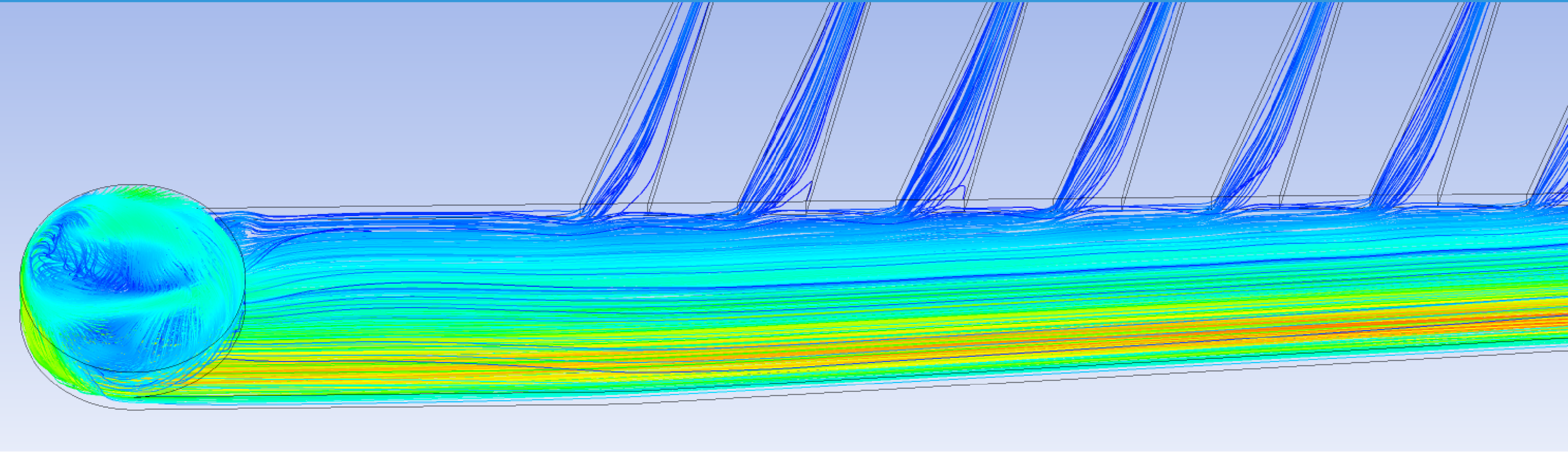
Micro-channel Cooling For Silicon Detectors



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Micro-channel Cooling
Strasbourg, 31.10.2016

HELMHOLTZ ASSOCIATION

ATLAS EXPERIMENT

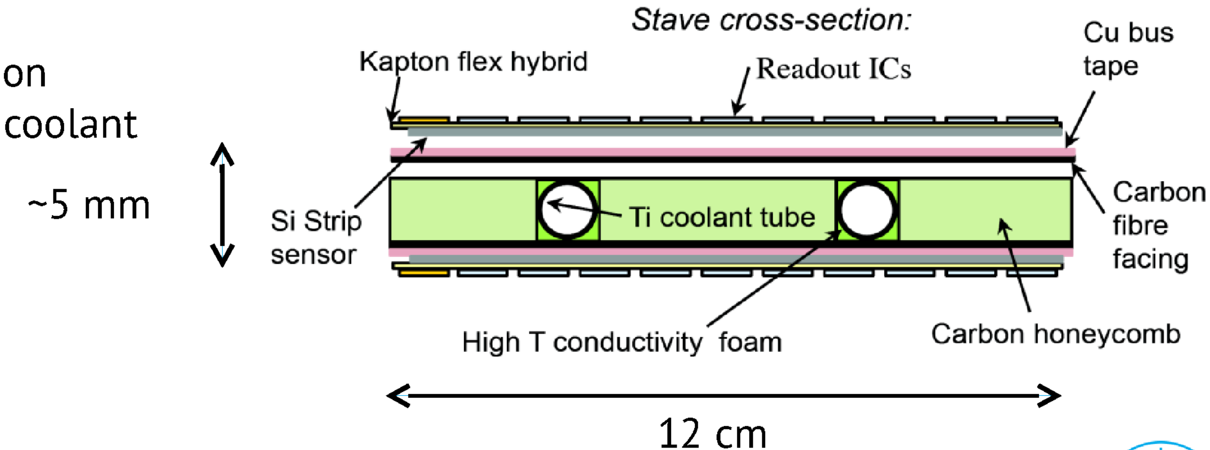
CNM Centro Nacional de Microelectronica CSIC

DESY

Content

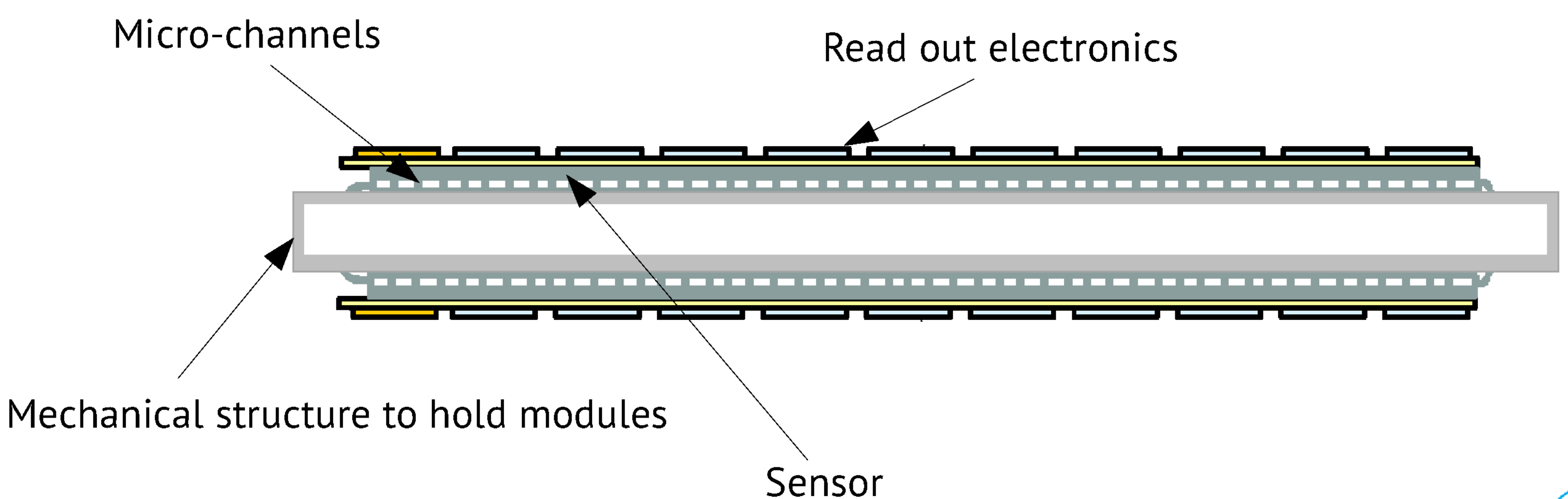
Motivation For A Micro-channel Cooling System

- Read-out electronics inside the detector produce significant heat
  - Risk of thermal runaway
  - Leakage current due to radiation damage resulting in increasing electronic noise during data taking
- Particles lose energy passing material in the detector via multiple scattering
  ➡ save material
- The ATLAS Inner Detector as an example
  - CTE mismatch
  - Cooling system based on titanium pipes for the coolant

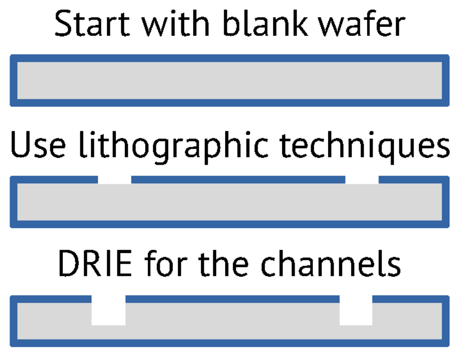


Improving The Cooling Design

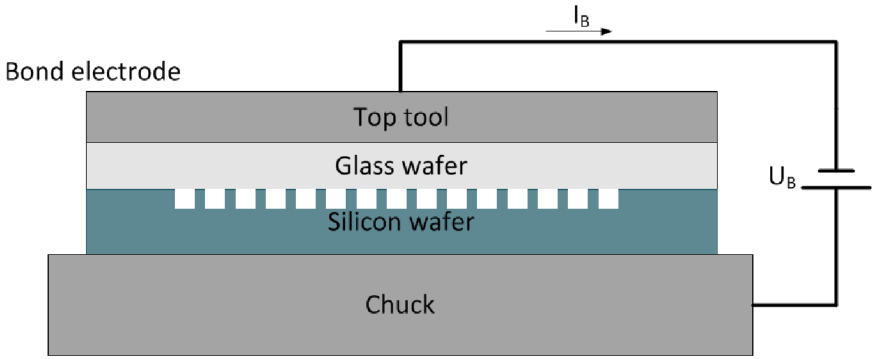
- What if we could include the cooling into the sensor?
  - CTE match
  - Saves material and cooling power
  - Micro-channel technology is a strong candidate
- Project of DESY/CNM considered as generic R&D
- Other projects are employing this technology (LHCb, Na62, ILC etc)

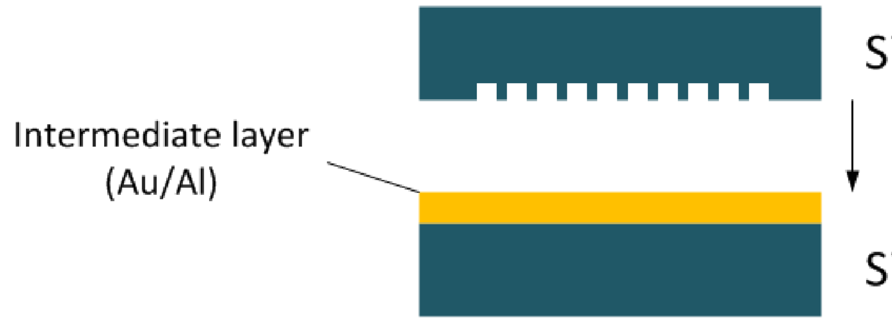


Micro-channel Fabrication



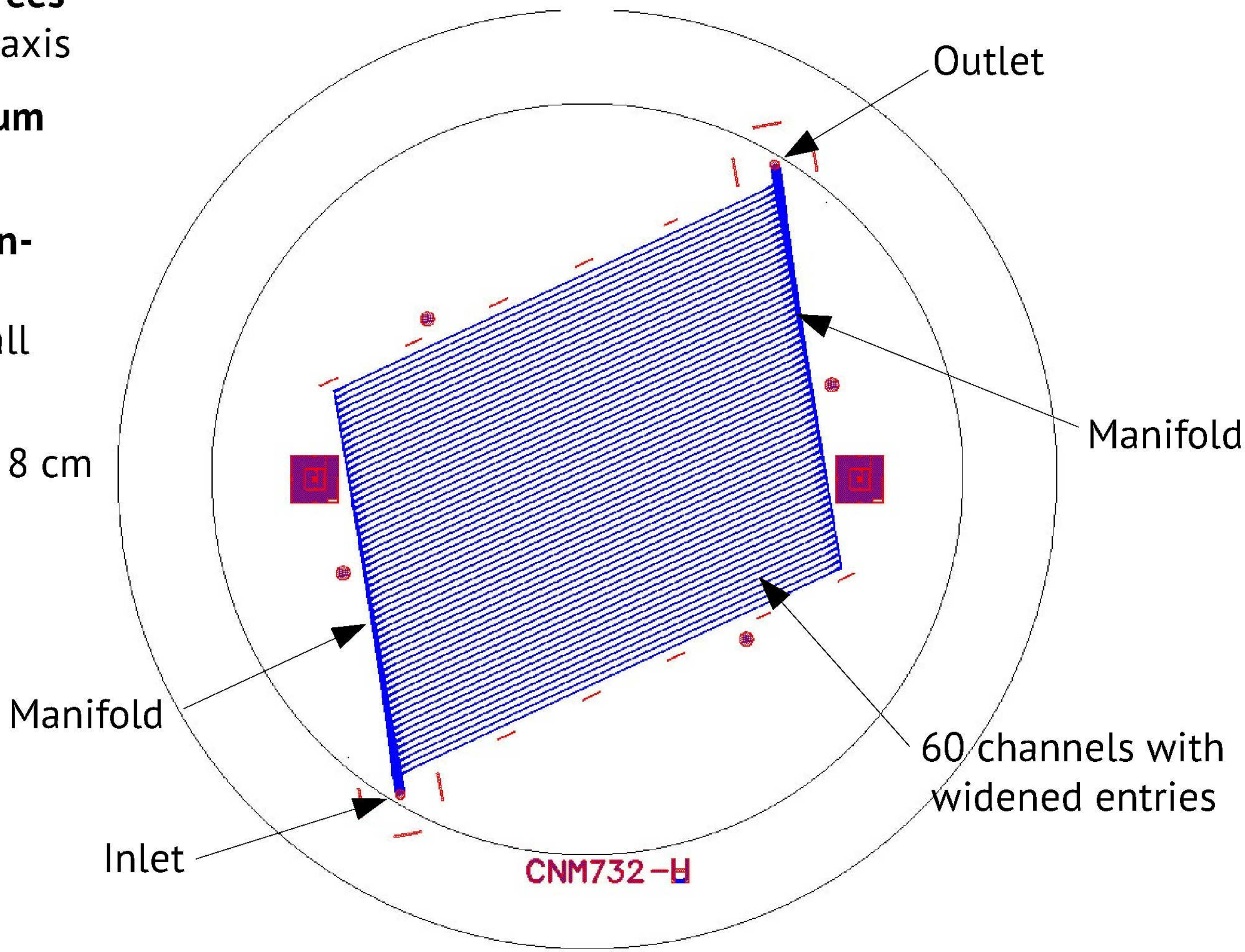
Anodic Bonding	Eutectic Bonding
Silicon-Pyrex	Silicon-silicon (intermediate metal layer)
Temperature and electrostatic field	Temperature and mechanical pressure
No intermediate layer	e.g. metal sputtered or CVD



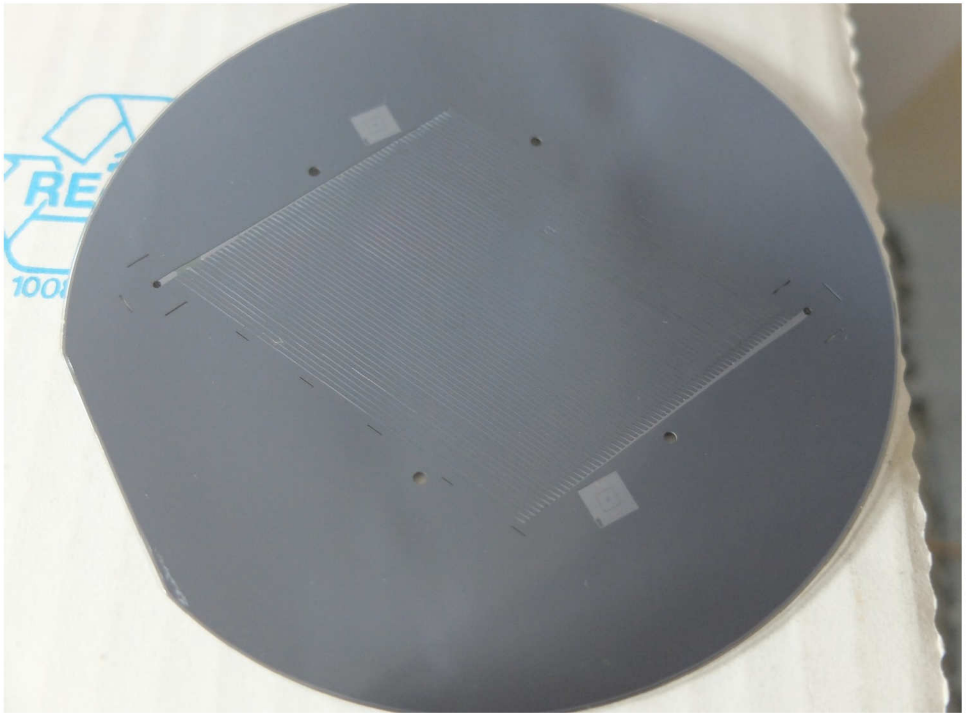


The Layout Of The Micro-channel Structure

- Channels are **rotated 15 degrees** with respect to the manifold axis
- Channels are **100 µm x 100 µm** wide and high
- Manifolds are **shaped in a non-linear way** to provide a homogeneous flow through all channels
- Distance from Inlet to Outlet 8 cm

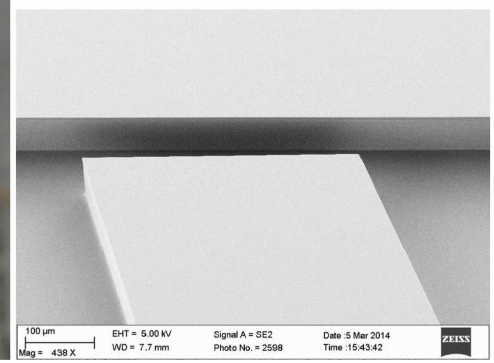


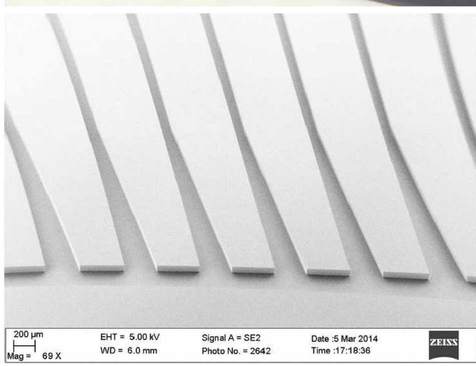
Prototype

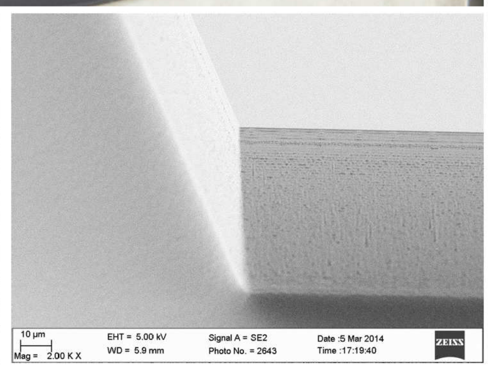


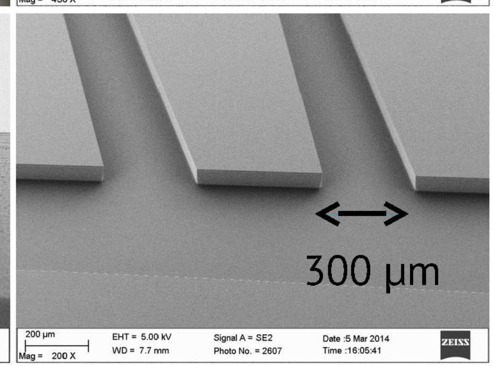
- Samples with Pyrex or silicon top
- Silicon thickness: 300-500 µm
- Pyrex/silicon thickness: 500 µm
- Pyrex useful to see clogged channels

SEM pictures



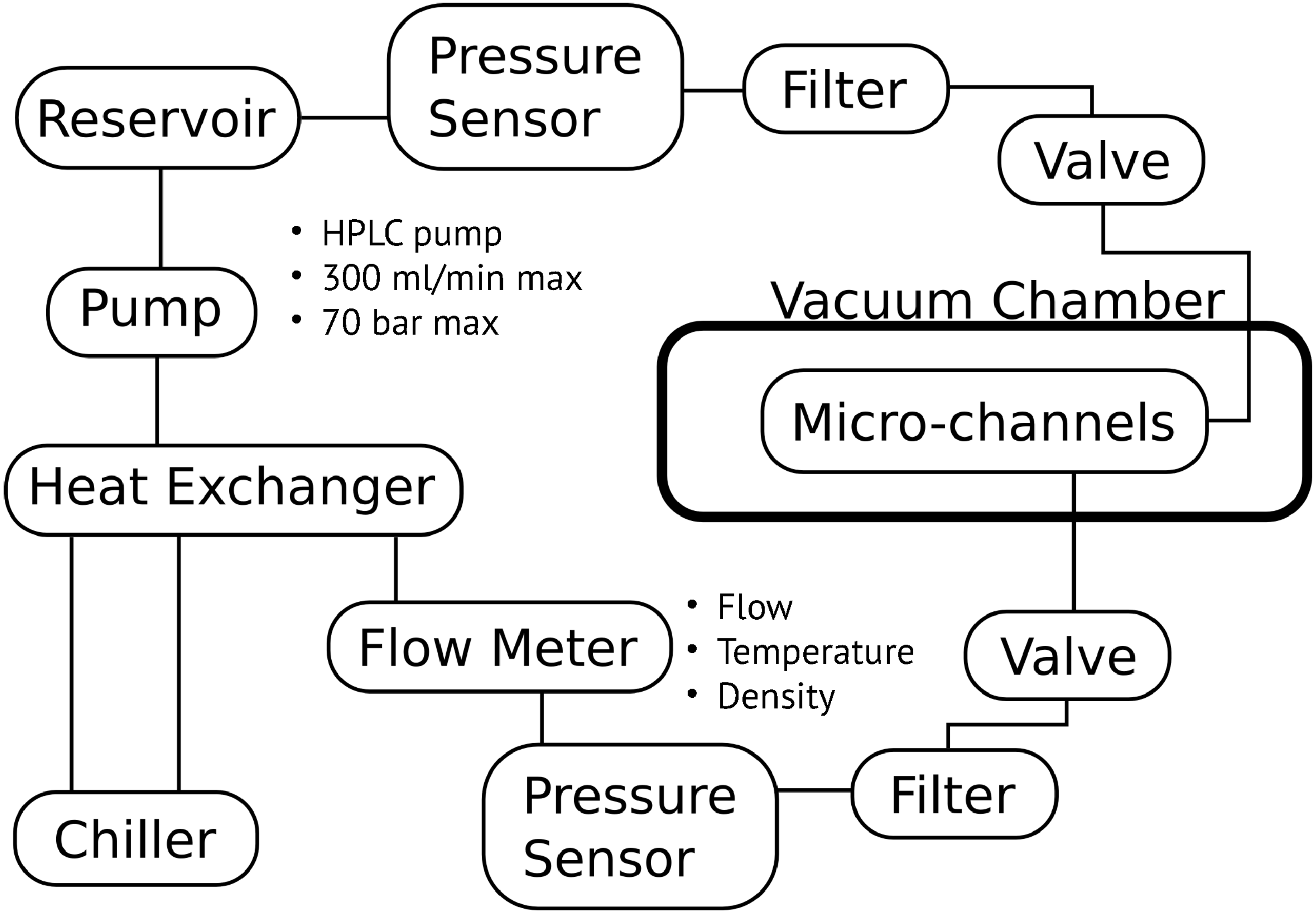






The Test Stand For The Measurements On The Prototype

- 3M HFE 7100 (Hydrofluoroether)
- Low viscosity at low temperatures 0.7 cSt
- At ~20 C for first studies



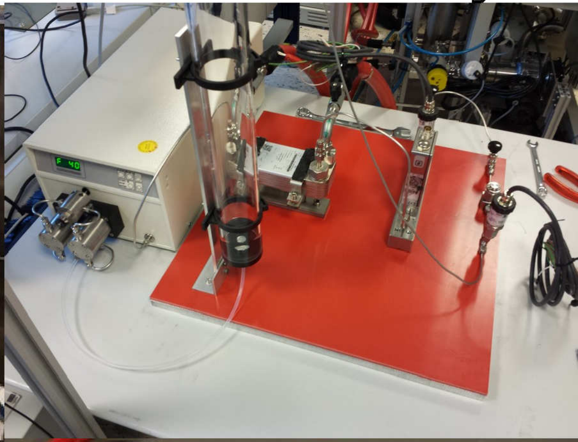
- Analog pressure sensors
- Read out by Arduino

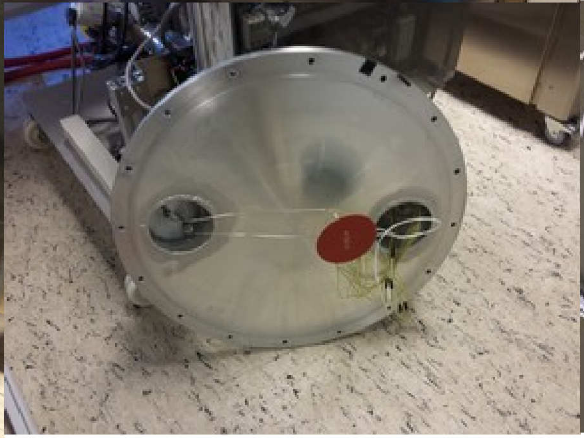
The Setup

Vacuum chamber

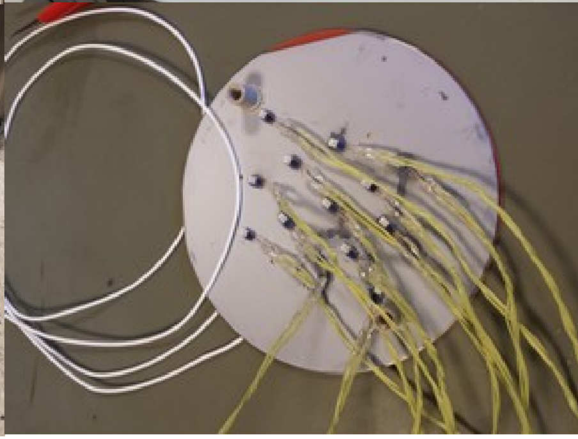
Top of the lid
with feedthrough

Pump, flow meter, pressure
sensors and heat exchanger



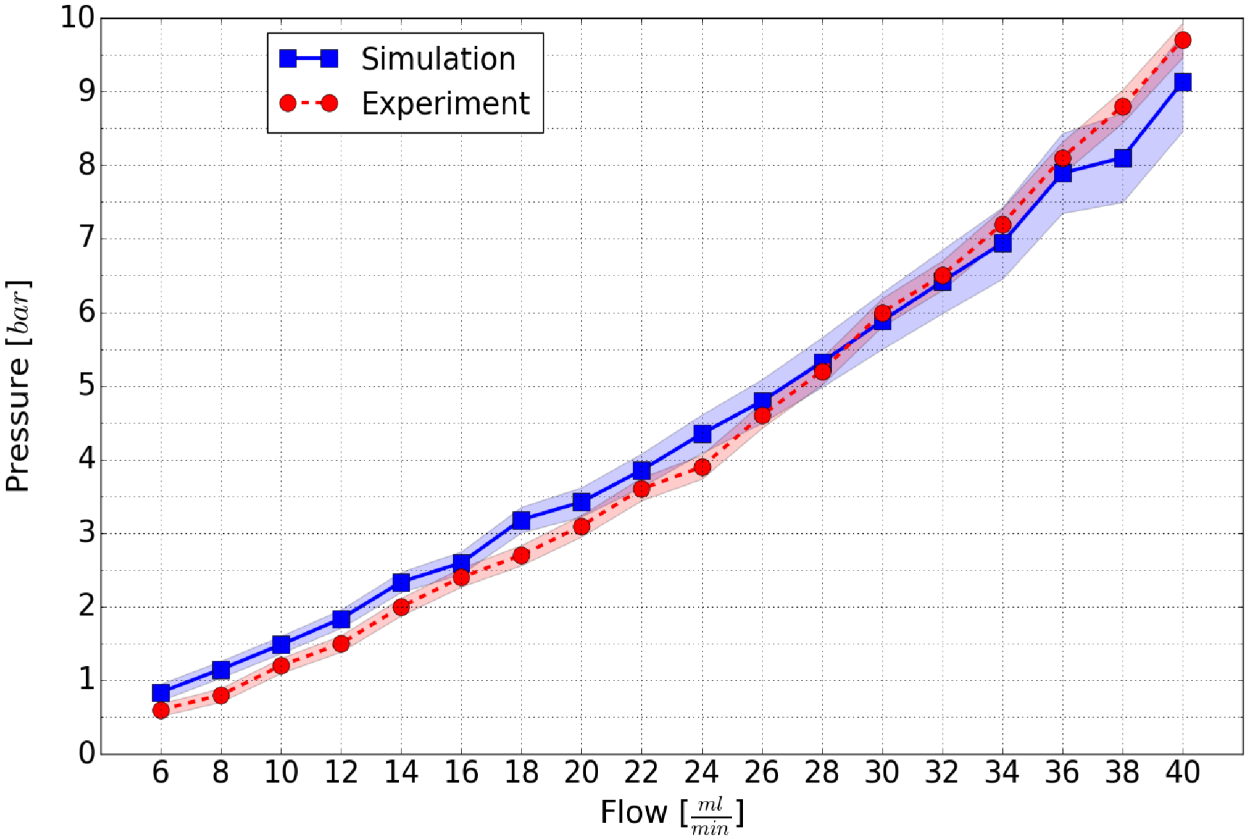


Bottom of the lid
with micro-channels



Temperature sensors arranged
on wafer with 4” heater
on the backside

Flow Measurements Versus Simulation



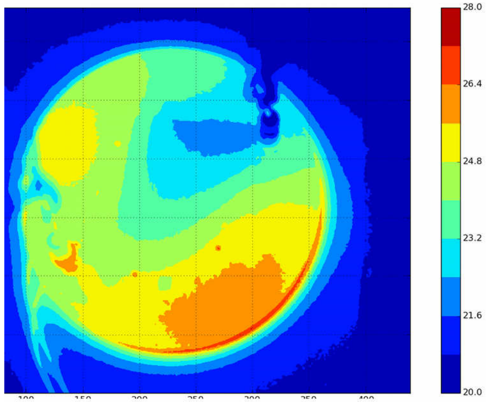
- Good agreement
- Fluctuations in the simulation grow towards higher flow rates

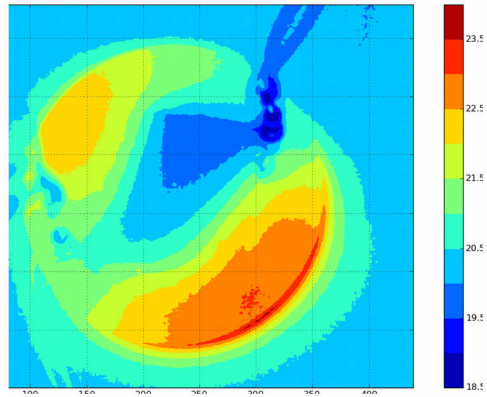
- Fluid is HFE at ~22 °C
- Error in simulation obtained through mesh refinement

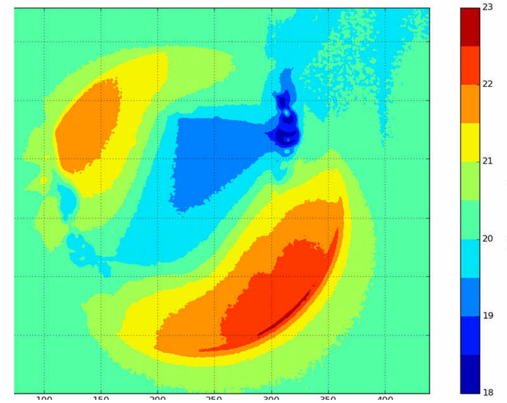
Temperature Distribution

Heater set to 2.5 W

Infrared camera (in air)







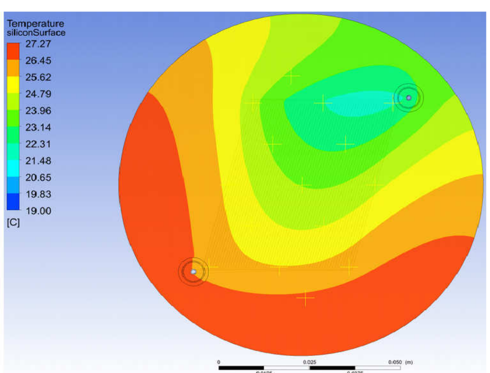
10 ml/min

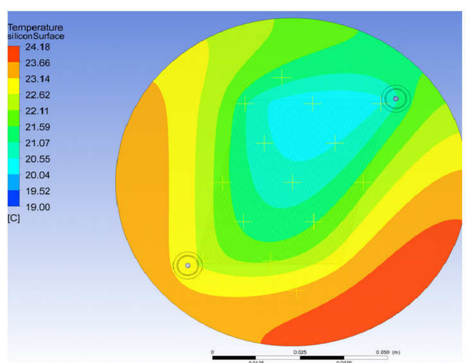
30 ml/min

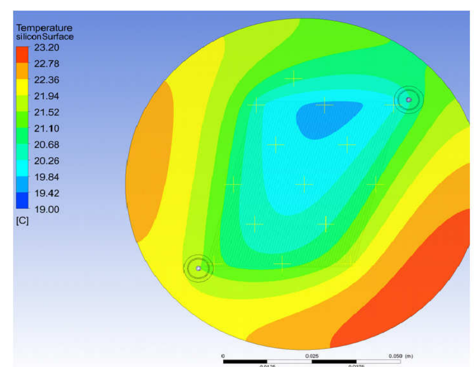
50 ml/min

Heater set to 2.5 W

Simulation (without convection)



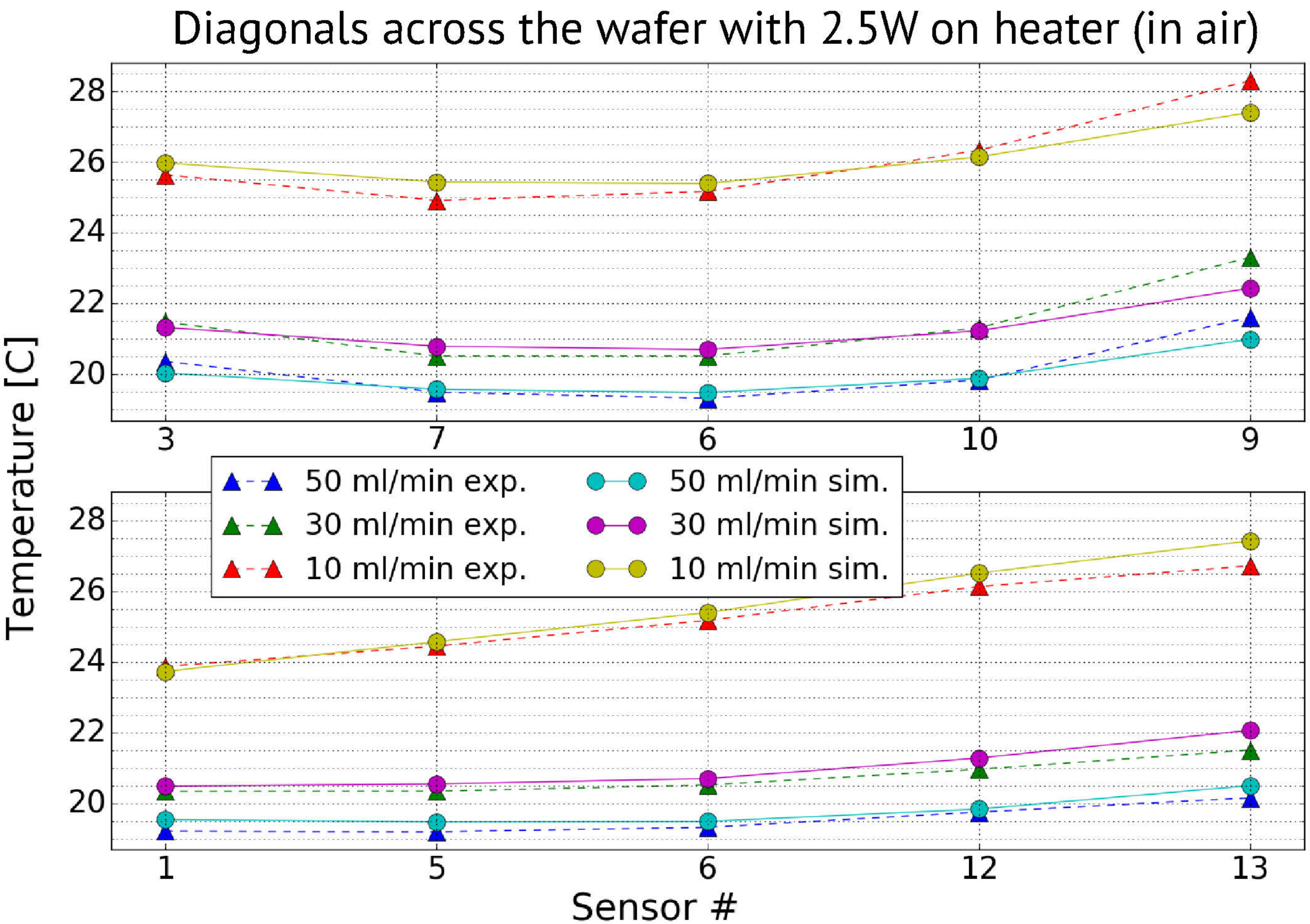


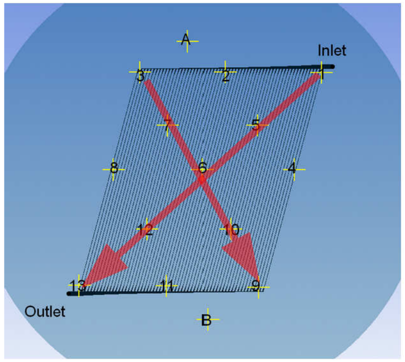


- Experiment and simulation in good agreement
- Actively cooled area has a gradient of below 4 °C

Fluid at ~19 °C

Temperature Along The Wafer Surface





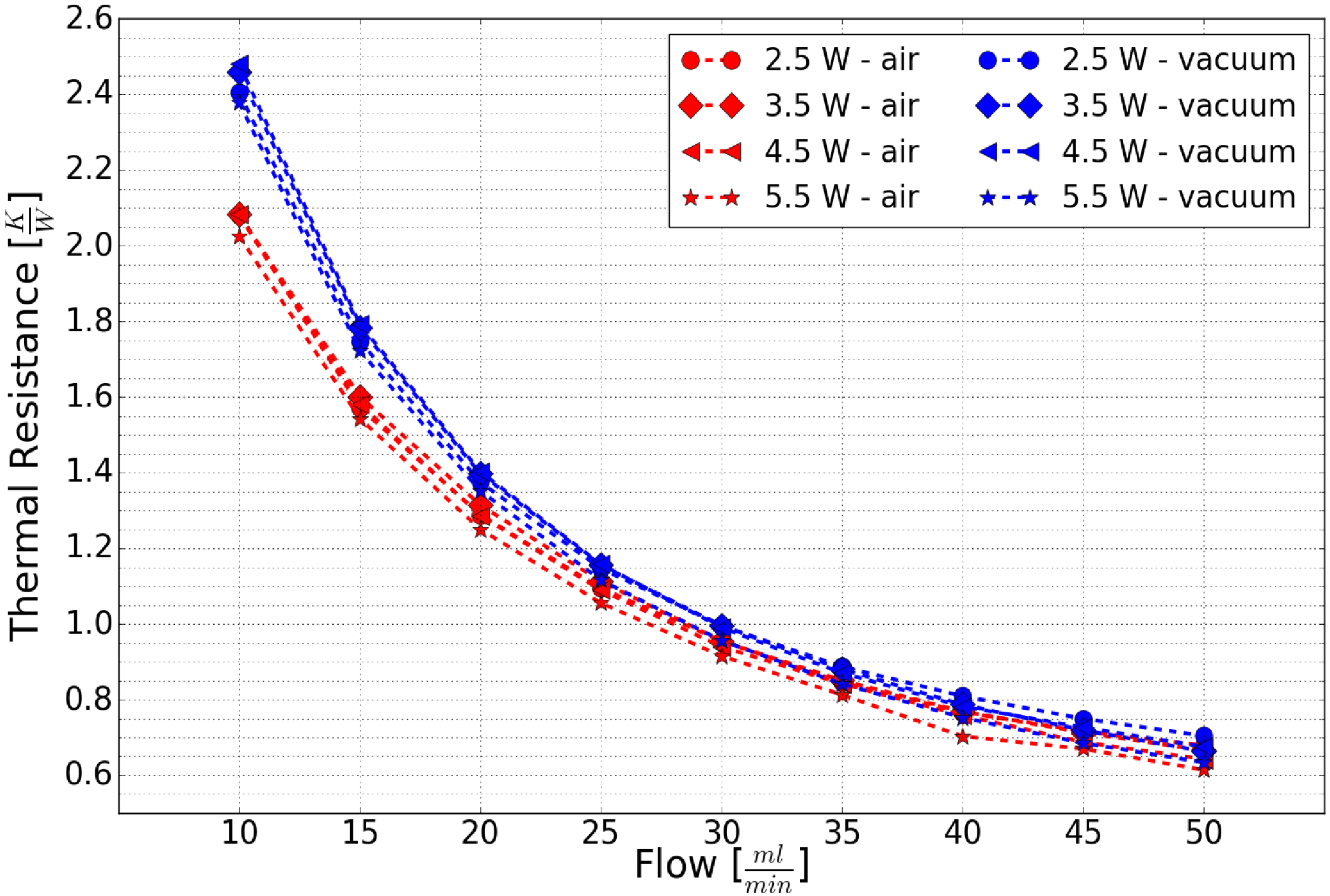
- Values corrected for varying inlet temperature in the experiment
- Temperature sensors are calibrated to one reference sensor

Fluid at ~19 °C

- No hot-spots!
- Simulation in a good agreement with the experiment

Maximum temperature difference below 4 °C between all sensors

Thermal Resistance



$$R = \frac{T_{outlet} - T_{inlet}}{P_{heater}}$$

- Grouped in vacuum and air measurements
- The effect of convection is visible

Summary & Future Steps

- A micro-channel structure and a test stand was designed and produced
- Flow and thermal tests show its general feasibility for large sensors
- Volumetric flows up to 50 ml/min were tested and found to be able to keep the maximum temperature difference over the micro-channel structure below 4 °C
- The simulation of the flow and the thermal properties is in a good agreement with the experiment

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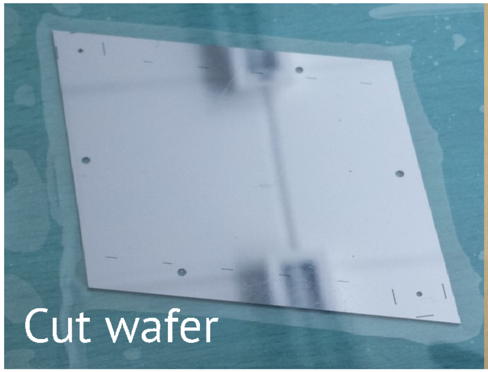
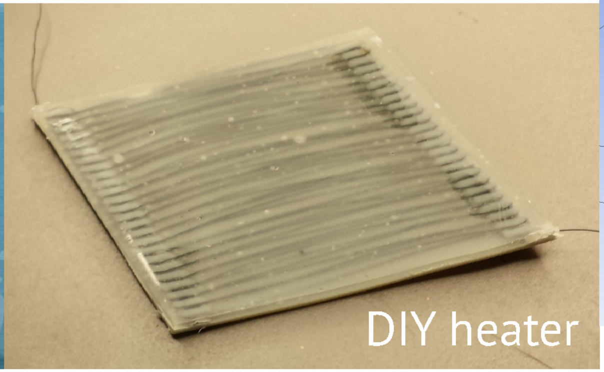
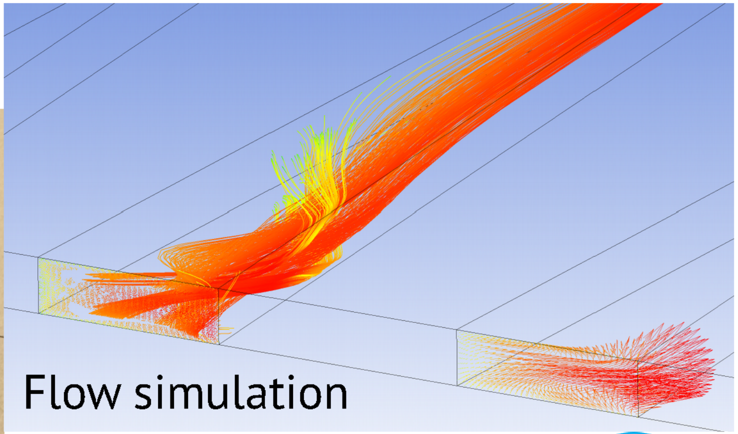
- Measurements with a wafer cut to the micro-channel structure dimensions
- Fluorescent spectroscopy flow measurements with fluorescent beads to compare with the simulation
- Paper under review!



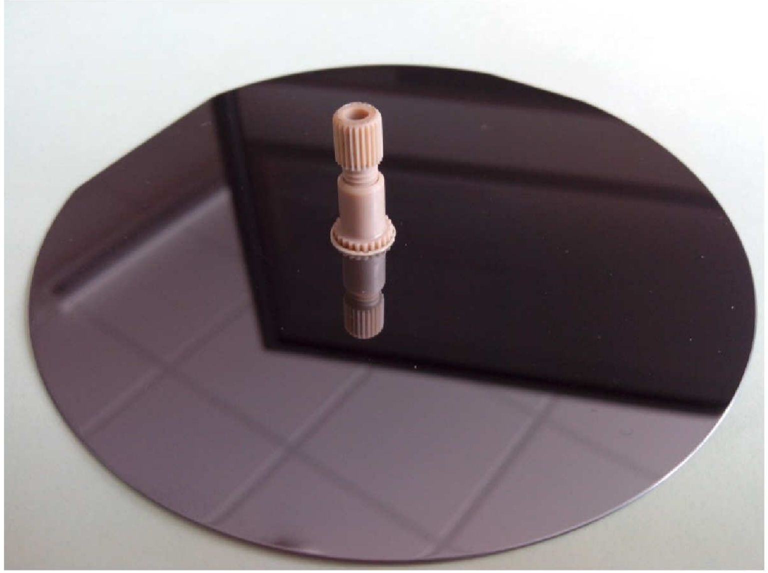


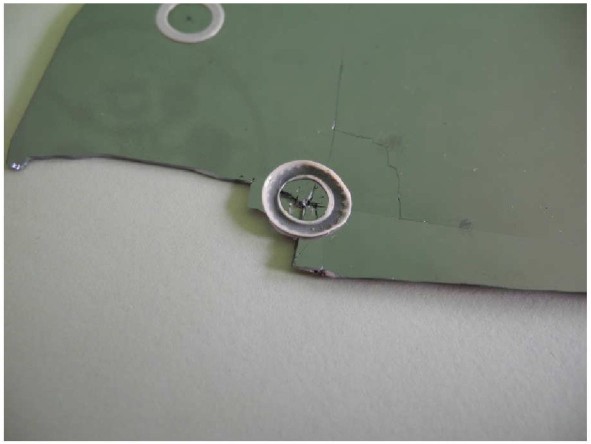


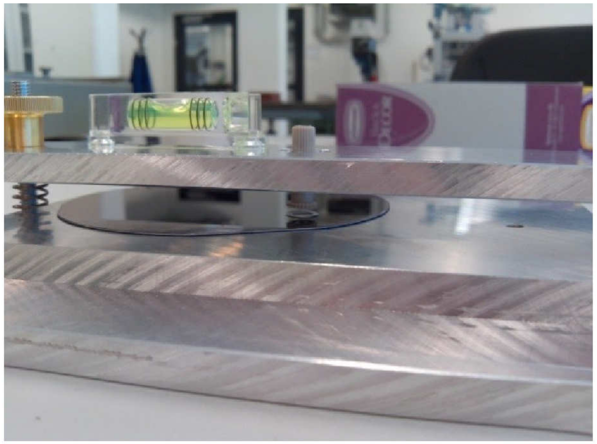
Thanks for your attention!

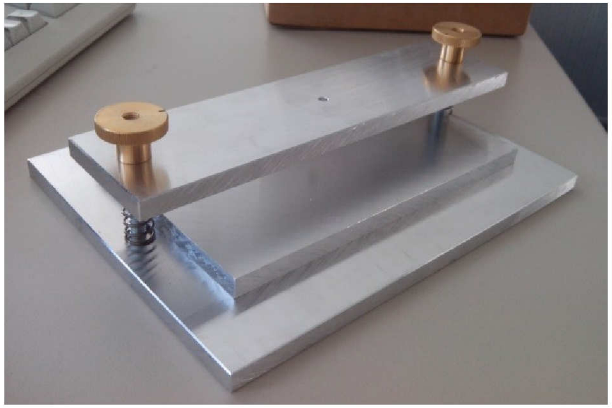
Putting The Sample Into The Setup

- NanoPorts are used to connect pipes to the micro-channels
- They are glued by heating up an adhesive ring between the NanoPorts and the silicon
- The NanoPorts are held in place by a self-made jig
- Pressure test showed that they can withstand pressures up to ~50 bar (tested on blank wafers)





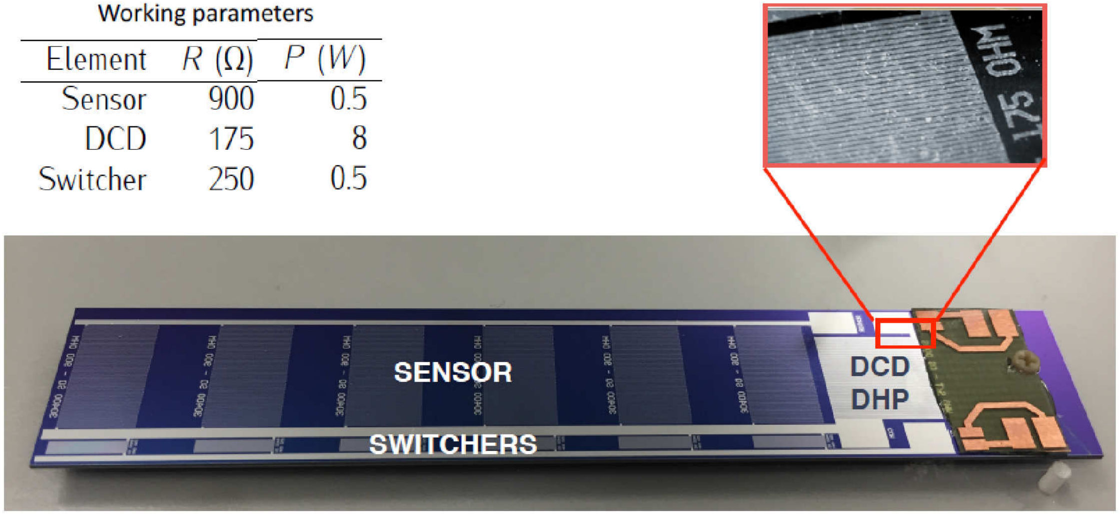




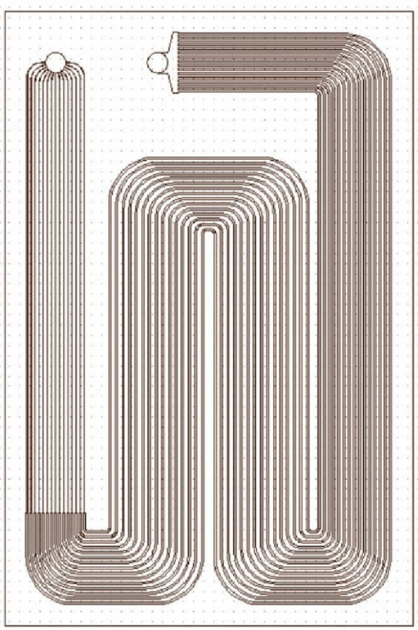
Other micro-channel projects

Working parameters

Element	R (Ω)	P (W)
Sensor	900	0.5
DCD	175	8
Switcher	250	0.5



- DEPFET ladder
  pixel detector for future colliders



- LHCb Velo

Laminar Or Turbulent

- Reynolds Number $$Re = \frac{\rho v d_H}{\mu}$$

  d_H :hydraulic diameter
  μ :kinematic viscosity
  ρ :density
  v :velocity

- Literature => Reynolds Number up to 1000 before transition
- Completely turbulent Re > 3000

Re	Flow [ml/min]
27	5
219	40
383	70
547	100

- With d_H = 100 µm
- With d_H set to maximal value Re(100 ml/min) = 995

Manifold Shape

- We want a homogeneous flow along all channels
- Same pressure at each channel coming off the manifolds

$$\Delta p_n = \Delta p_{n+1}$$

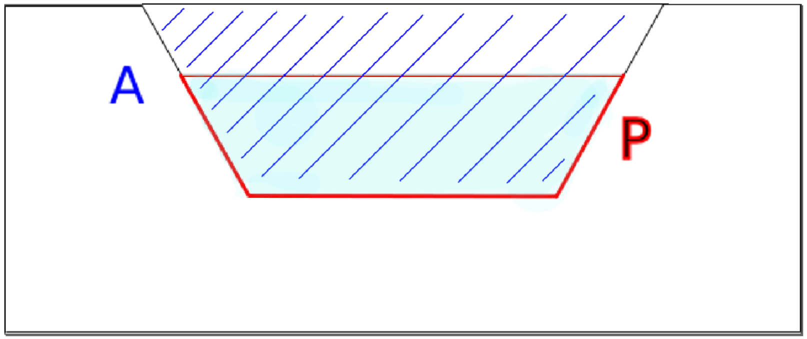
- Pressure and flow can be derived from the Navier-Stokes equation

$$Q = \frac{\pi a^4}{8\eta L}$$

Q : flow
a : characteristic length (hydraulic diameter)
L : channel length
η : viscosity

$$d_H = \frac{4A}{P}$$

A: Area of channel cross section
P: wetted perimeter (circumference)



Manifold Shape

- Which results in a manifold-width as a function of channel number *n*

$$w_m(n) = \frac{h(\frac{w^4 h^4 (N-n)}{(w+h)^4 * N})^{1/4}}{h - (\frac{w^4 * h^4 * (N-n)}{(w+h)^4 * N})^{1/4}}$$

h : channel height
w : channel width