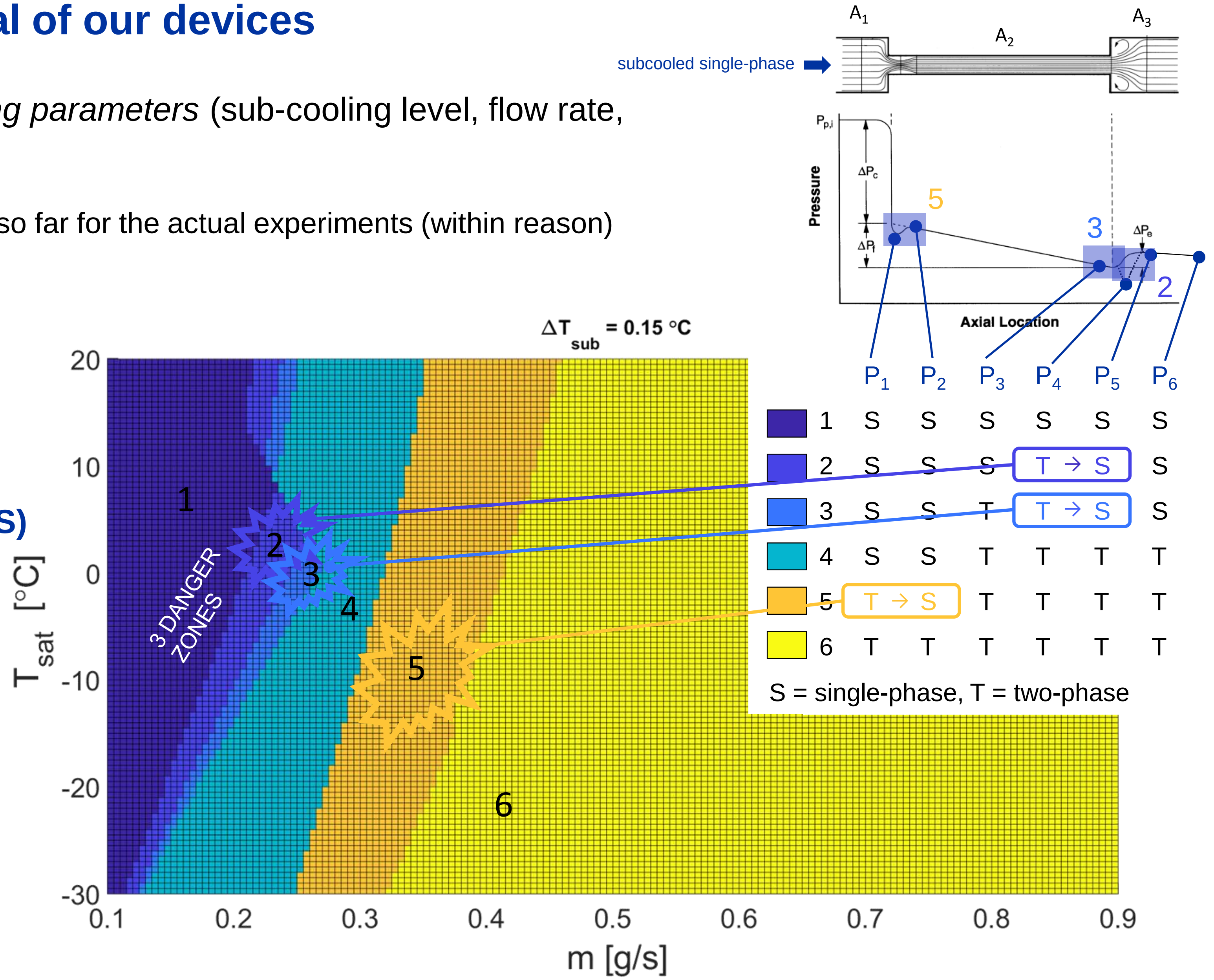

	P_1	P_2	P_3	P_4	P_5	P_6
1	S	S	S	S	S	S
2	S	S	S	T →	S	S
3	S	S	T	T →	S	S
4	S	S	T	T	T	T
5	T →	S	T	T	T	T
6	T	T	T	T	T	T

S = single-phase, T = two-phase

Note: no true flash boiling occurs:
S-S-S-T-S-T

Estimation of the cavitation potential of our devices

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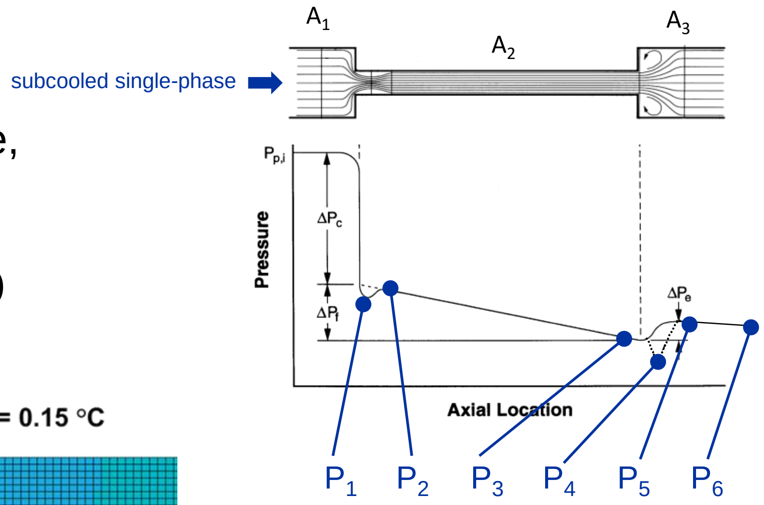


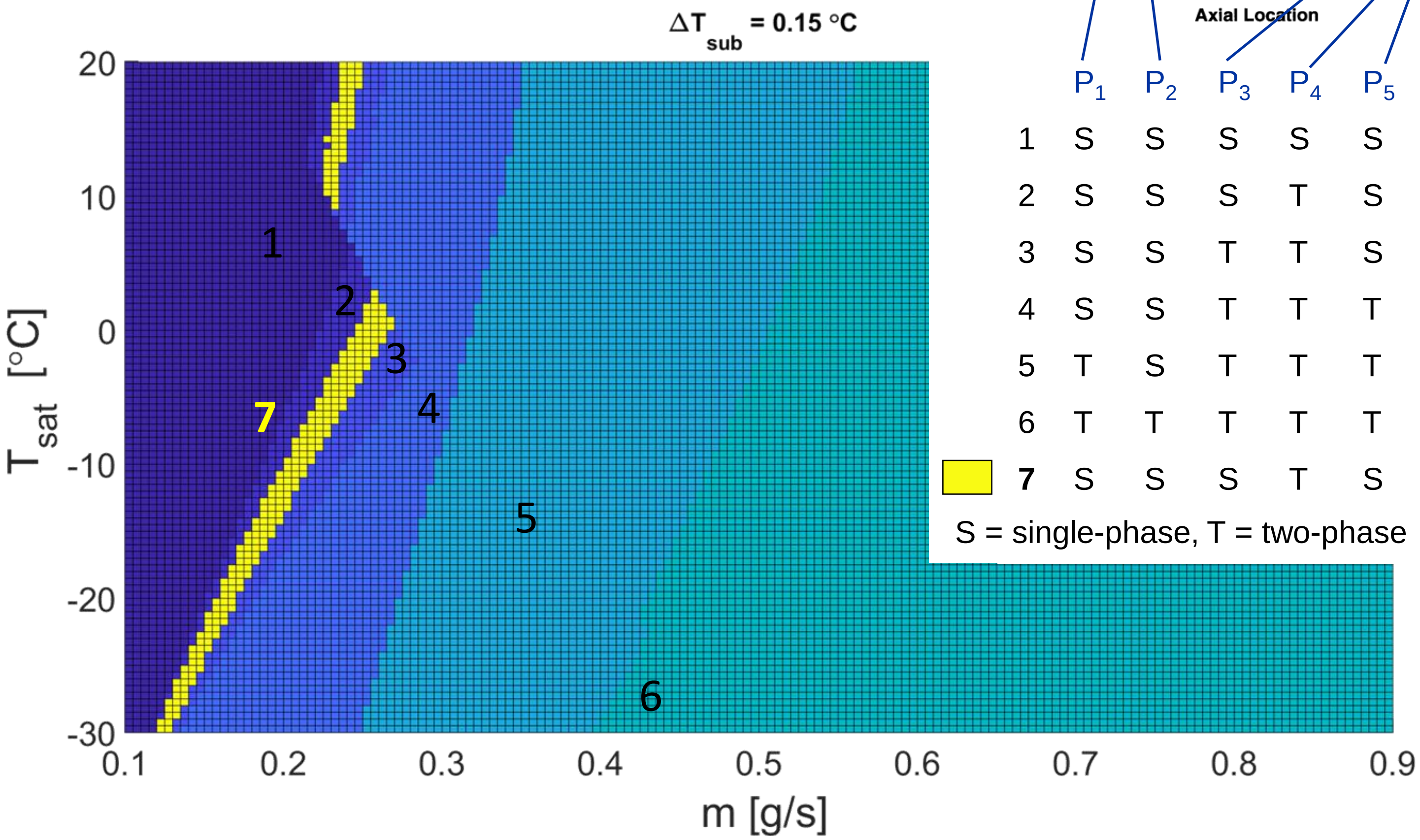
	P_1	P_2	P_3	P_4	P_5	P_6
1	S	S	S	S	S	S
2	S	S	S	T	S	S
3	S	S	T	T	S	S
4	S	S	T	T	T	T
5	T	S	T	T	T	T
6	T	T	T	T	T	T
7	S	S	S	T	S	T

S = single-phase, T = two-phase

← reverse-tuning the map by changing the geometrical inputs:

EXAMPLE: include actual flash boiling
by reducing the main channel area
= reduce ratio between restriction and main channel

(Similar outcome can be achieved with fine-tuning the sub-cooling level)



Solution:
Use the map as a preliminary design guide for future micro-channel cooling devices

= Actively seeking out or avoiding certain flow regimes

Estimation of the cavitation potential of our devices

??? Only a very rough estimate due to multiple issues not easily foreseen without further experiments:

- Cavitation at the micro-scale differs to macro-scale (surface tension forces at the micro-scale may delay fluid rupture)
- actual cavitation inception (gaseous and vapourous cavitation, depends on many factors, not studied at all with CO_2 at the micro-scale)
- uneven flow distribution in multi-channels might affect the outcome
- the peculiar geometry of the devices not fully accounted for in approach so far most likely alters the real outcome
- meta-stable flow might alter outcome drastically (= ability of the fluid to sustain tension before rupture, although already under apt conditions to form vapour cavities)
- …

→ Clearly some CFD simulations would be useful, but still tricky for bi-phase CO_2

!!! Further emphasising the general cavitation hypothesis in our case:

- low surface tension of CO_2: low surface tension fluids rupture more easily (→ cavitate more easily, meta-stability less likely)
- Other reports from literature of bubbles collapsing far downstream of restriction/expansion (vs. immediately)
- Comparison of parametrical map with visual results reveals non-cavitating and cavitating flow patterns from literature in rough accordance with the map

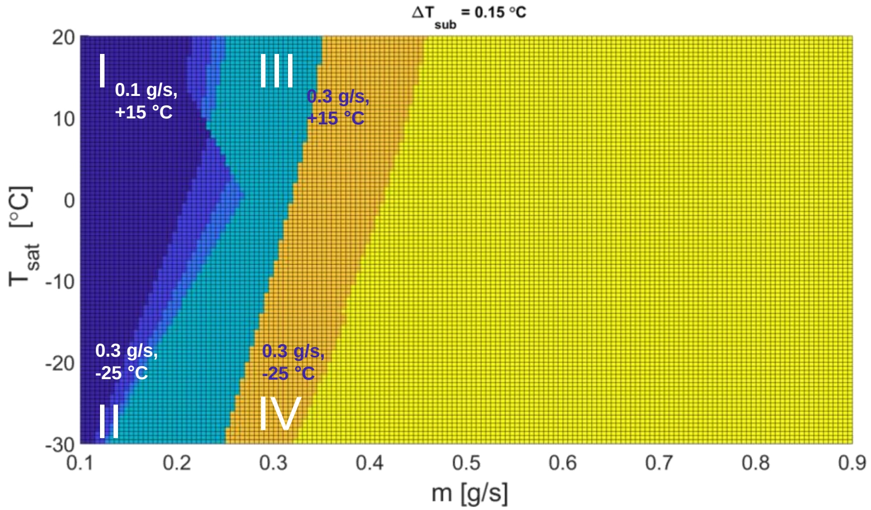
Estimation of the cavitation potential of our devices

→ Comparison of map with visual results and results from literature

Experimental parameters

- total flow rates: 0.1 and 0.3 g/s
- T_{sat} : +15 to -25°C, examples here +15 and -25°C
- <u>No heat flux</u>!

= 4 points (I, II, III, IV) in map ready for comparison

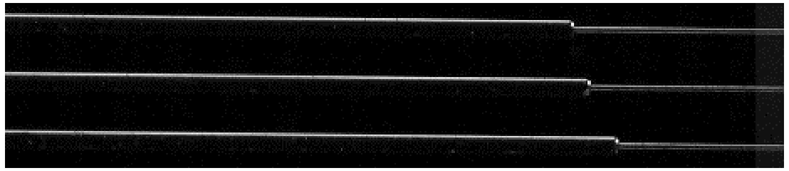


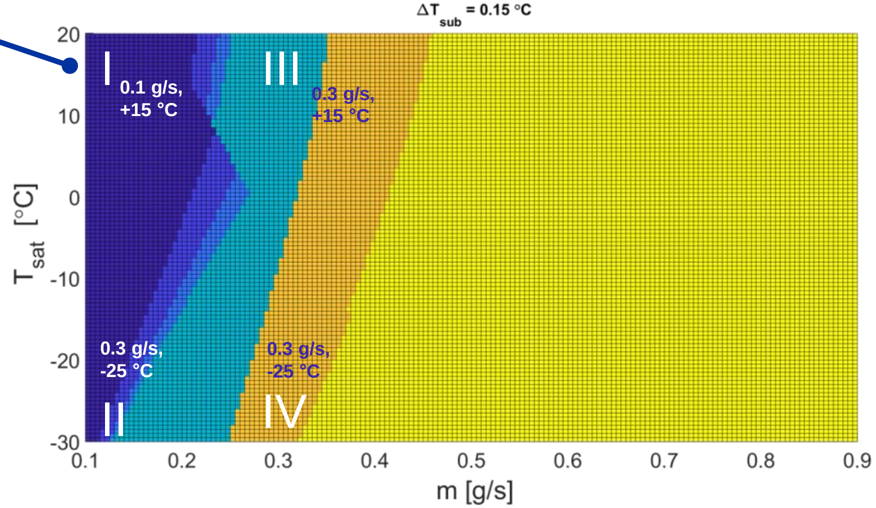
Estimation of the cavitation potential of our devices

I 0.1 g/s, +15 °C

Prediction:
deep in single-phase flow regime

Visual observation:
- Not so deep in single-phase flow
- minor boiling observed, initiated due to heat leaks
- No cavitation flow pattern observed





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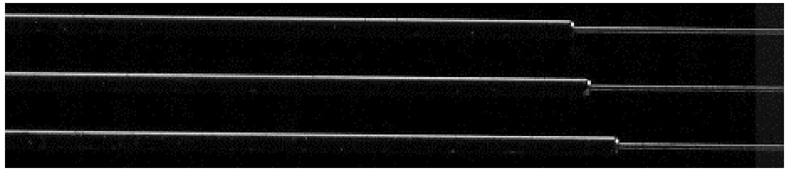
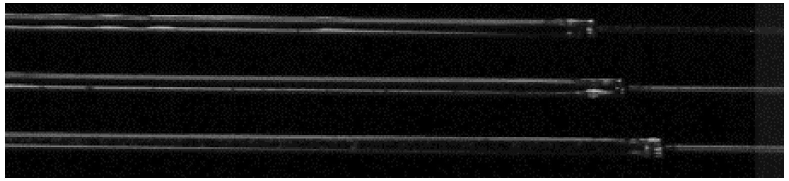
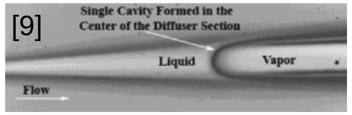


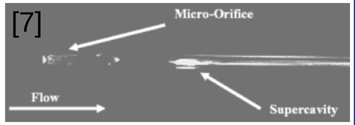
II 0.1 g/s, -25 °C

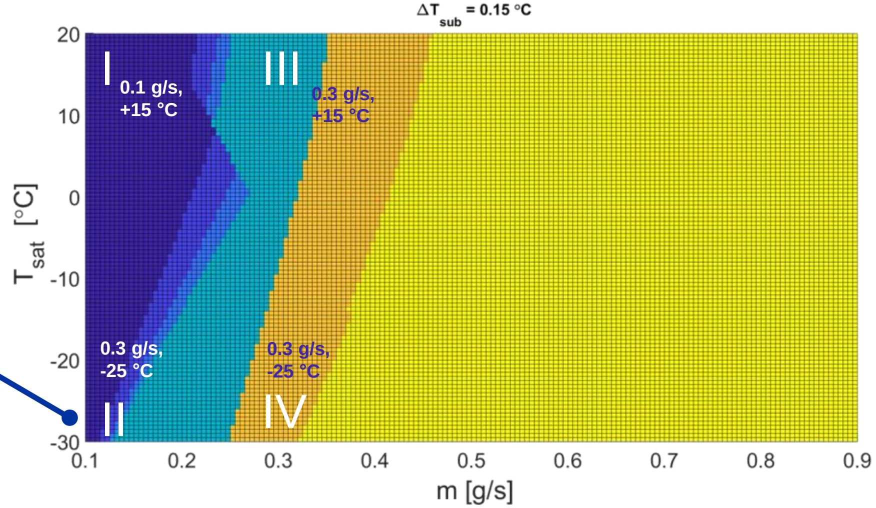
Prediction:
single-phase flow adjoining danger zone 2 & 3 = cavitation potential at restriction outlet

Visual observation:
- Single phase flow alternating between cavitating and non-cavitating two-phase flows with “normal” bubbles
- Cavitating flows form single stationary super-cavity
- Higher surface tension at lower T_{sat} favours larger cavities









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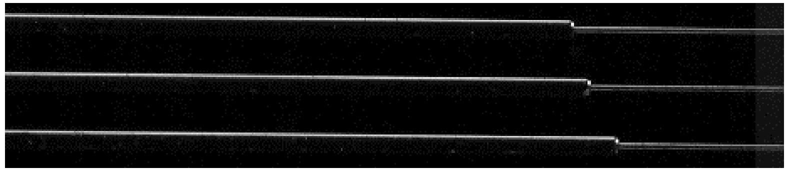
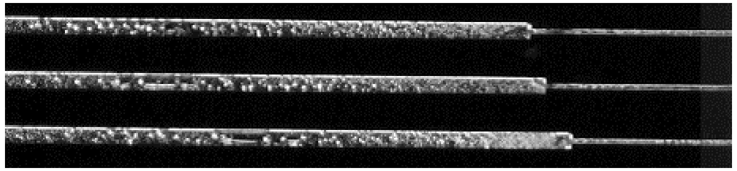


III 0.3 g/s, +15 °C

Prediction:
Normal two-phase flow establishing in restriction adjoining danger zone 1 = cavitation potential at restriction inlet

Visual observation:
- non-cavitating bubbly flow with bubble bursts of cavitating nature already observed in restriction
= periodical bubble shedding typical to cavitating flows
- bubble collapse observable



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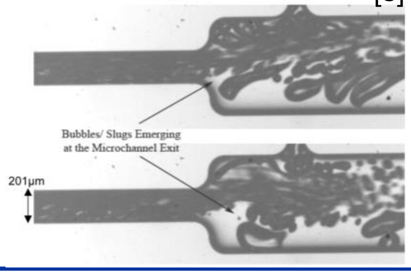

II 0.1 g/s, -25 °C

Prediction:
single-phase flow adjoining danger zone 2 & 3 = cavitation potential at restriction outlet

Visual observation:
- Single phase flow alternating between cavitating and non-cavitating two-phase flows with "normal" bubbles
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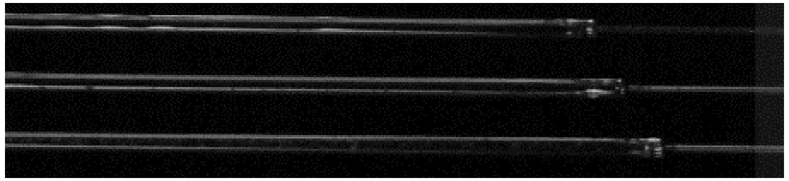

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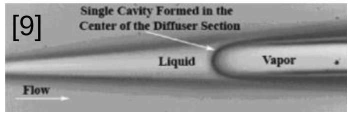

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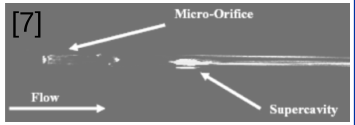

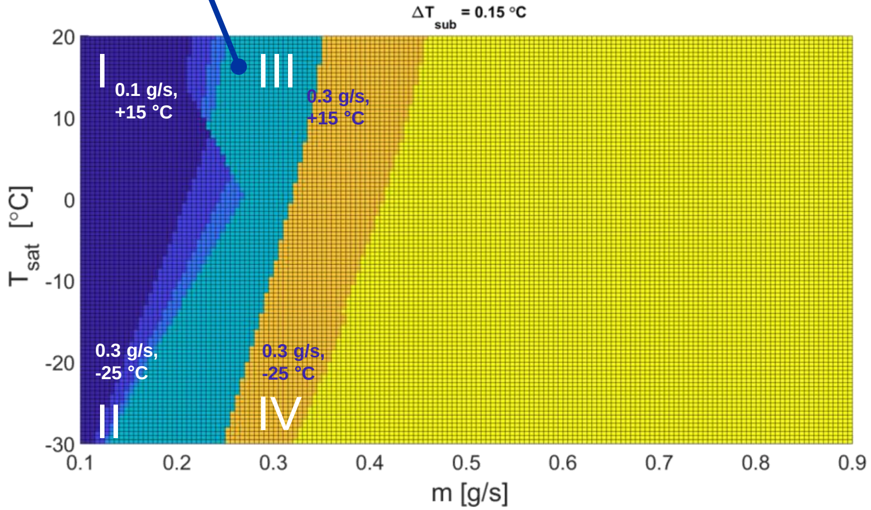

Estimation of the cavitation potential of our devices

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deep in single-phase flow regime

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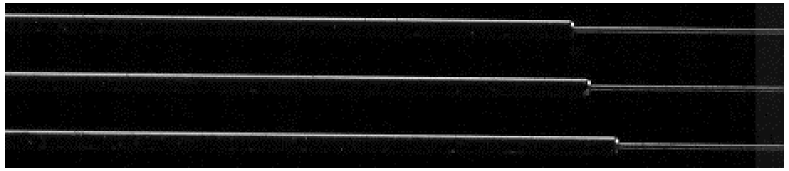

III 0.3 g/s, +15 °C

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Visual observation:
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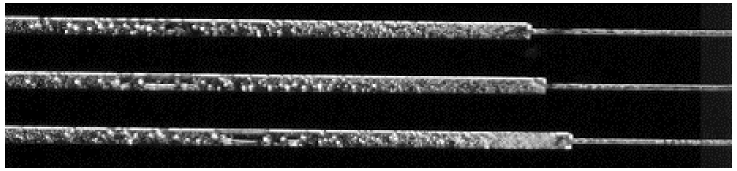

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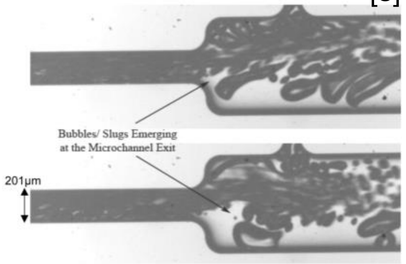

II 0.1 g/s, -25 °C

Prediction:
single-phase flow adjoining danger zone 2 & 3 = cavitation potential at restriction outlet

Visual observation:
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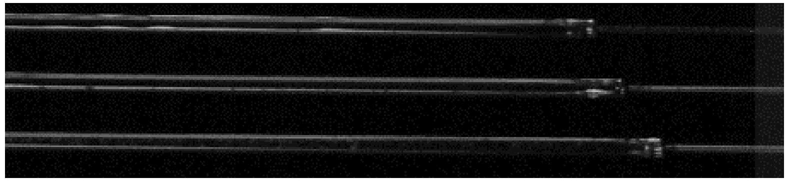

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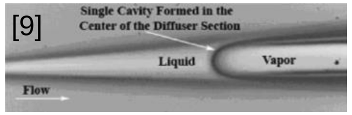

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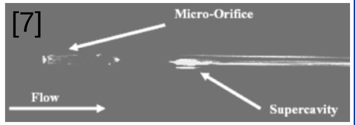
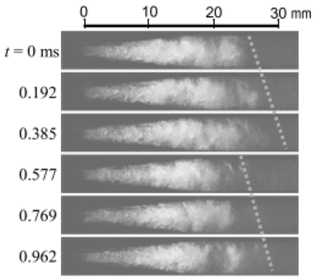


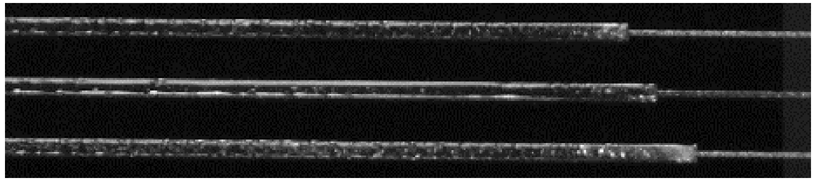
IV 0.3 g/s, -25 °C

Prediction: danger zone 1 = cavitation potential at restriction inlet

[10]

Visual observation:
- Restrictions filled with cavitation bubbles or single cavities
- change into other regime not too frequent, as predicted
- Pulsating flow structure at the outlet
- bubble collapse and pressure waves observable
- Similar to report on cavitation in macro-venturi tube
- inverted annular flow; wavy twin vapour cavities with entrained bubbles?





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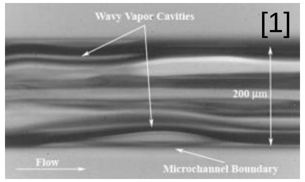

Conclusion & lessons learned

= existing and future two-phase micro-channel cooling devices require an inlet restrictive inlet section to allow for a proper functionality without flow oscillations

= if not chosen carefully in tandem the geometry and flow parameters used so far induce cavitating flows and the associated erosion damage

= to avoid this destructive flow regime in hindsight for existing micro-channel geometries and in foresight for future micro-channel geometries a parametrical map can be created, indicating the "safe" and "dangerous" flow parameters

= the true - *initially intended* - flash boiling regime can be sought out with reverse-tuning the channel geometry

= the approximate validity of this map could be confirmed by means of flow visualisation and comparison to examples from literature

→ in view of the new era of micro-channel detector cooling with 3D-printed light-weight realisations in metals or ceramics any potential pitting damage may prove much more disastrous, compared to those produced by MEMS techniques in monocrystalline silicon or glass

→ the proposed map may be used as guidance for designers and experimentalists, designing and investigating future multi-micro-channel cold plate layouts, tuning the geometry and the flow parameters for a safe and efficient operation

Outlook & open issues

→ acknowledging that more investigations are needed to understand the issue of cavitating CO_2 at the micro-scale

_ further systematic high-speed camera recordings with existing devices

_ direct confirmation by means of cavitation number: new device geometries with pressure ports

_ further investigation: including data with heat flux, ATLAS device analysis

Thank you for your attention!

Quick-References

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