The ultralight mechanics and cooling system of a DEPFET-based pixel detector for future colliders

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(On behalf of the DEPFET collaboration)

Outline

Micro Channel Cooling on all-silicon ladders

- Motivation: The DEPFET Ladder and cooling strategies
- MCC concept and prototypes

Experimental test

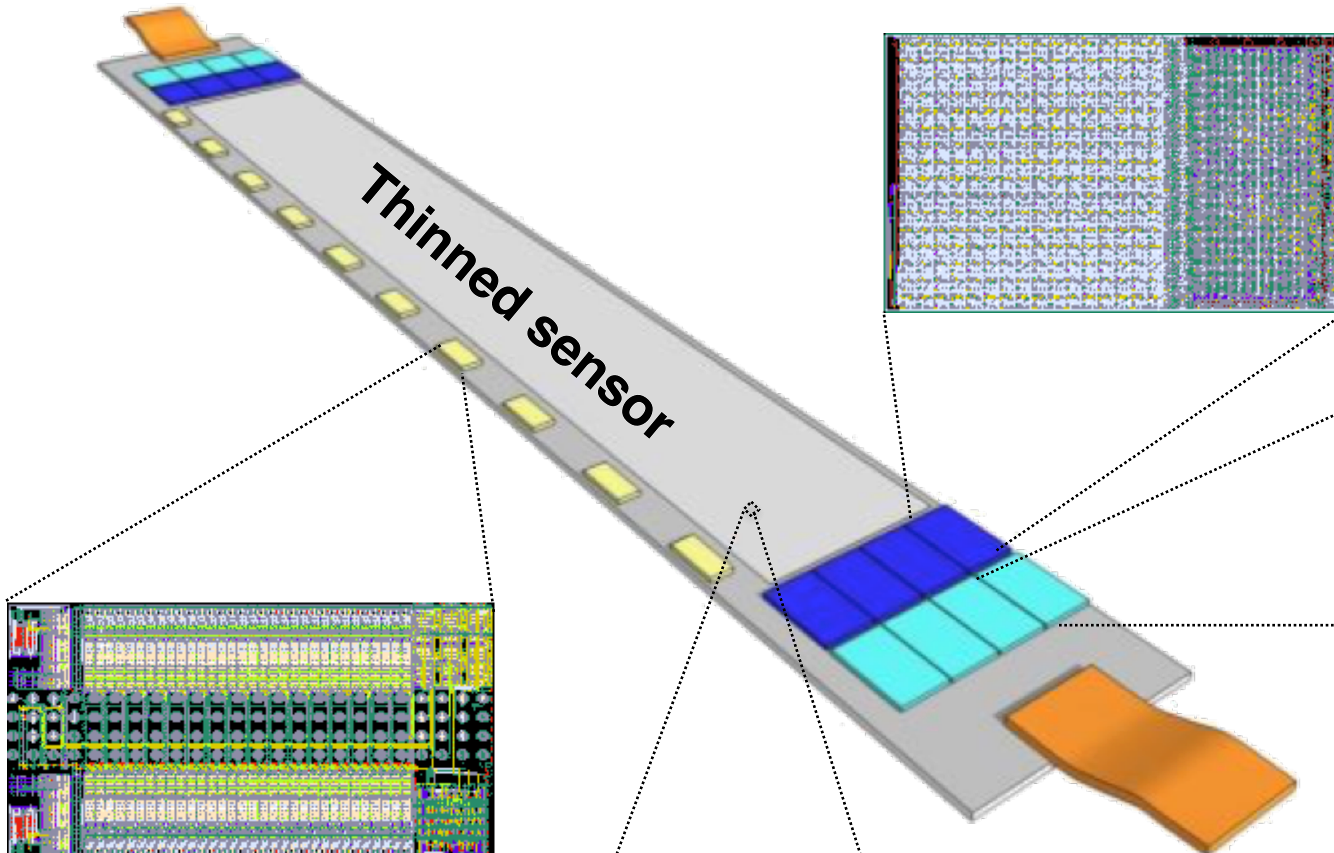
- Experimental setup
- 3D-printed inlet/outlet connector

Thermo-mechanical measurements and results

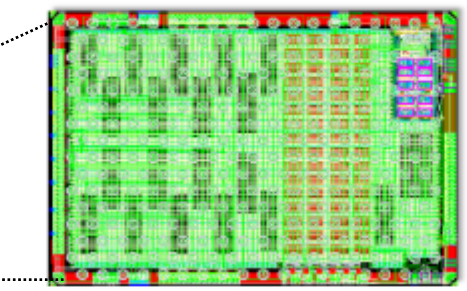
- MCC and MCC+air thermal measurements
- Vibrations and deformations

Next steps and conclusions

The DEPFET Ladder

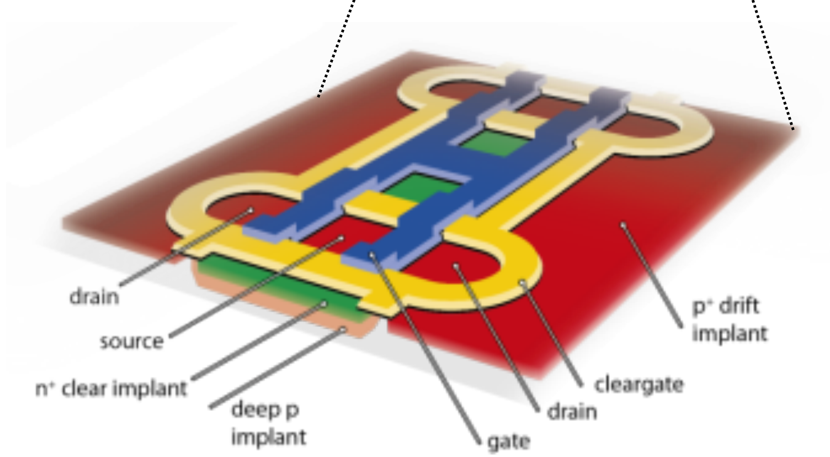


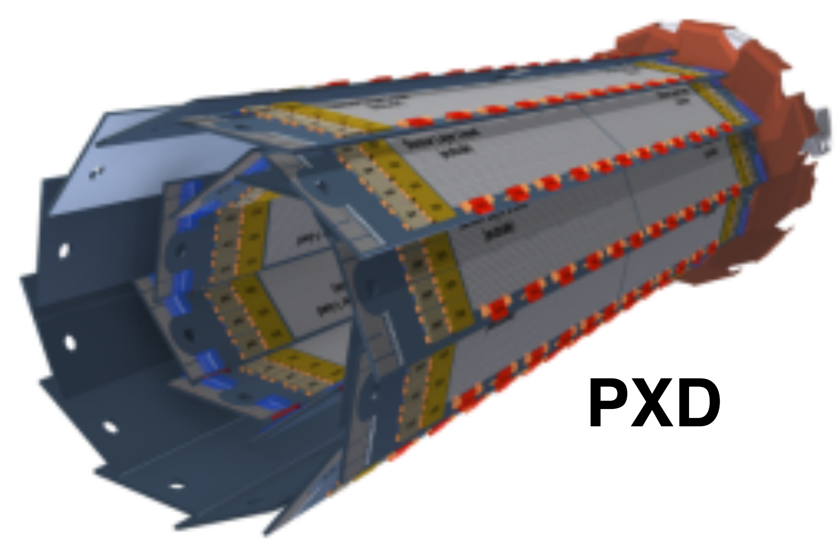
DCD (Drain Current Digitizer)
Analog frontend



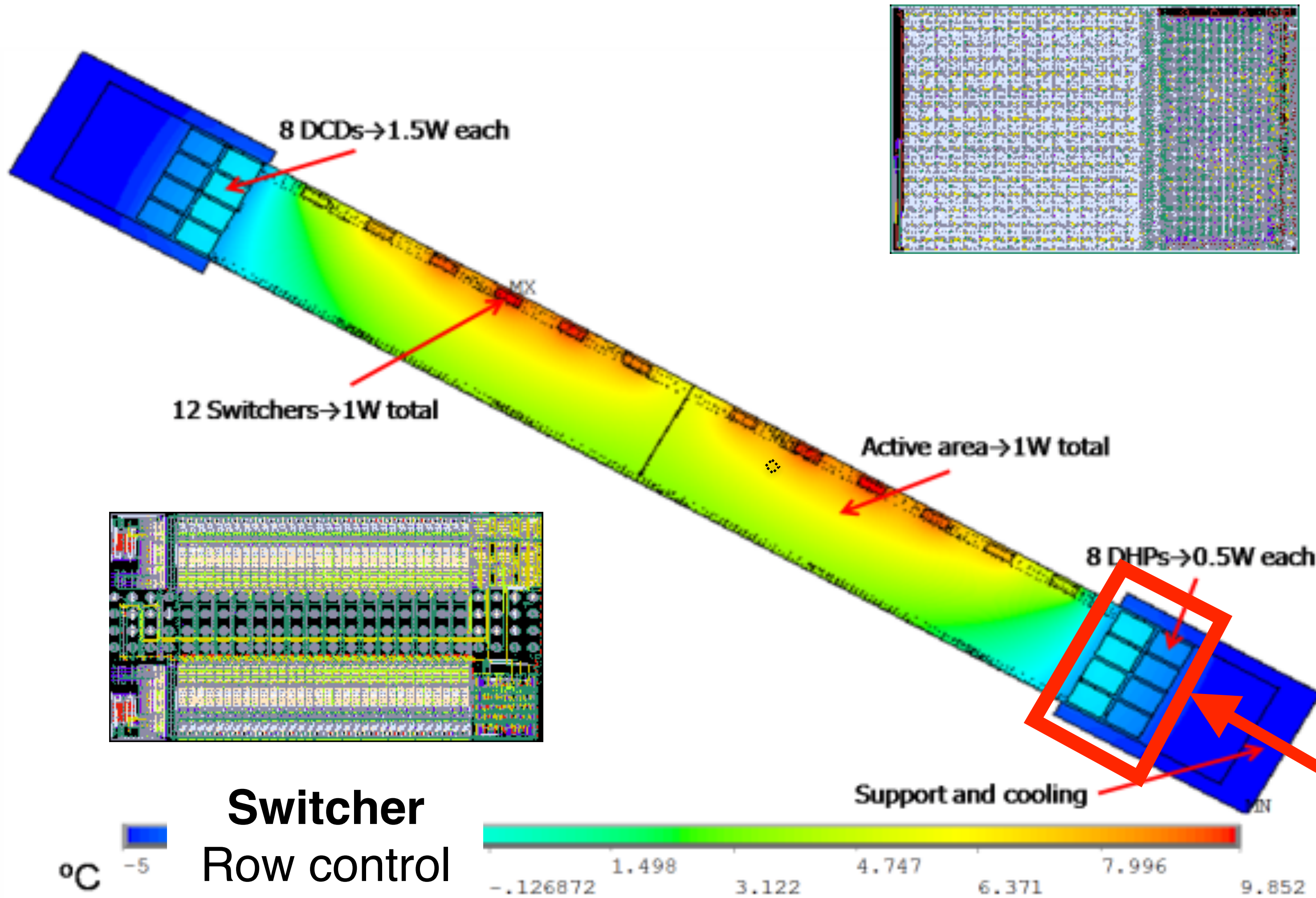
DHP (Data Handling Processor)

Switcher
Row control





The DEPFET Ladder



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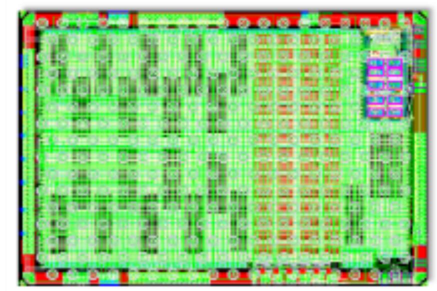

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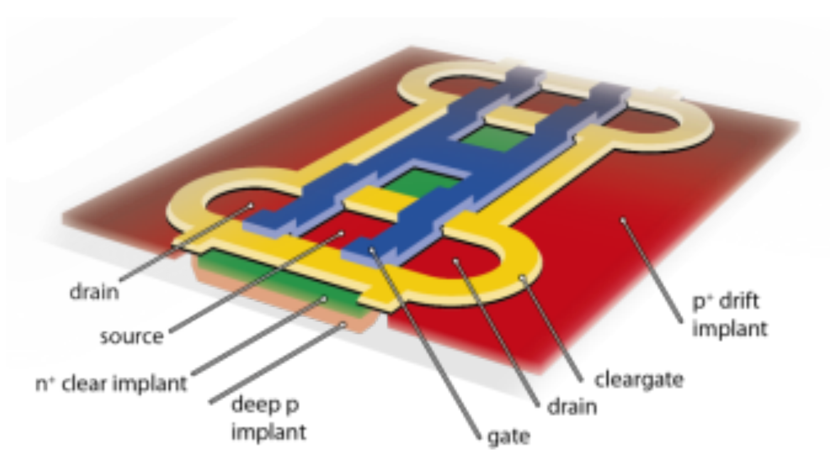
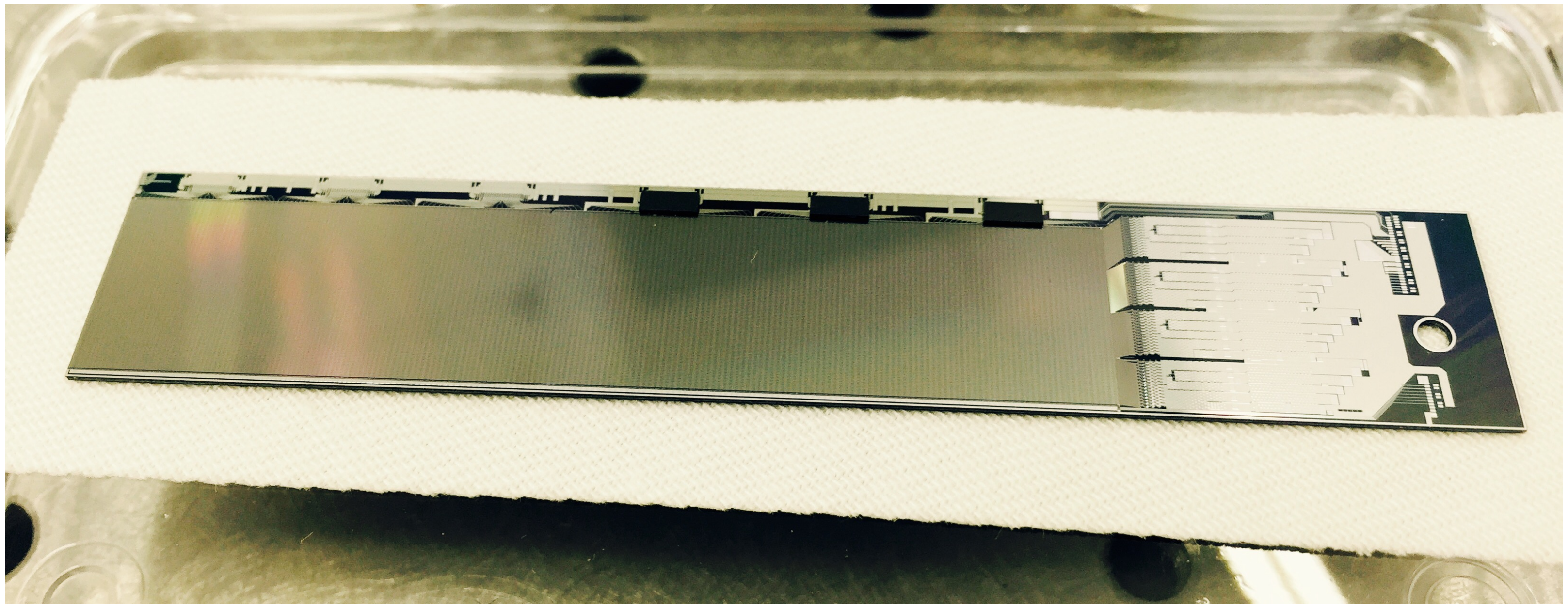


The end of the module is where most part of the heat is generated (front end electronics)

The DEPFET Ladder: applications

New tracker detectors require **ultra-thin** sensors to reduce multiple scattering:

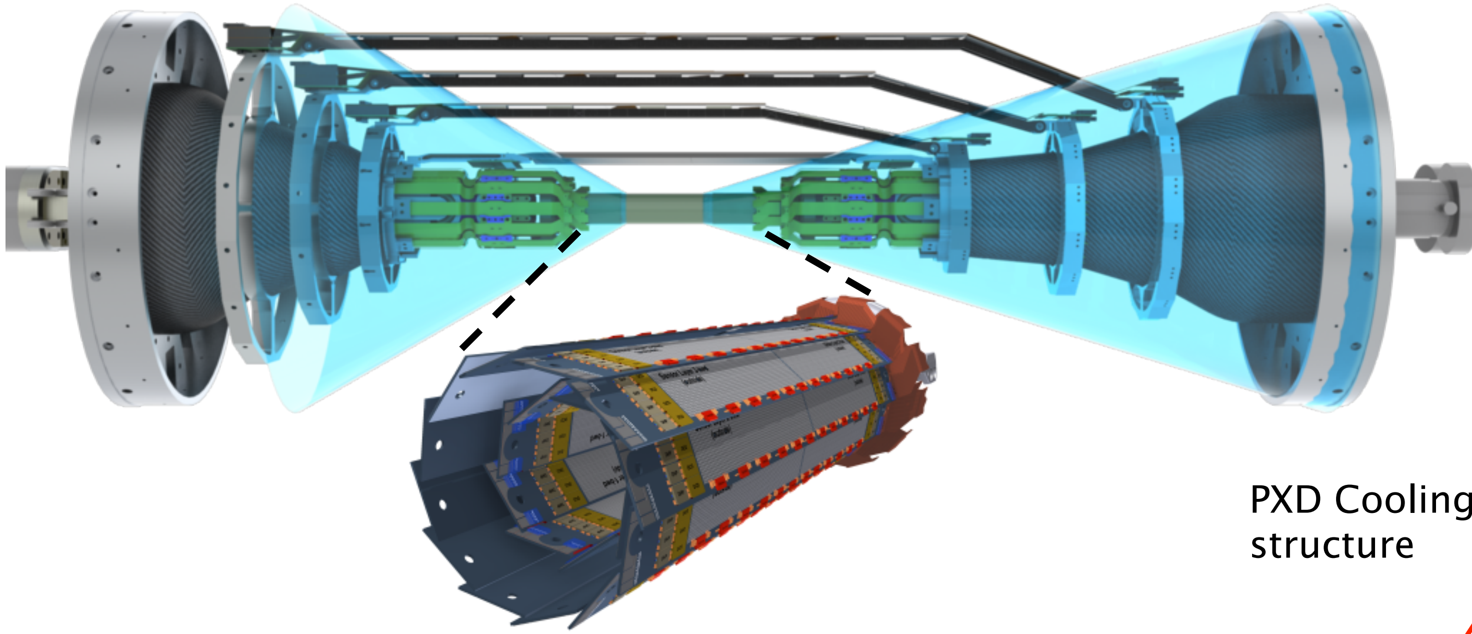
- e.g. DEpleted P-channel Field Effect Transistor (**DEPFET**)
- **Chosen technology for Belle II PXD**
- **Candidate for ILC**
- The thinning technique is not bound to any particular sensor technology



Layout designed with the highest power dissipating elements in the end flanges

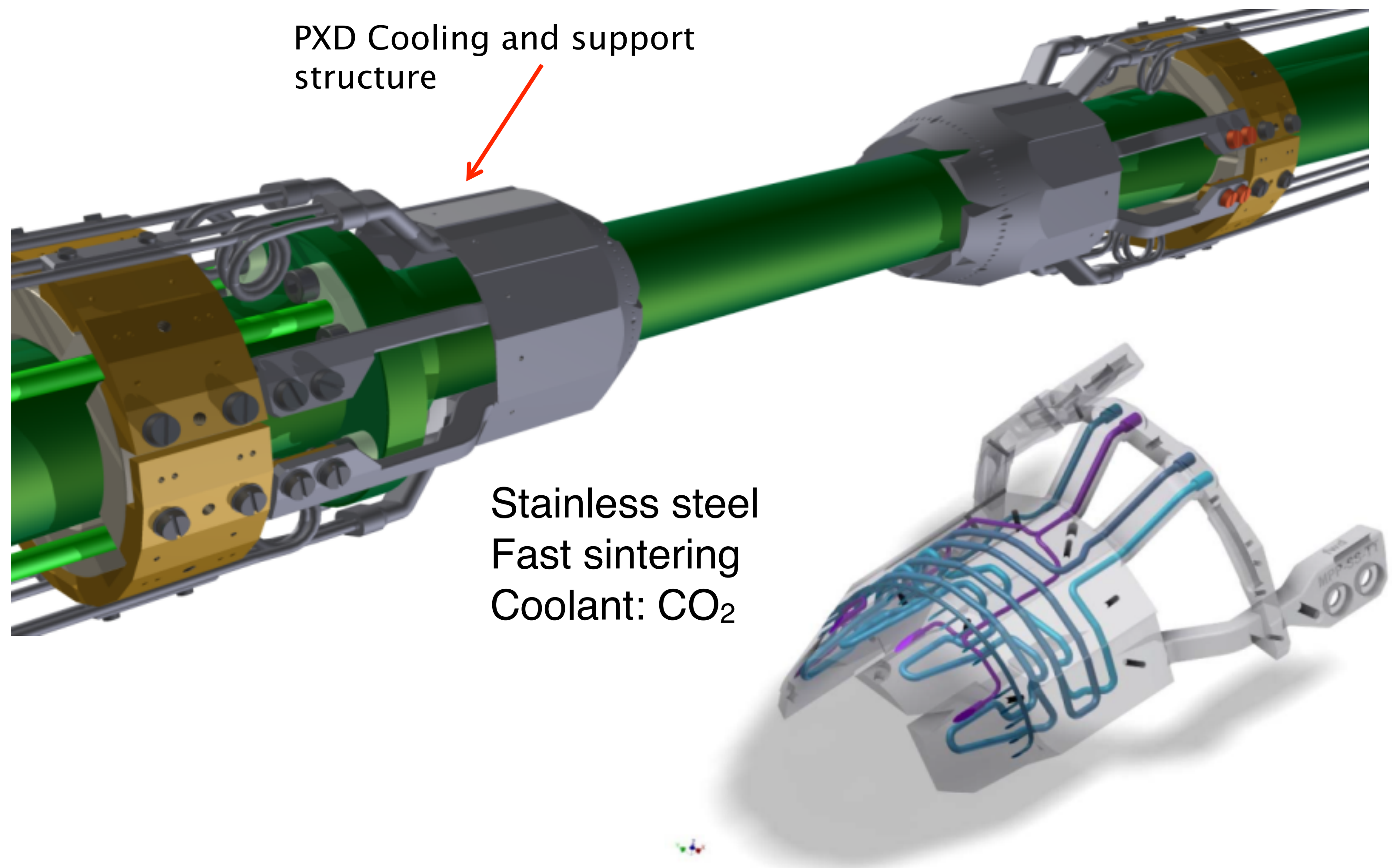
All-silicon modules allow for sensors integrated on a **self supporting** silicon **structure**

Cooling strategies



Belle II

PXD Cooling and support structure

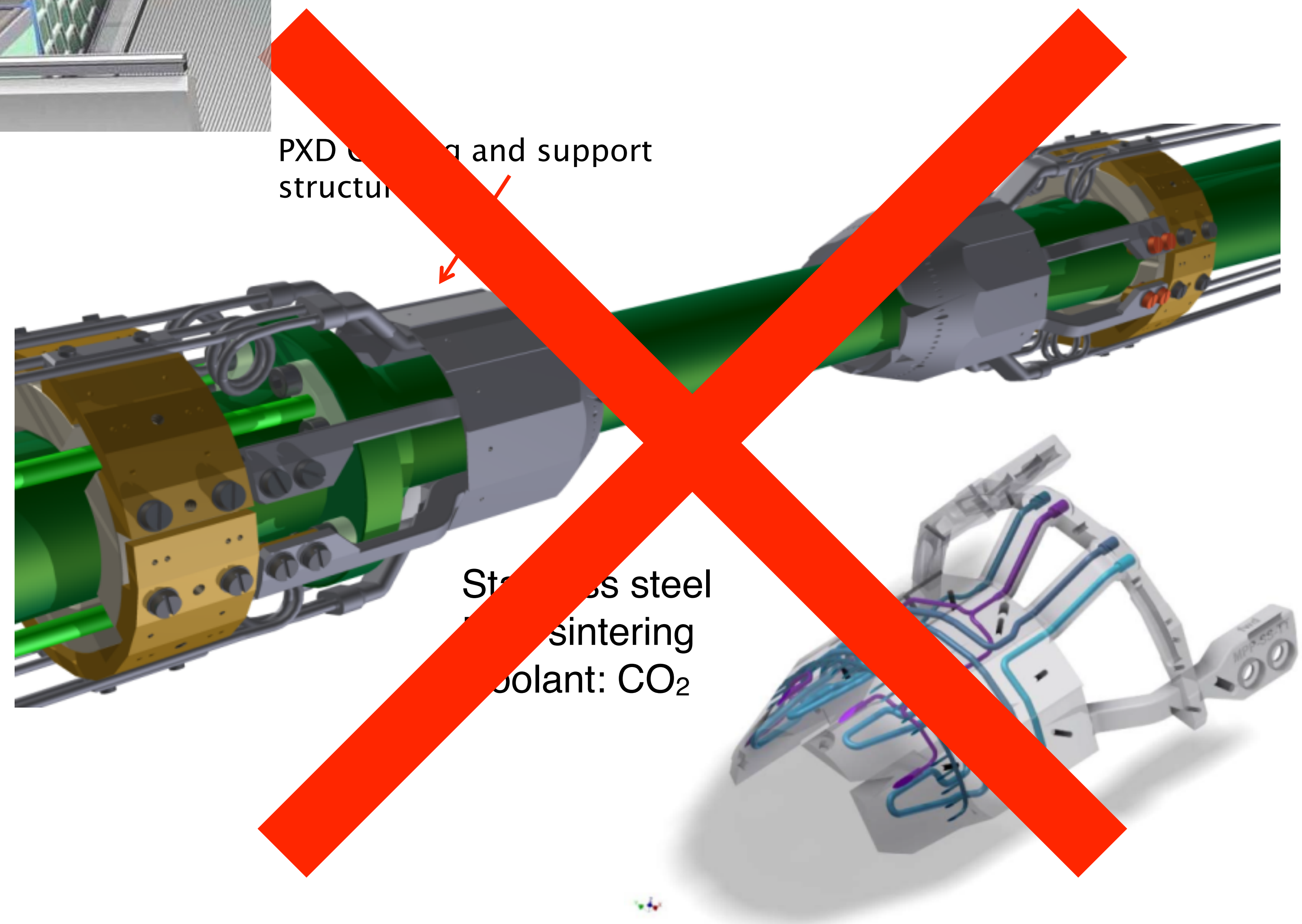


Stainless steel
Fast sintering
Coolant: CO_2

Massive structures outside the acceptance to cool down the readout chips

Cooling strategies

ILC



This amount of material is not permitted for the ILC detector

↓

Natural solution: integrated micro-channels instead of massive cooling blocks

Micro channels on all-Silicon dummies

Start with oxidized handle wafer

Micro channels on all-Silicon dummies

Start with oxidized handle wafer

Define lithographically μ-channels, etch oxide

Micro channels on all-Silicon dummies

Start with oxidized handle wafer

Define lithographically μ-channels, etch oxide

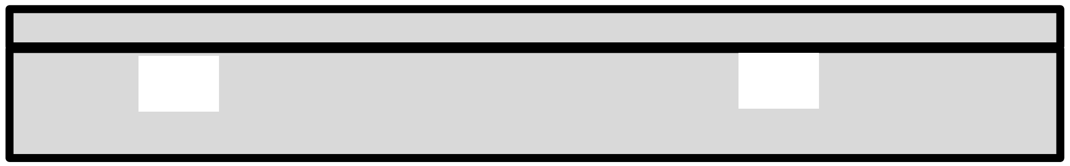
Etch micro-channels

Micro channels on all-Silicon dummies

Start with oxidized handle wafer

Define lithographically μ-channels, etch oxide

Etch micro-channels



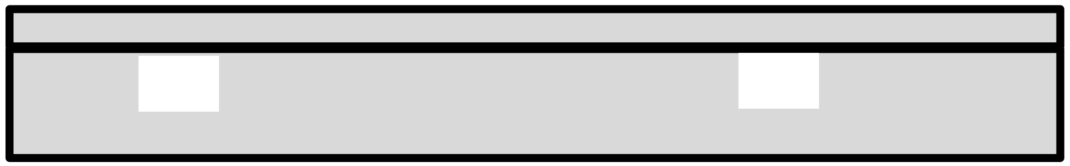
Bond prepared top wafer
Finish SOI wafer ("Cavity SOI")
top wafer for DEPFETs
Handle wafer with μ-channels under ASICs

Micro channels on all-Silicon dummies

Start with oxidized handle wafer

Define lithographically µ-channels, etch oxide

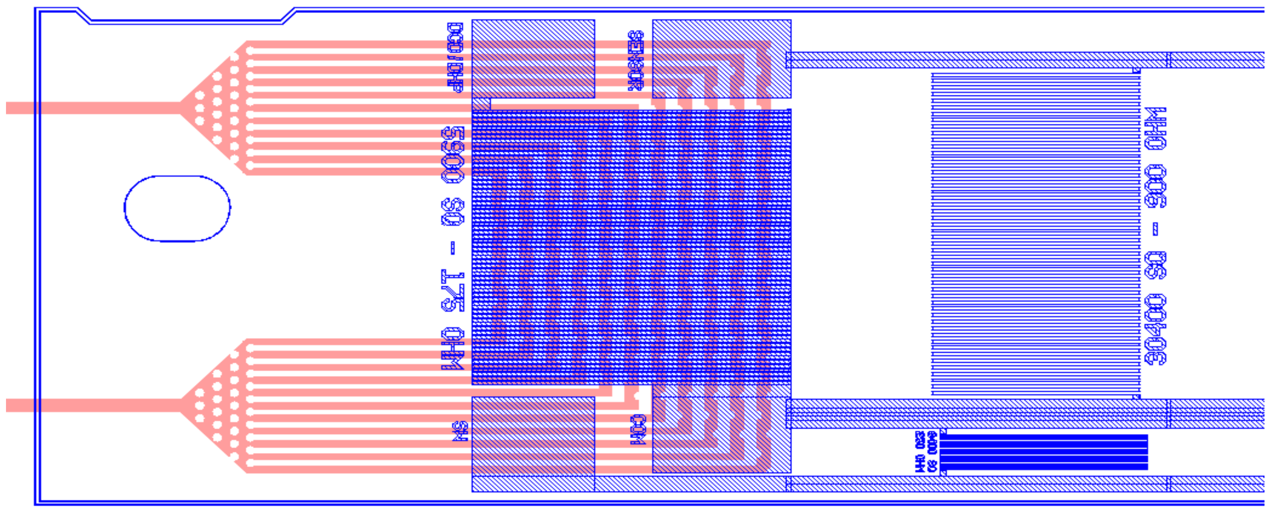
Etch micro-channels

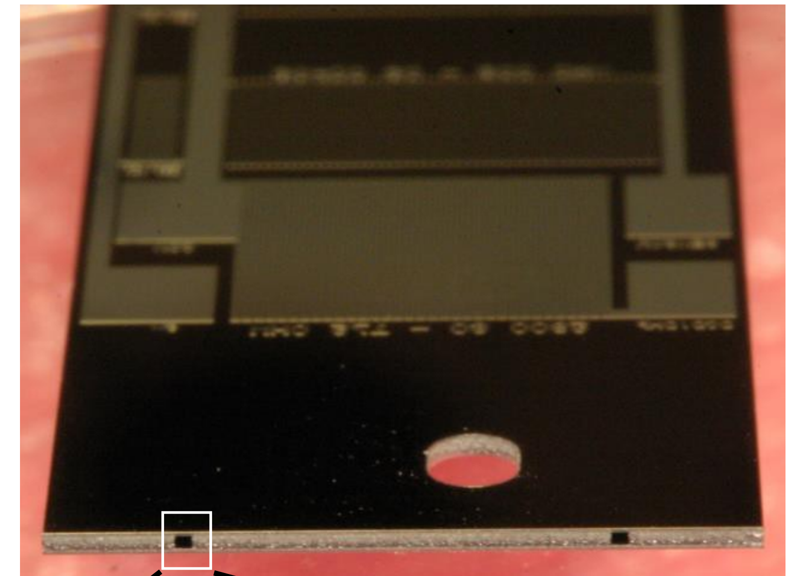


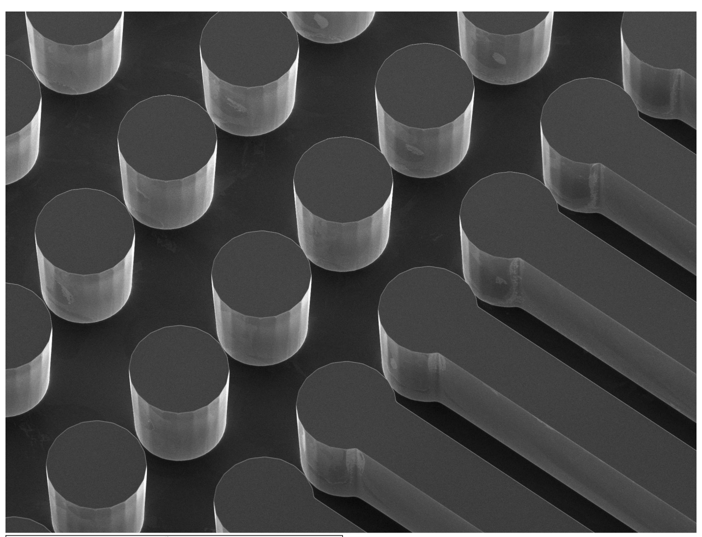
Bond prepared top wafer
Finish SOI wafer ("Cavity SOI")
top wafer for DEPFETs
Handle wafer with µ-channels under ASICs

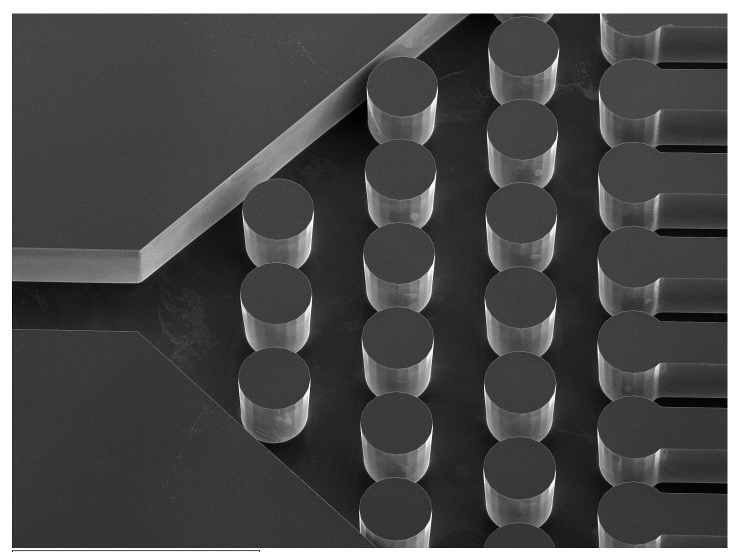
Handle removed in sensitive area
Channels exposed after cutting

MCC prototype

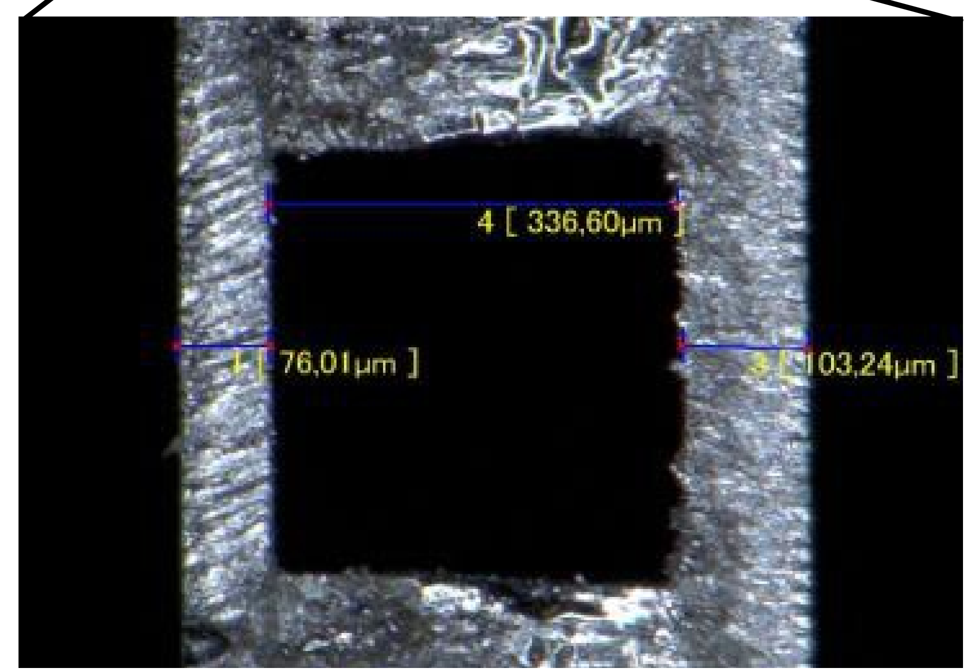








Micro-channel pattern in handle wafer



Inlet and outlet: ~350 x 350 μm

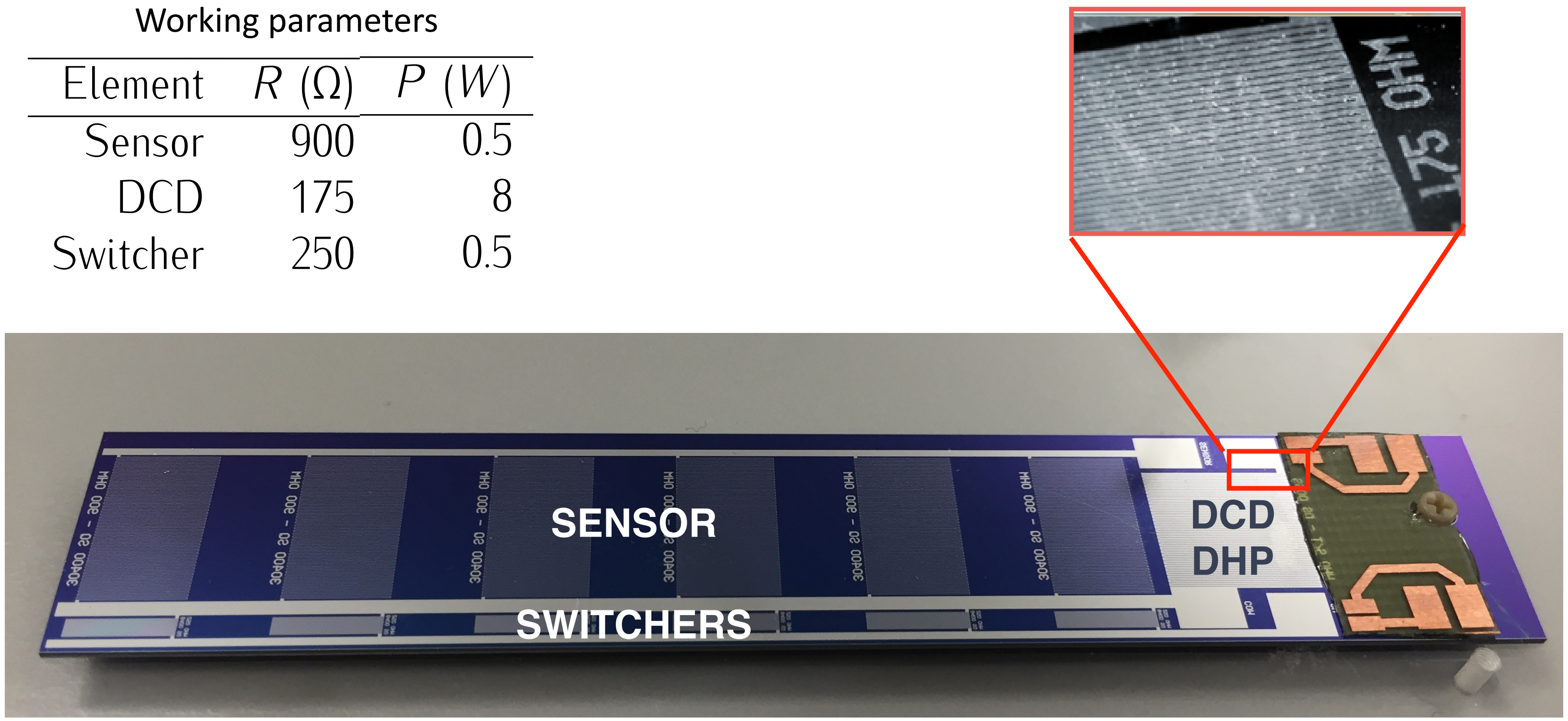
Ultra-thin self-supporting Silicon dummies: concept

The resistive dummies with integrated micro-channels

- Si modules with the designed dimensions of the detectors
- Homogeneous thickness (thinned sensor area not needed)
- Modules do **not include** the **real electronics**
- Aluminum layer with resistor meanders on thin top wafer -> **simulate the power distribution**

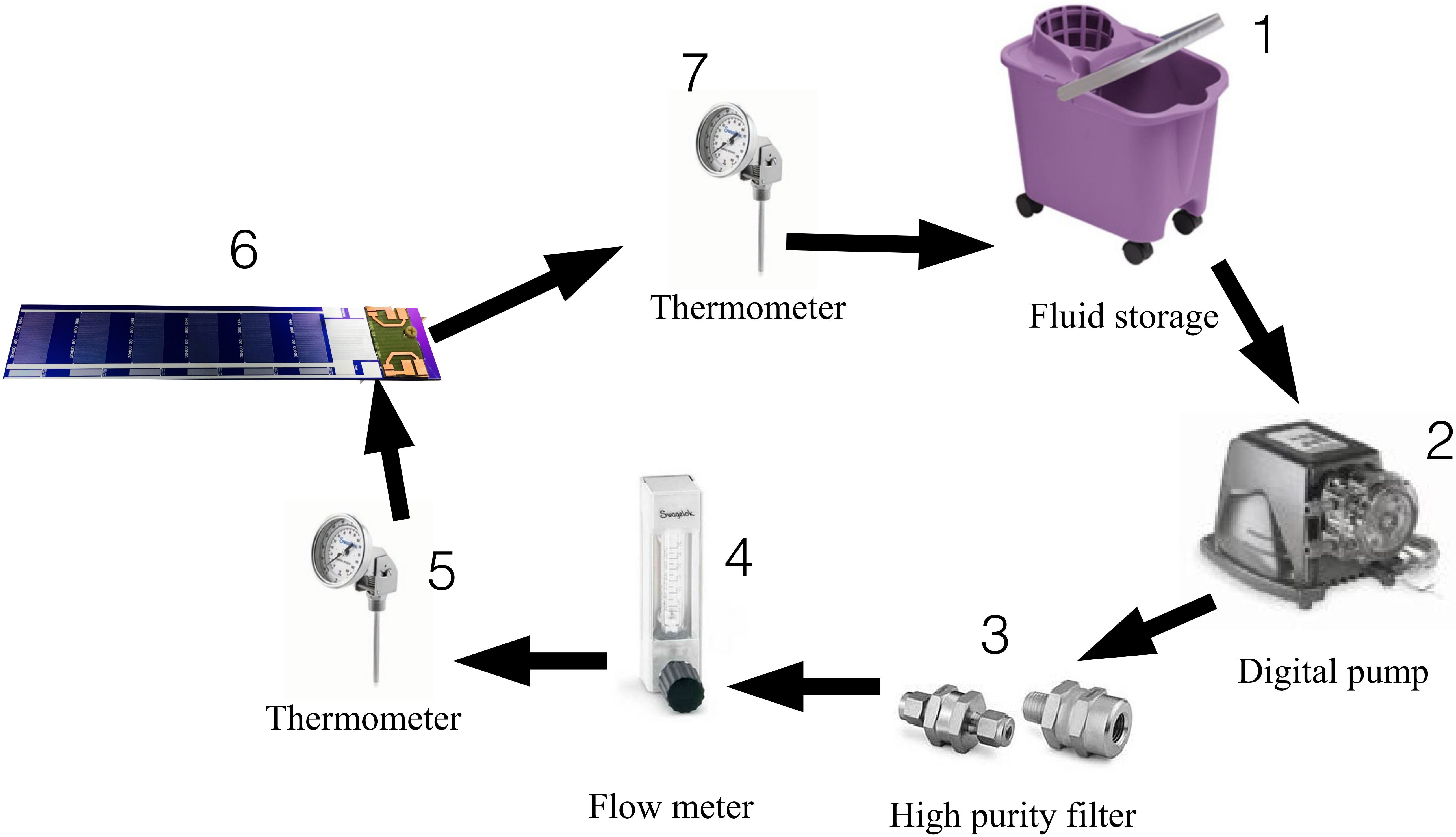
Working parameters

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

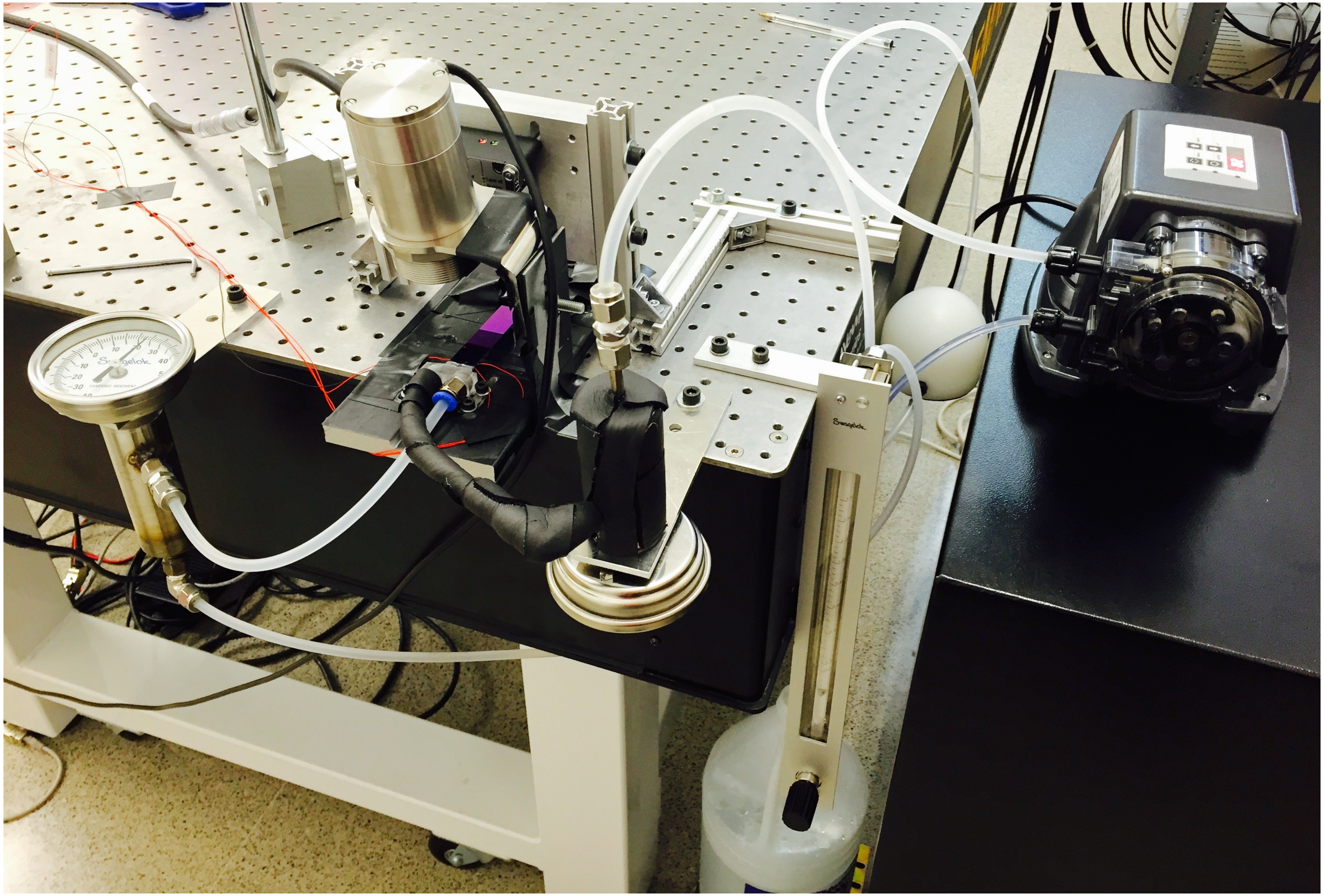


Half-Ladder for the inner vertex detector

Experimental setup



Experimental setup



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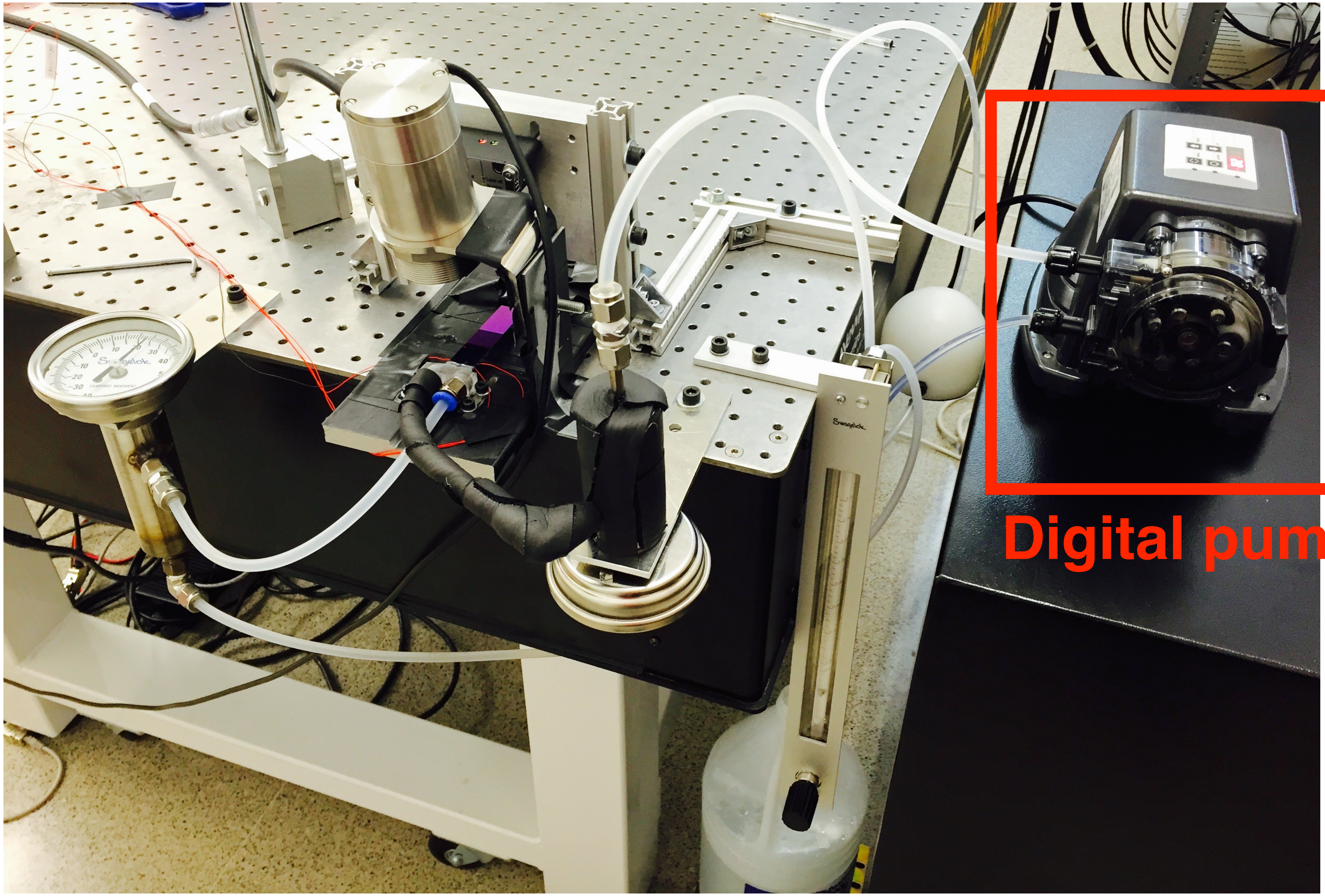
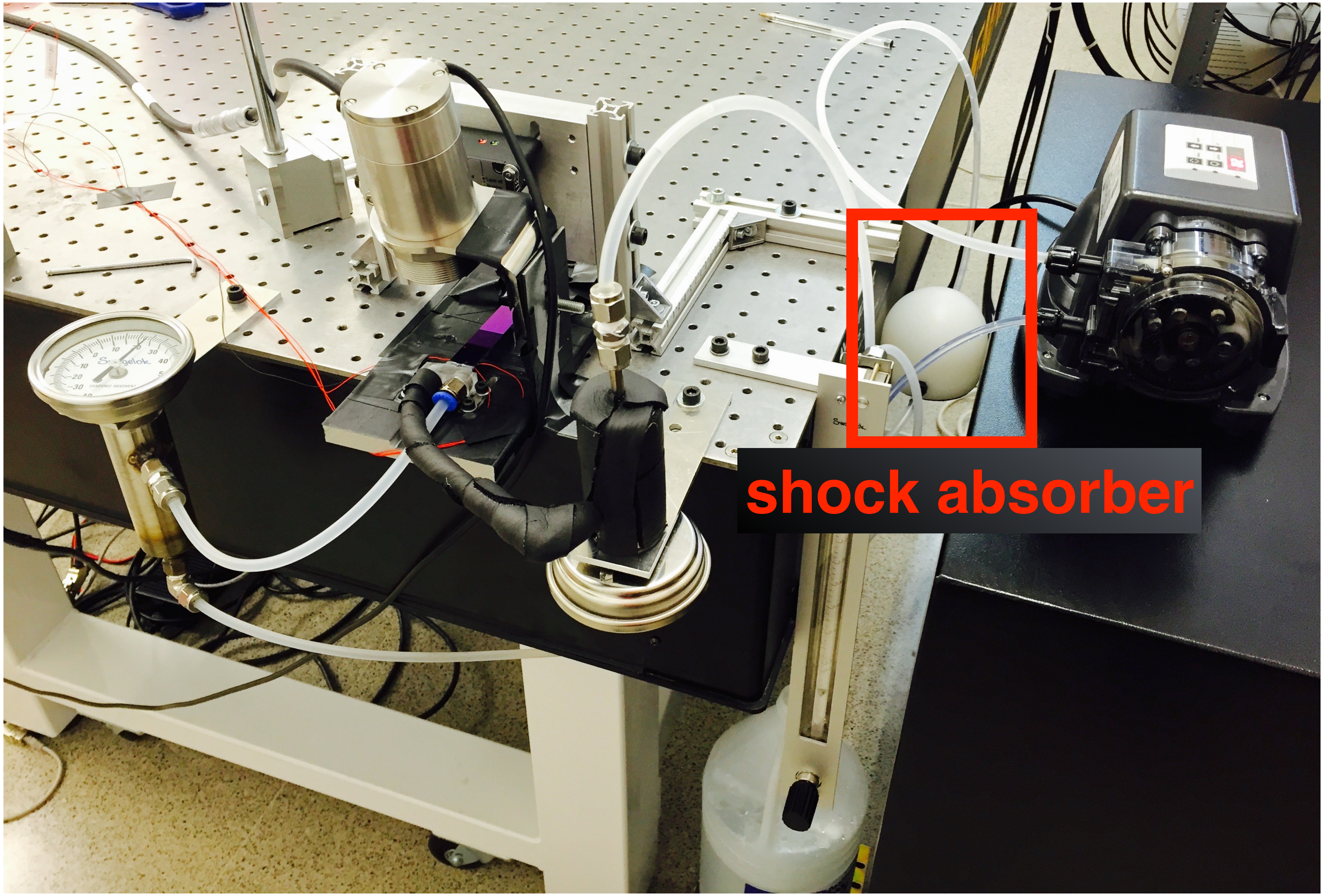
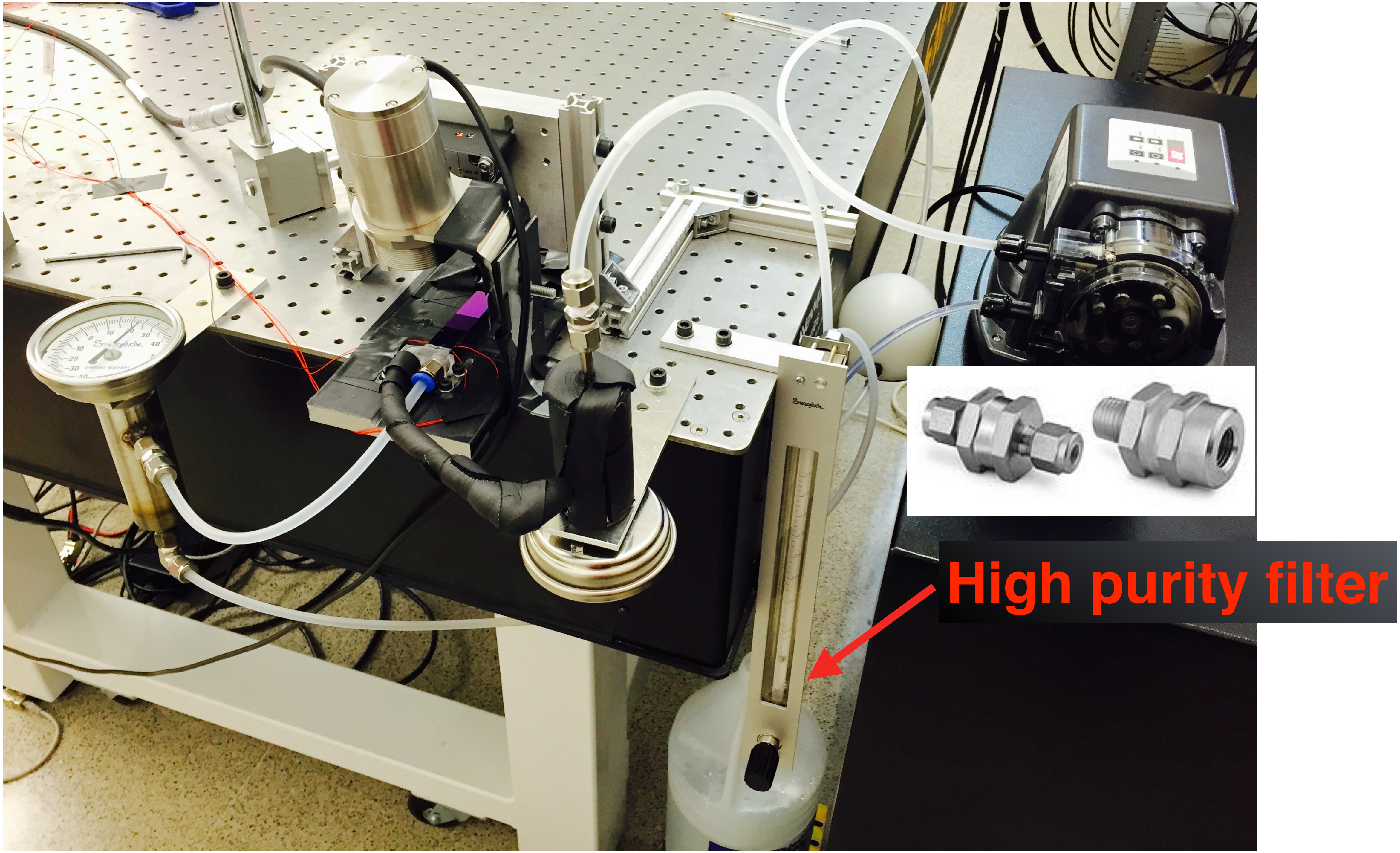


Digital pump

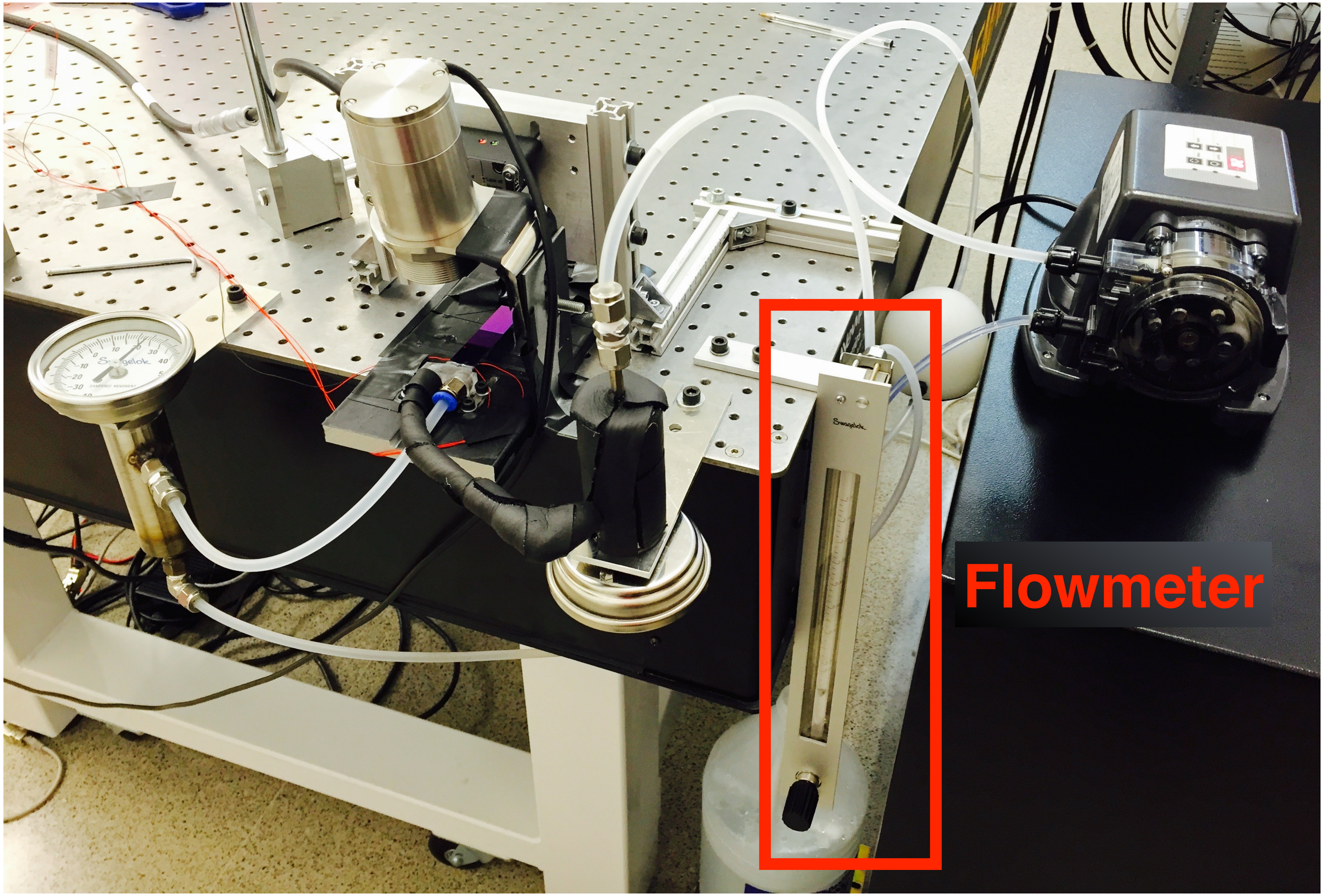
Experimental setup



Experimental setup



Experimental setup



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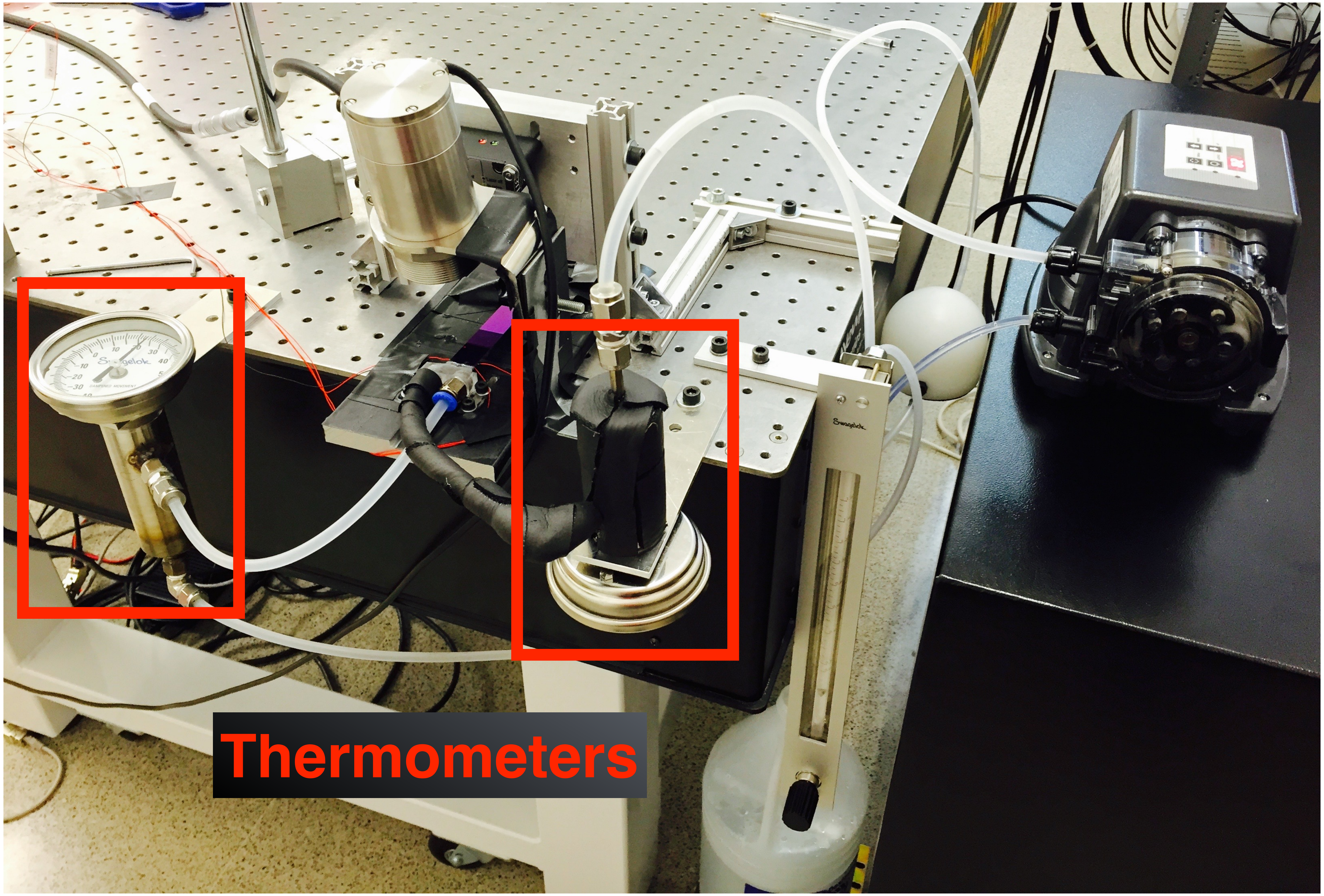

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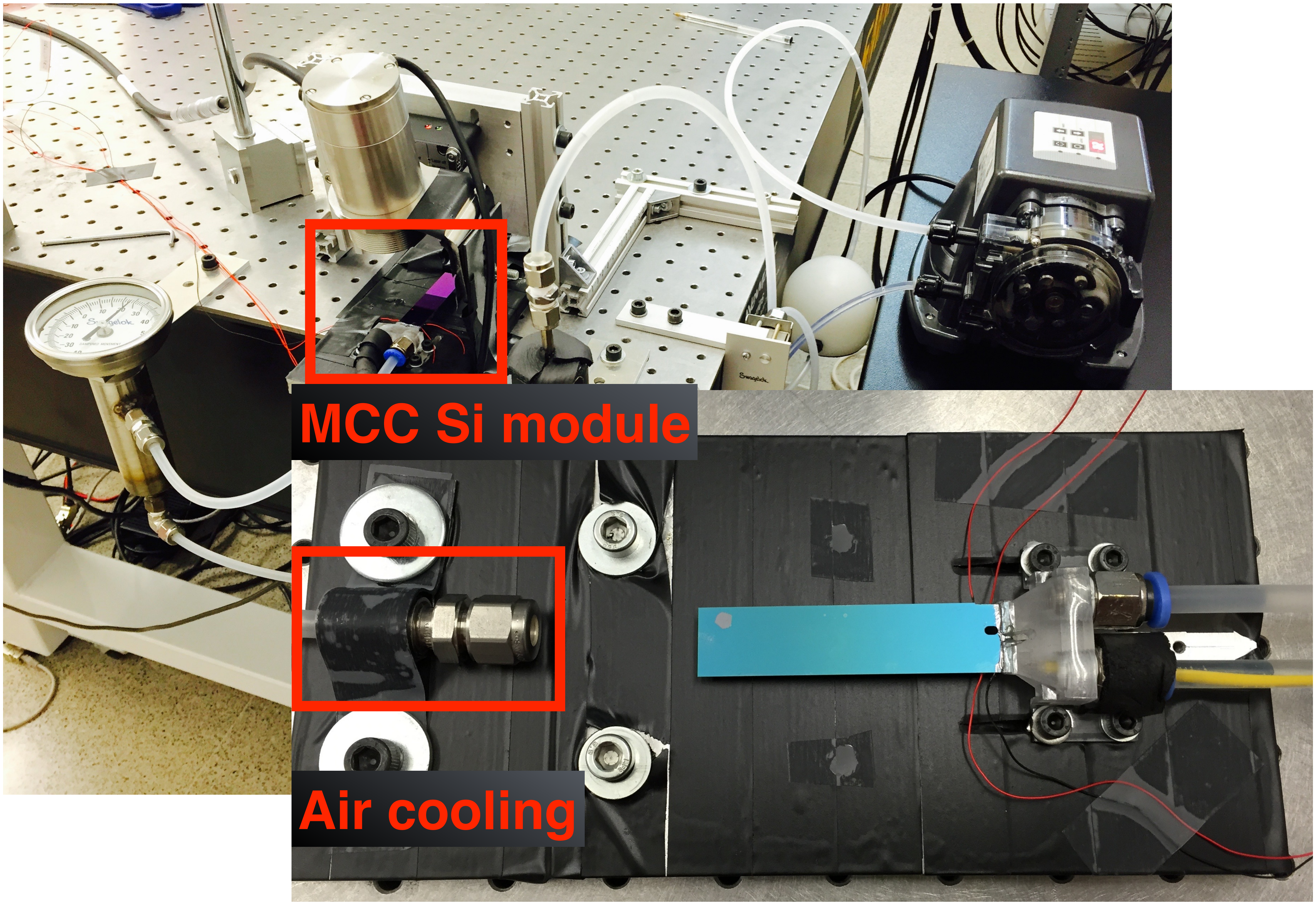

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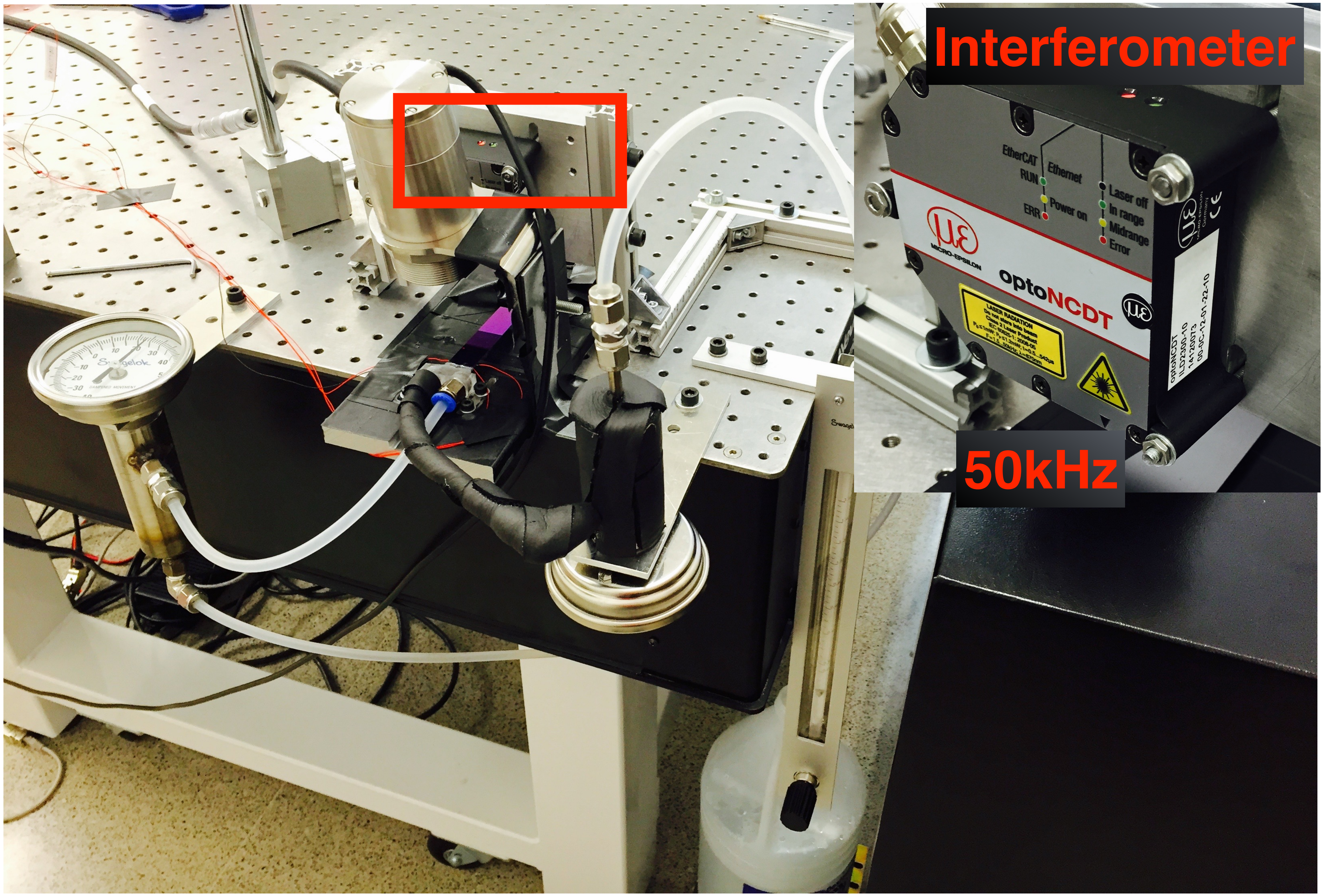
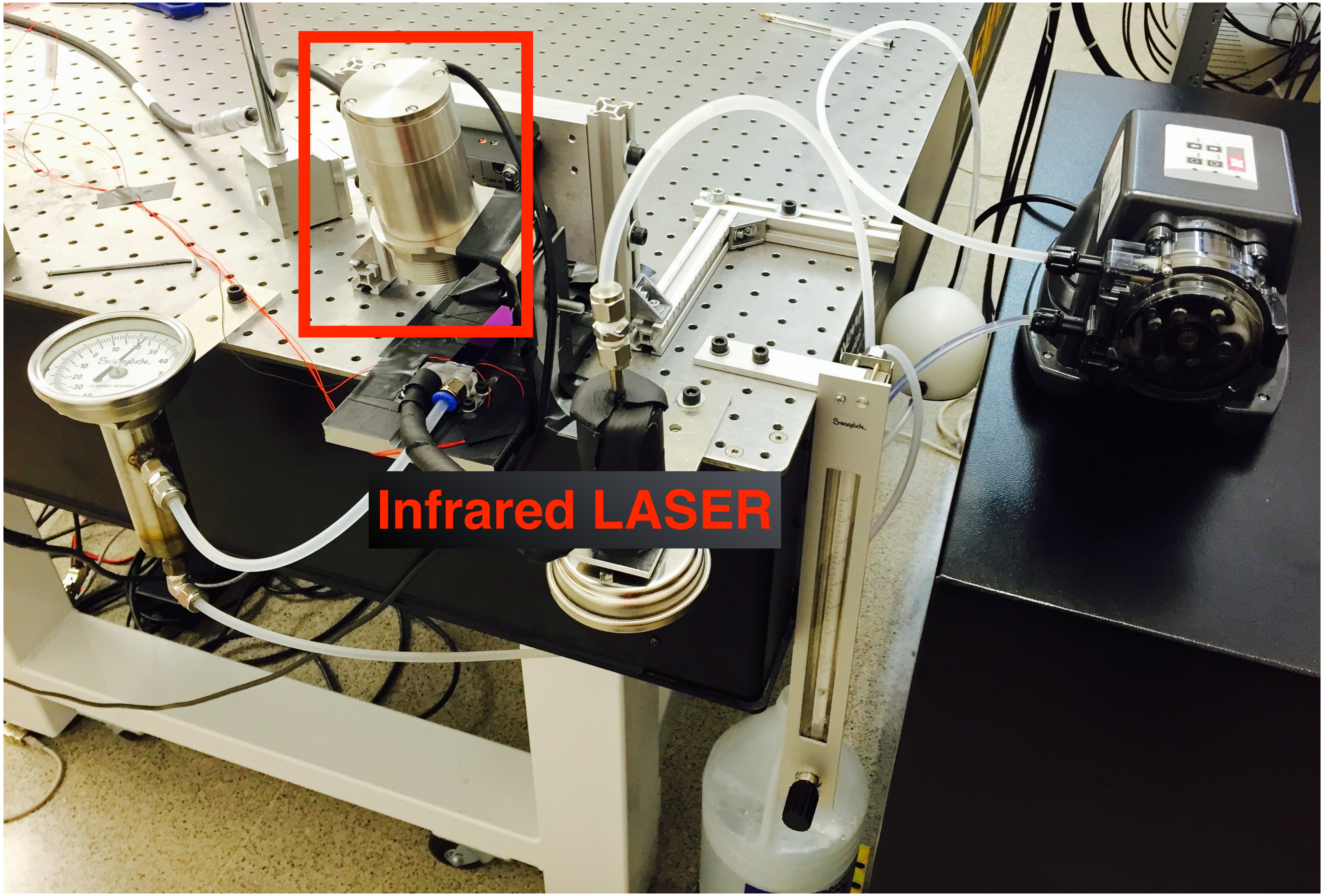
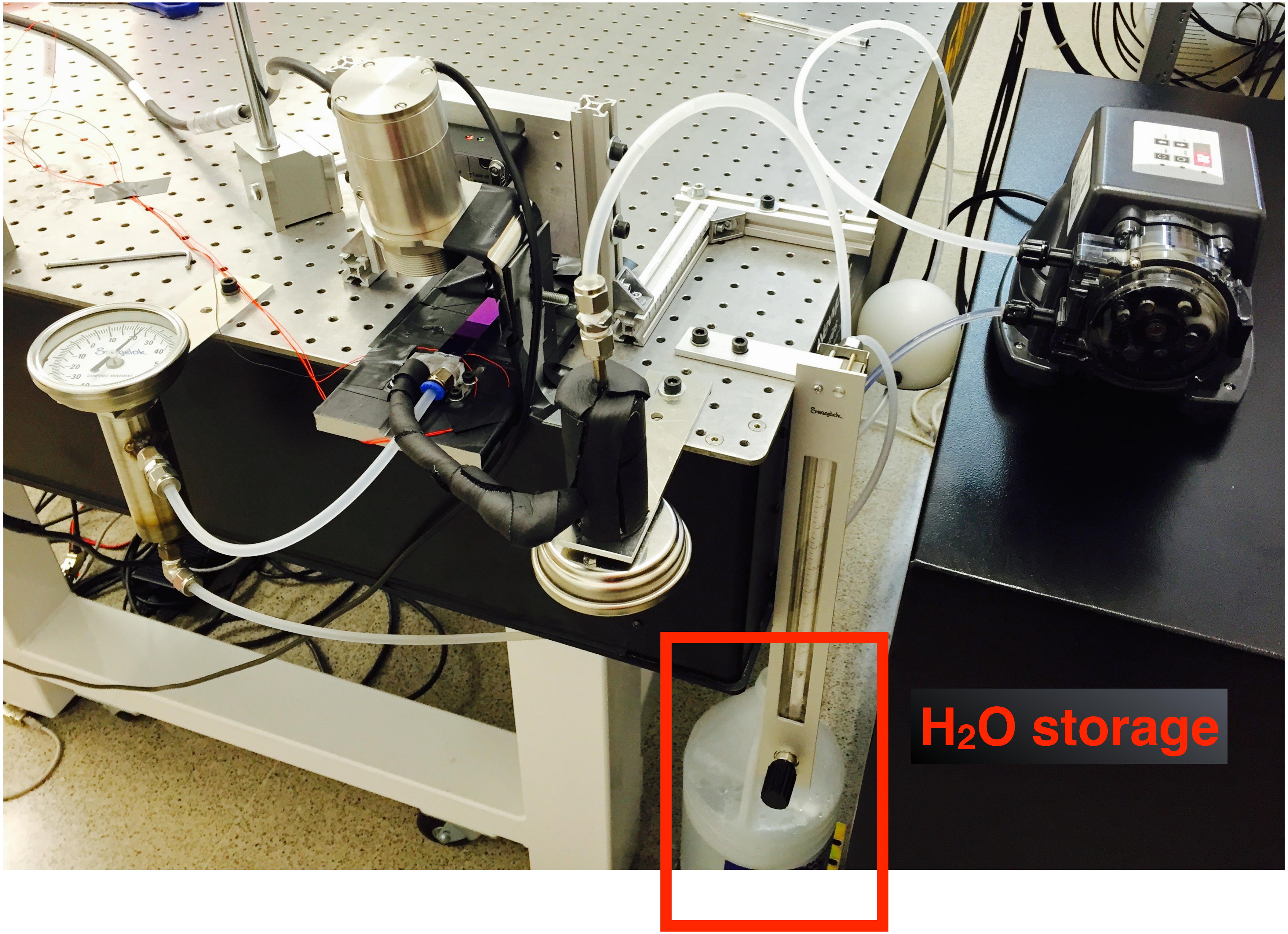


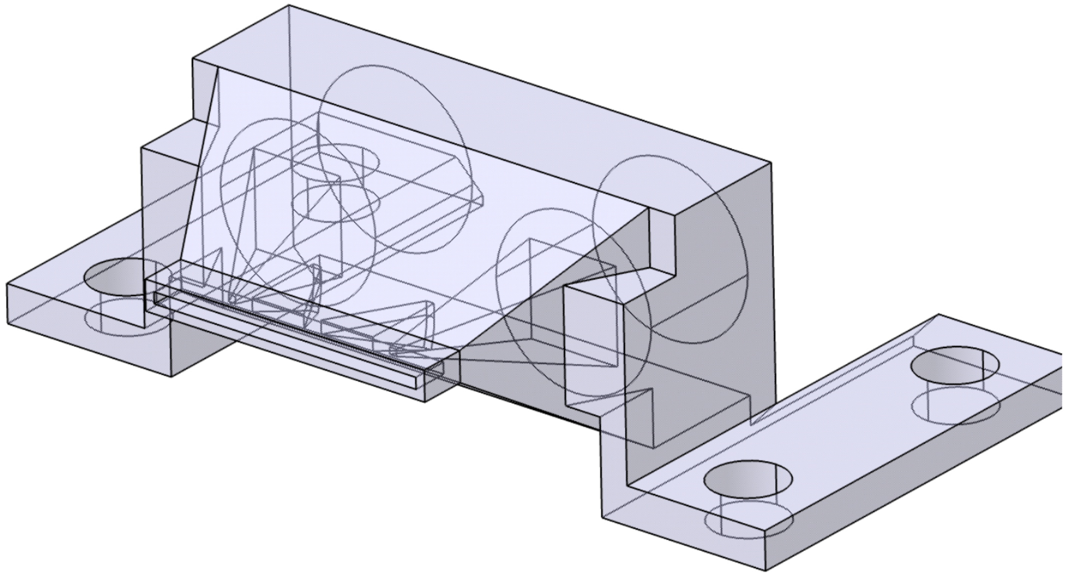
Experimental setup



Experimental setup

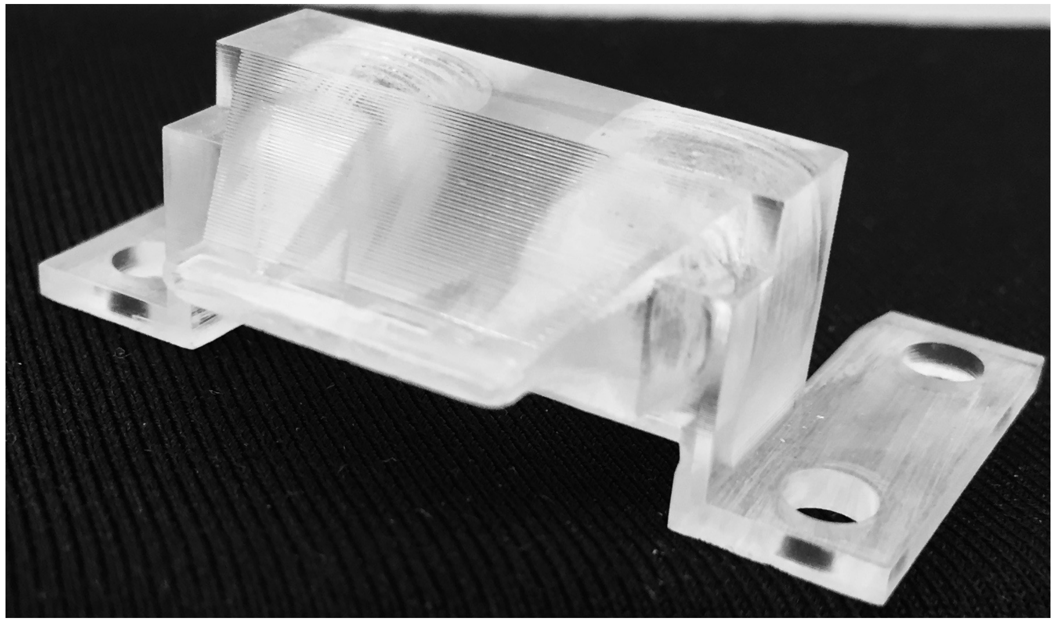


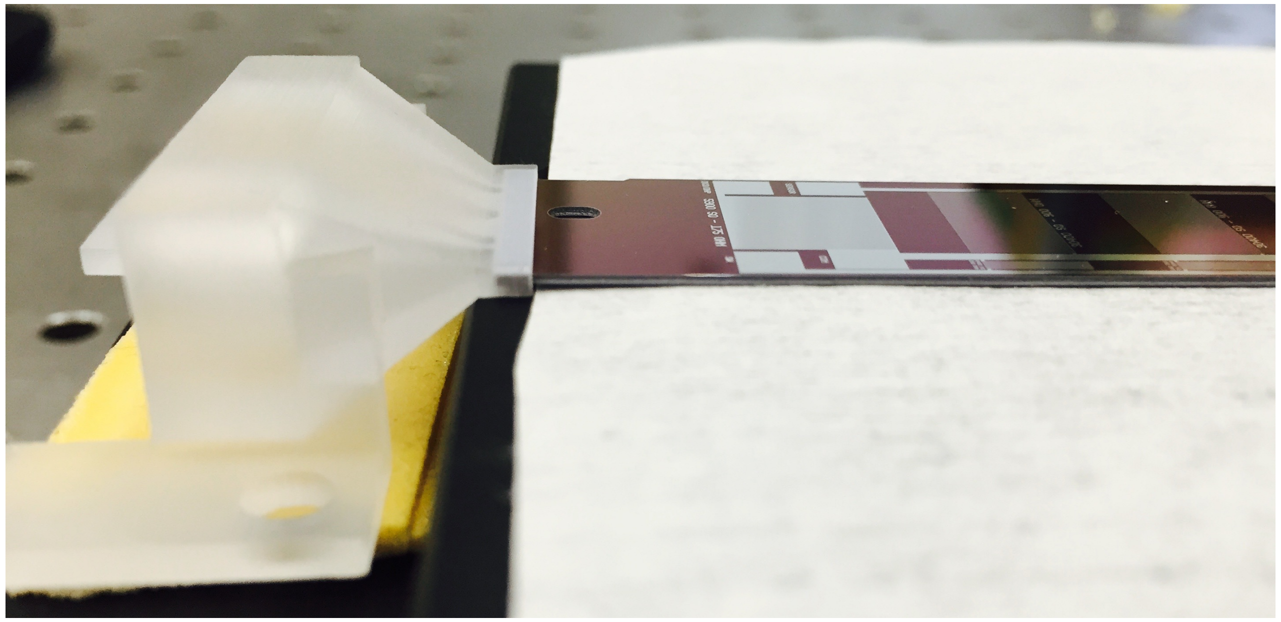
3D-printed adaptor



Design to join the high pressure commercial *Swagelok* elements to the 350x350 μm holes of the Silicon module

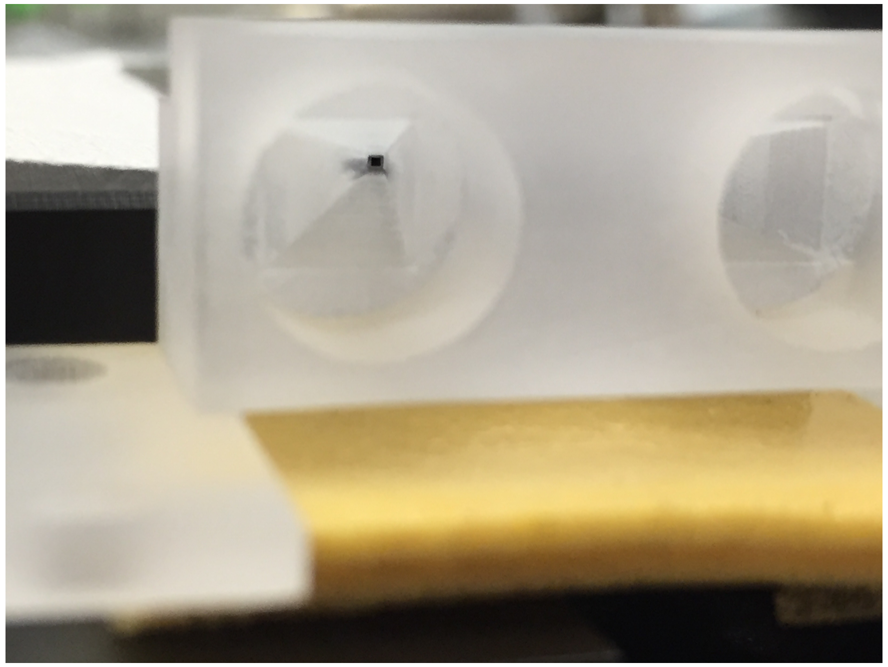
Built by 3D-printer (stereolithography technology)
- 15 μm precision
- 300 μm per layer



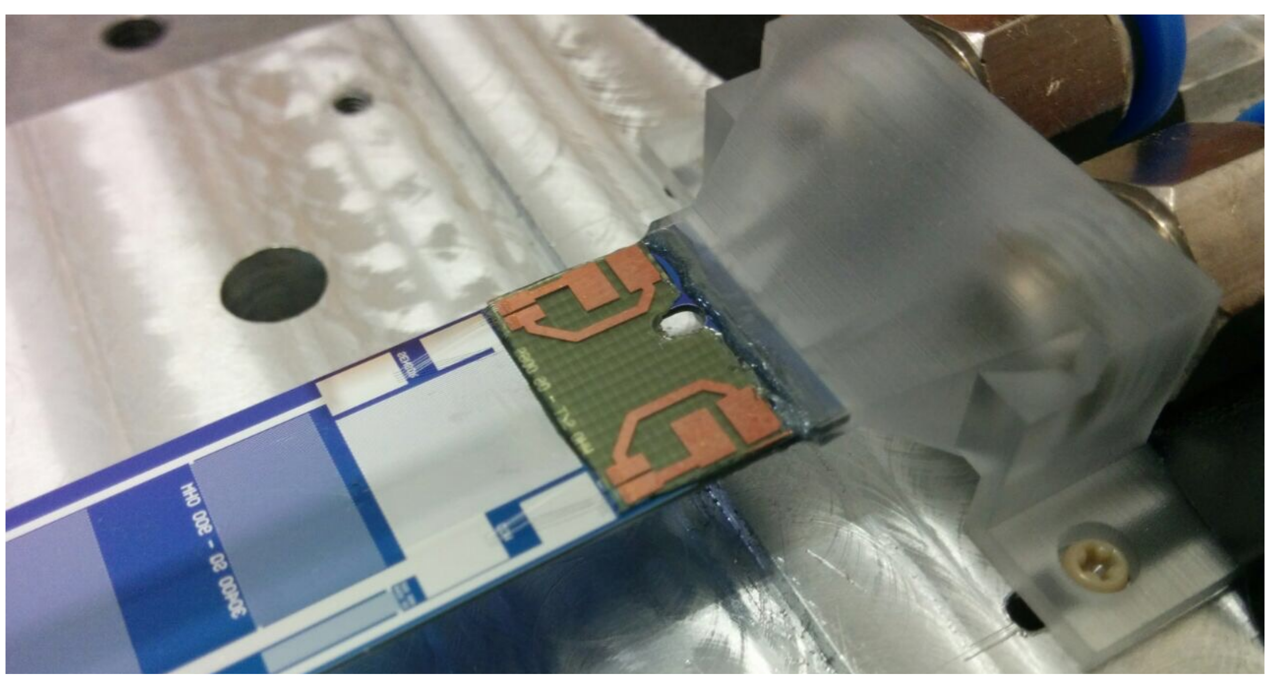


Alignment

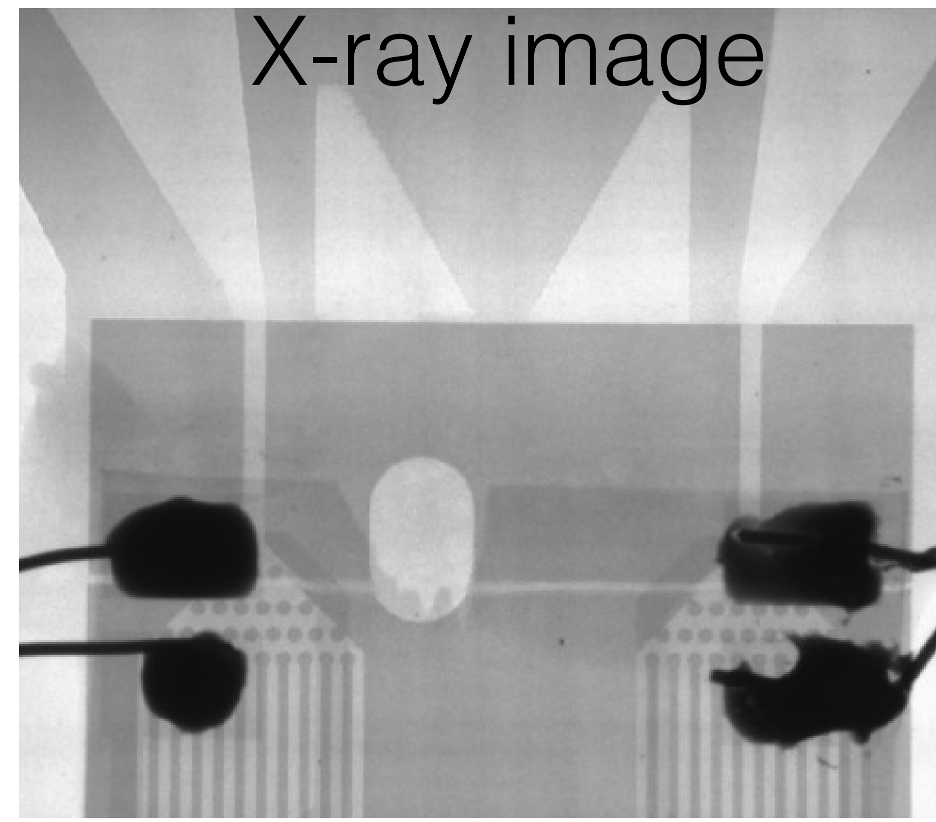
1) Self aligning: 3D adaptor fits accurately



2) Sealed with glue



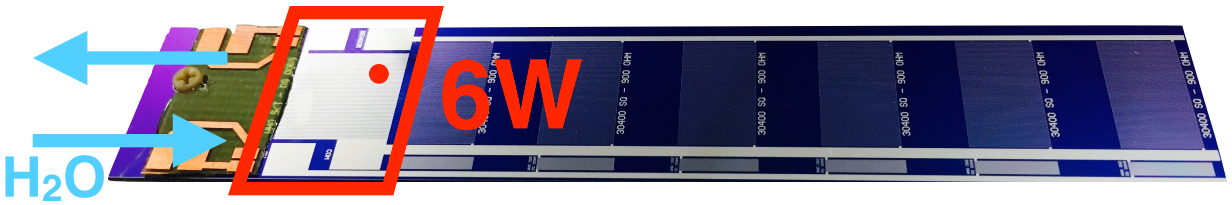
3) Success rate 3/3

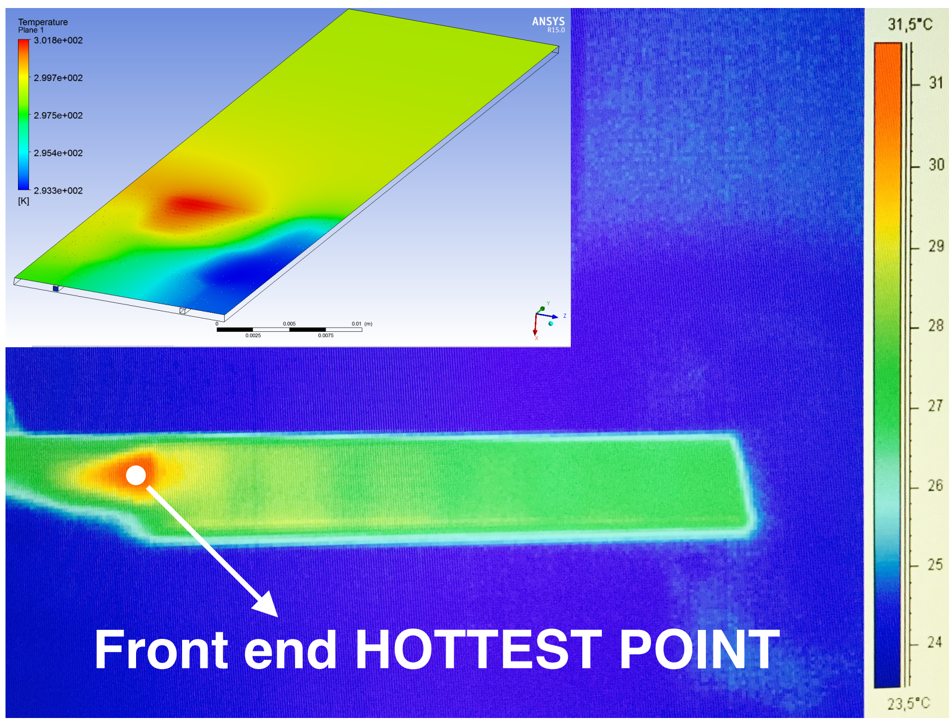


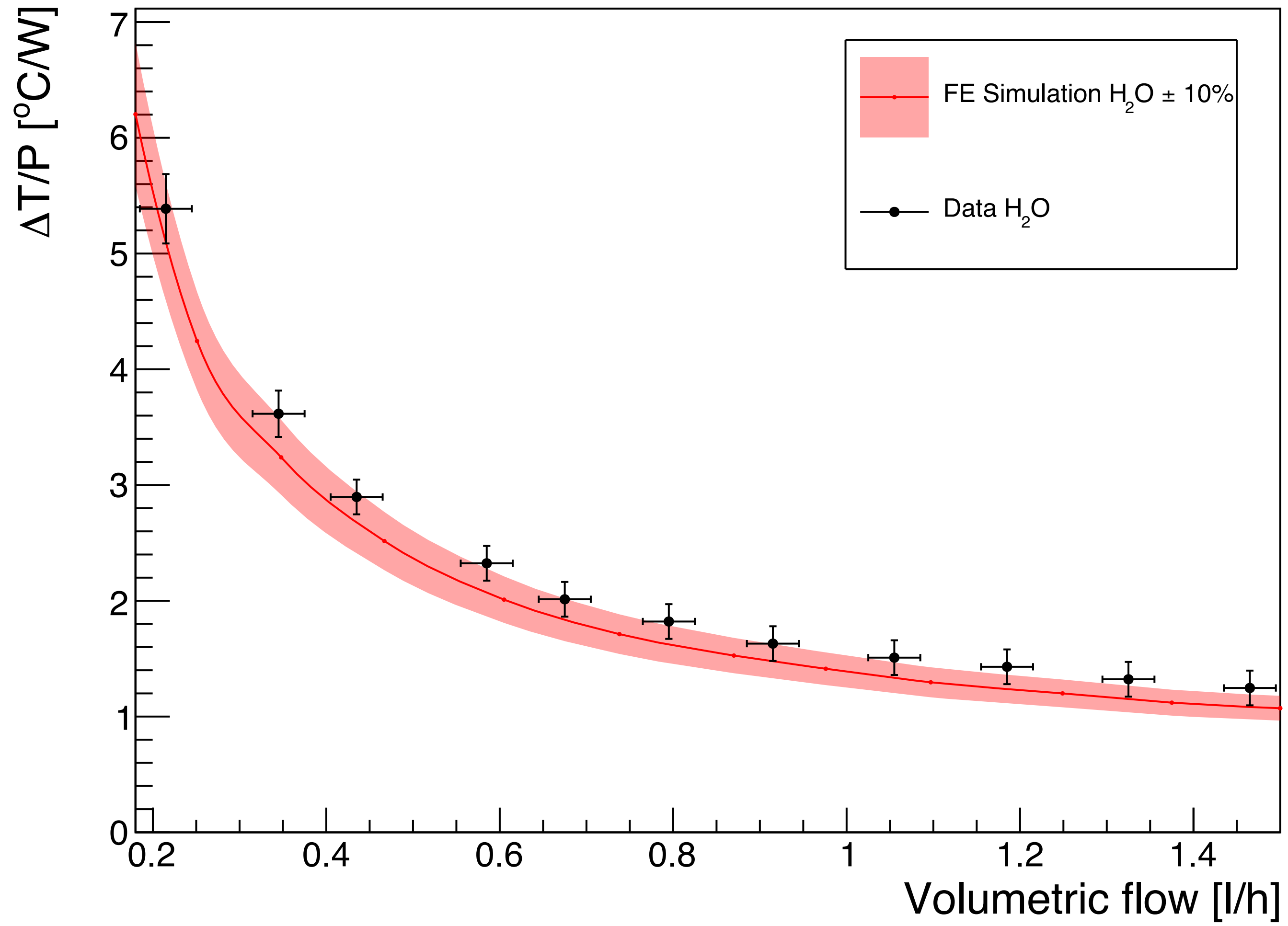
Experiment conditions

- For all-Silicon resistive dummies operating above 0°C **mono-phase fluid** is chosen (**H_2O**)
- **Possibility of use CO_2 at high pressure but not necessary at the power densities we have to manage**
- Controlled environment to quantify cooling performance. **Room temperature stable at 25°C**
- Operated non-stop for a week with **no leaks, no clogging**

Thermal measurements: MCC







- Low cost mono-phase fluid: H_2O

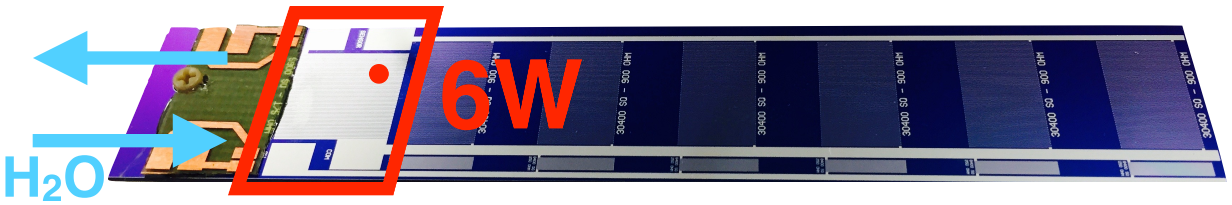
- **Low volumetric flows (~1l/h) and low pressure (<1bar) are enough to dissipate the heat in the front end**

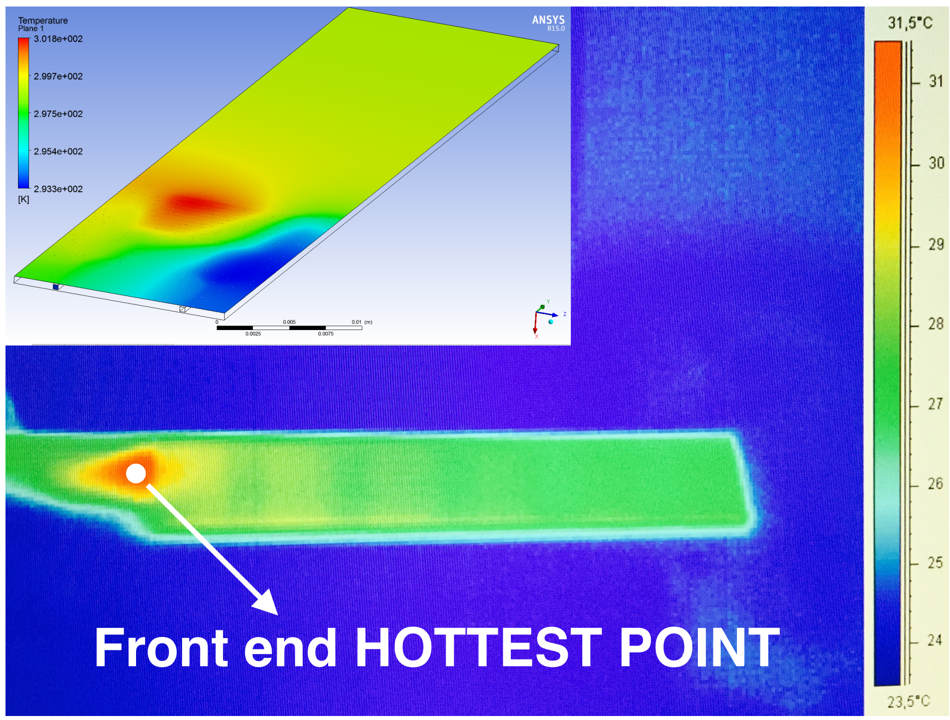
- **Good agreement** with the **FE simulation** inside an error area of **10%**

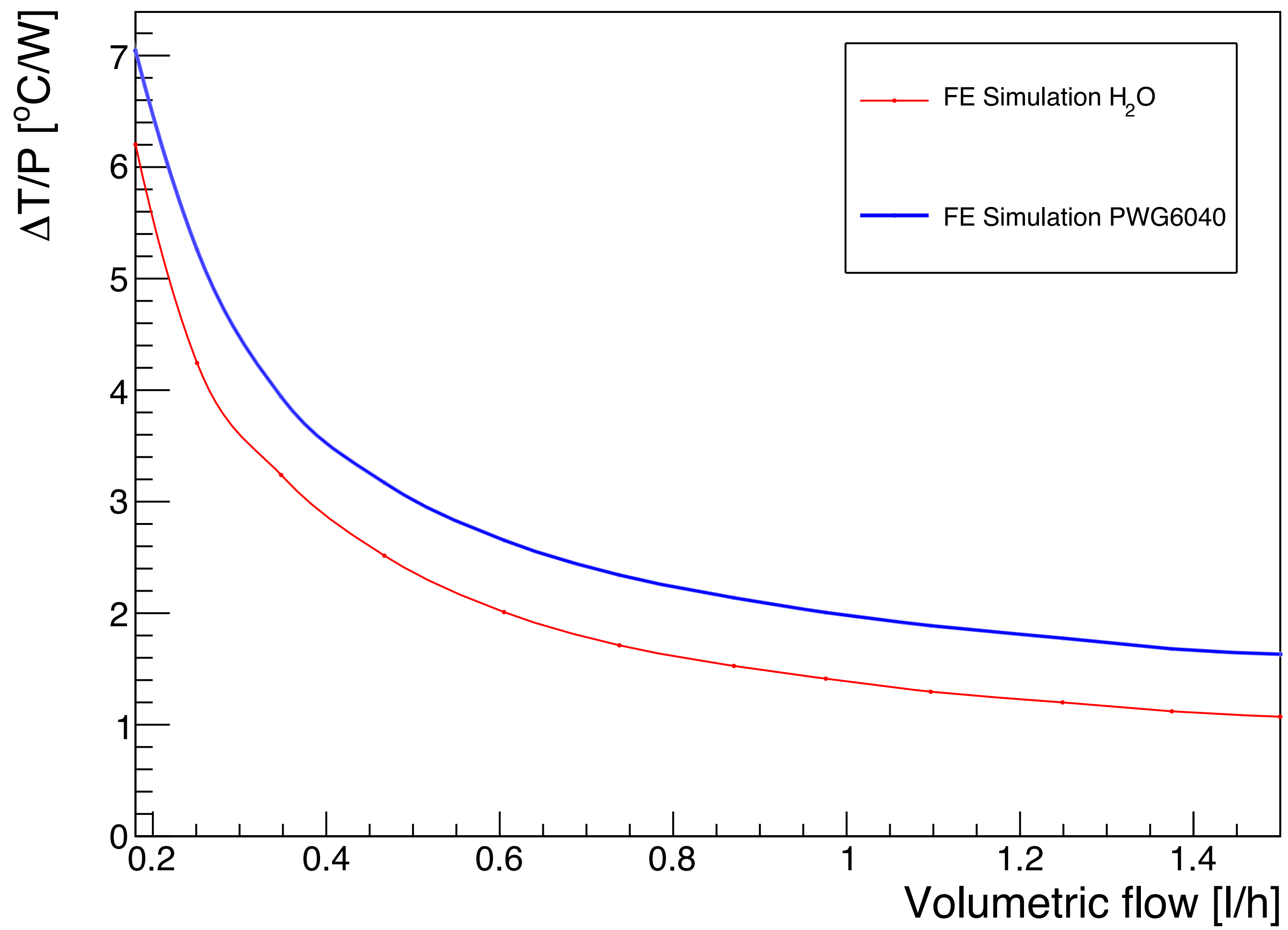
Measurement data errors

- P ±1% W
- T ± 1 °C
- ΔT/P ± 0,15 °C/W
- flow ± 0,03 l/h

Thermal measurements: MCC







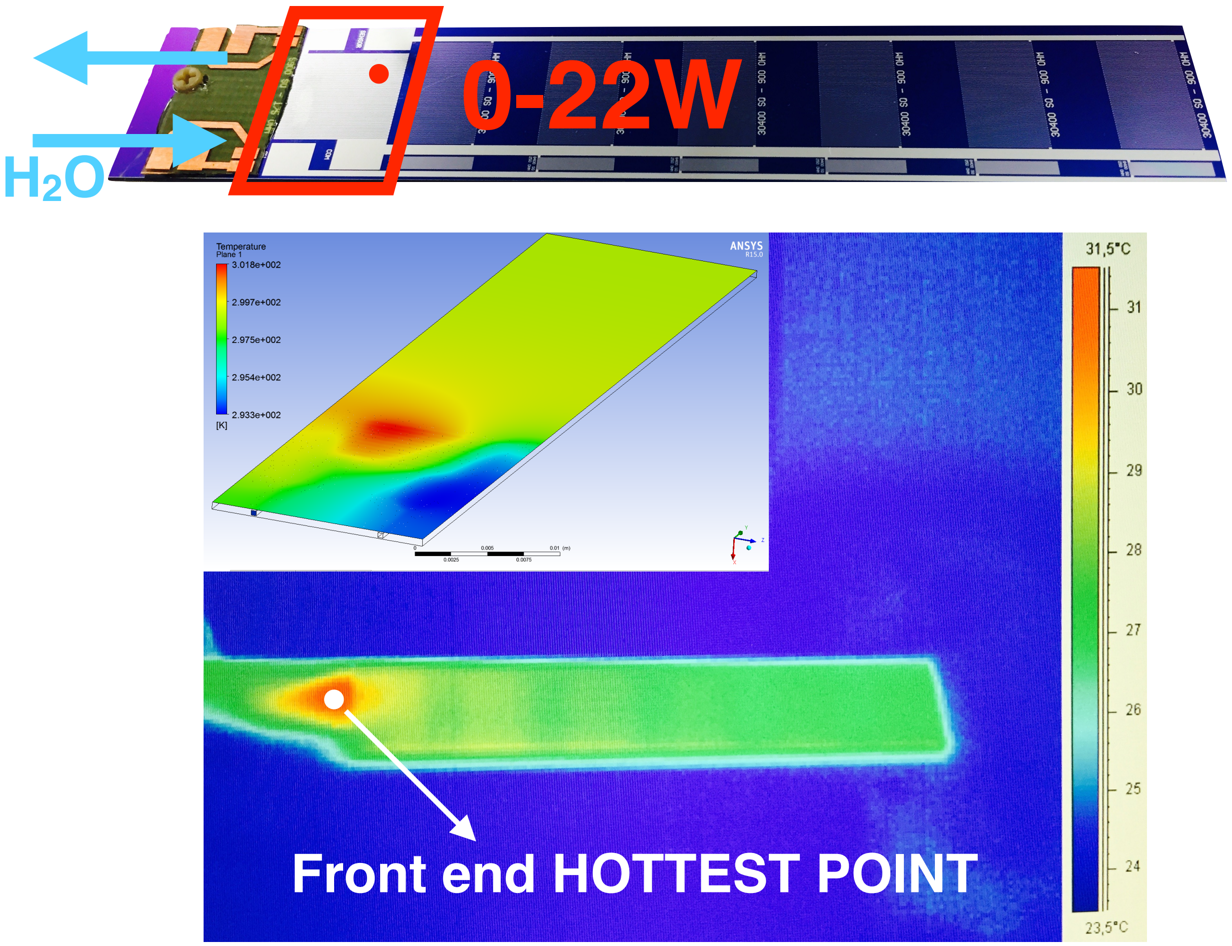
- Low cost mono-phase fluid: H_2O
- Additional coolant simulated (*PWG6040*) (60% glycol + 40 % H_2O)

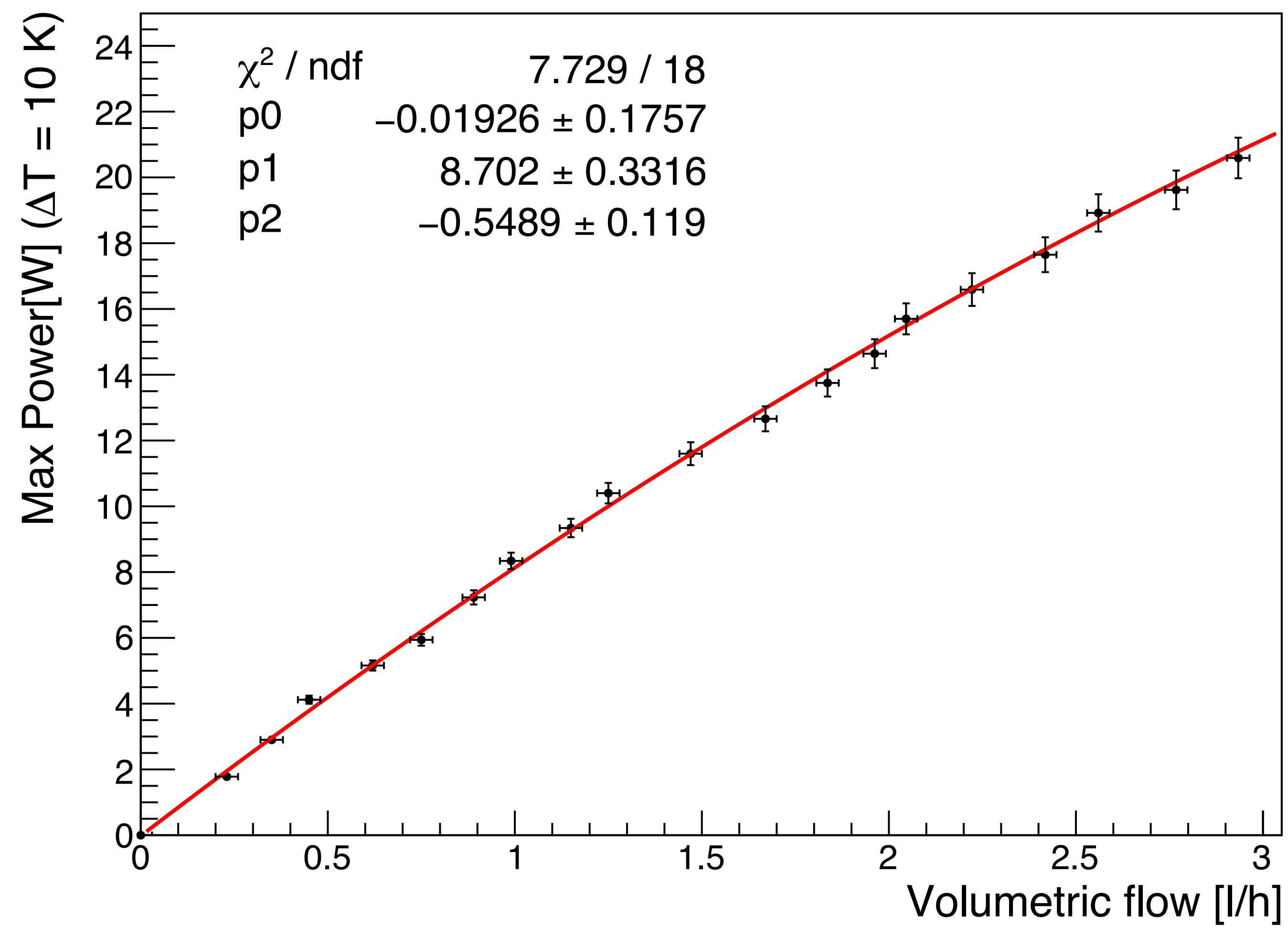
Measurement data errors

- P ±1% W
- T ± 1 °C
- ΔT/P ± 0,15 °C/W
- flow ± 0,03 l/h

FE simulation with other fluids in progress

Thermal measurements: Maximum Power vs Volumetric flow

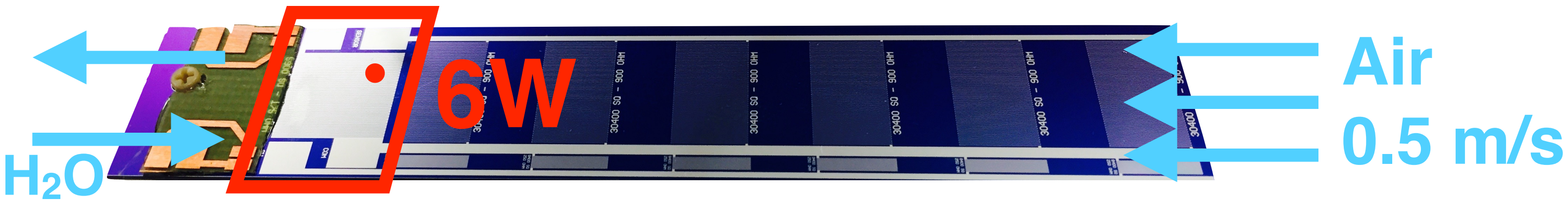


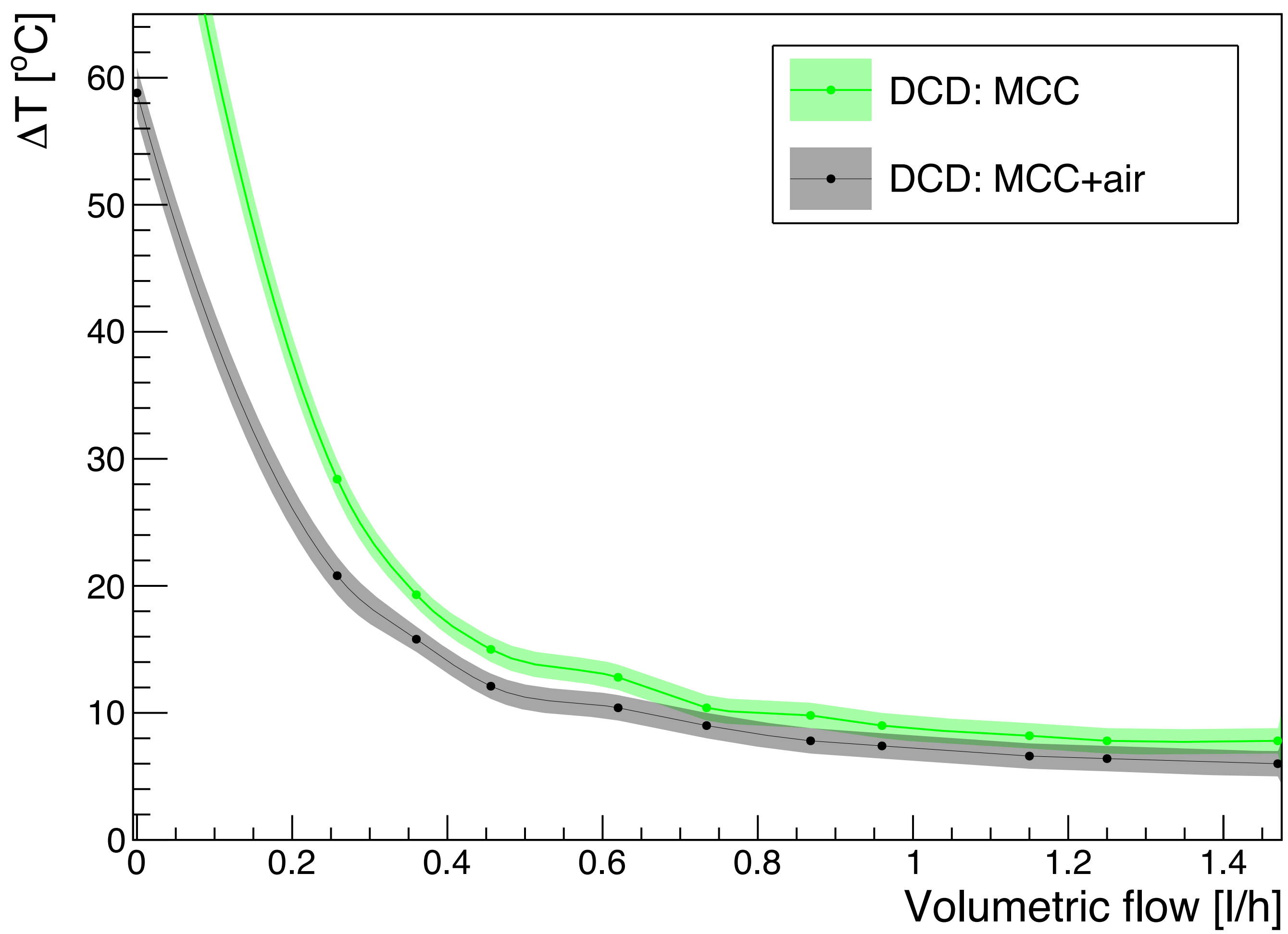


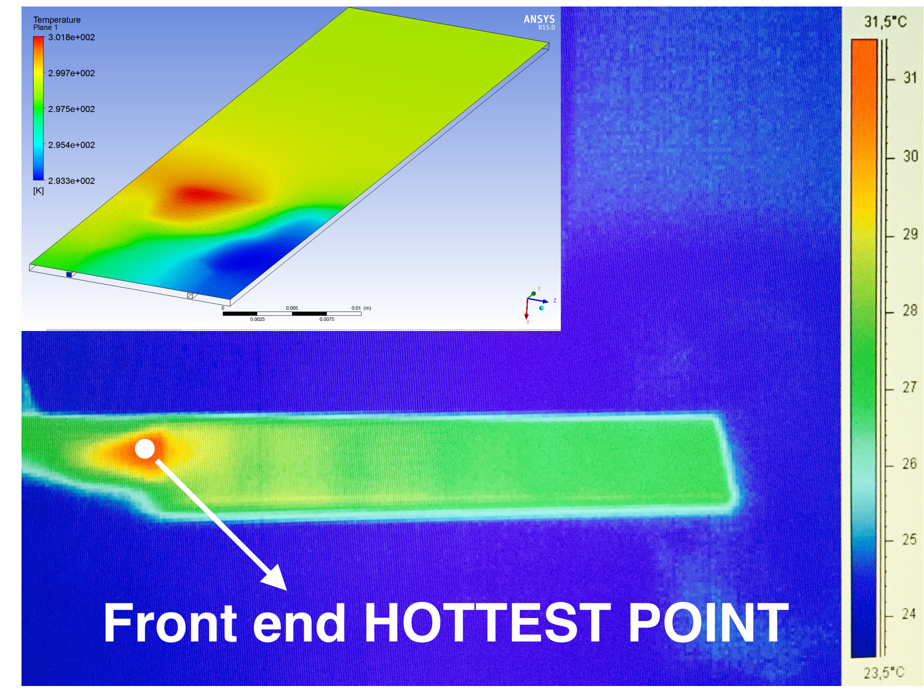
Maximum power supported for a ΔT of 10 ºC as a function of the volumetric flow

- **Temperature stable** even with **25 W/cm²**
- **Power vs vol. flow** at max. pump power (~ 3 l/h)
- **Low pressure** needed: 0.2 - 1.5 bar

Thermal measurements: MCC+air



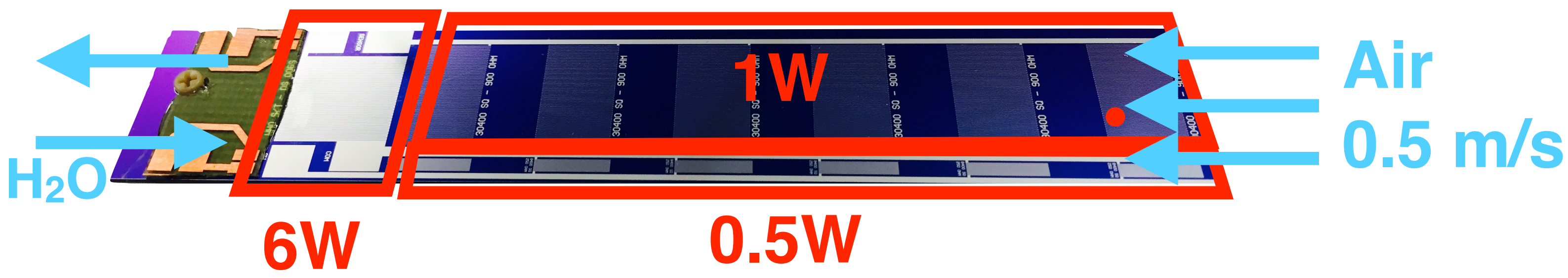


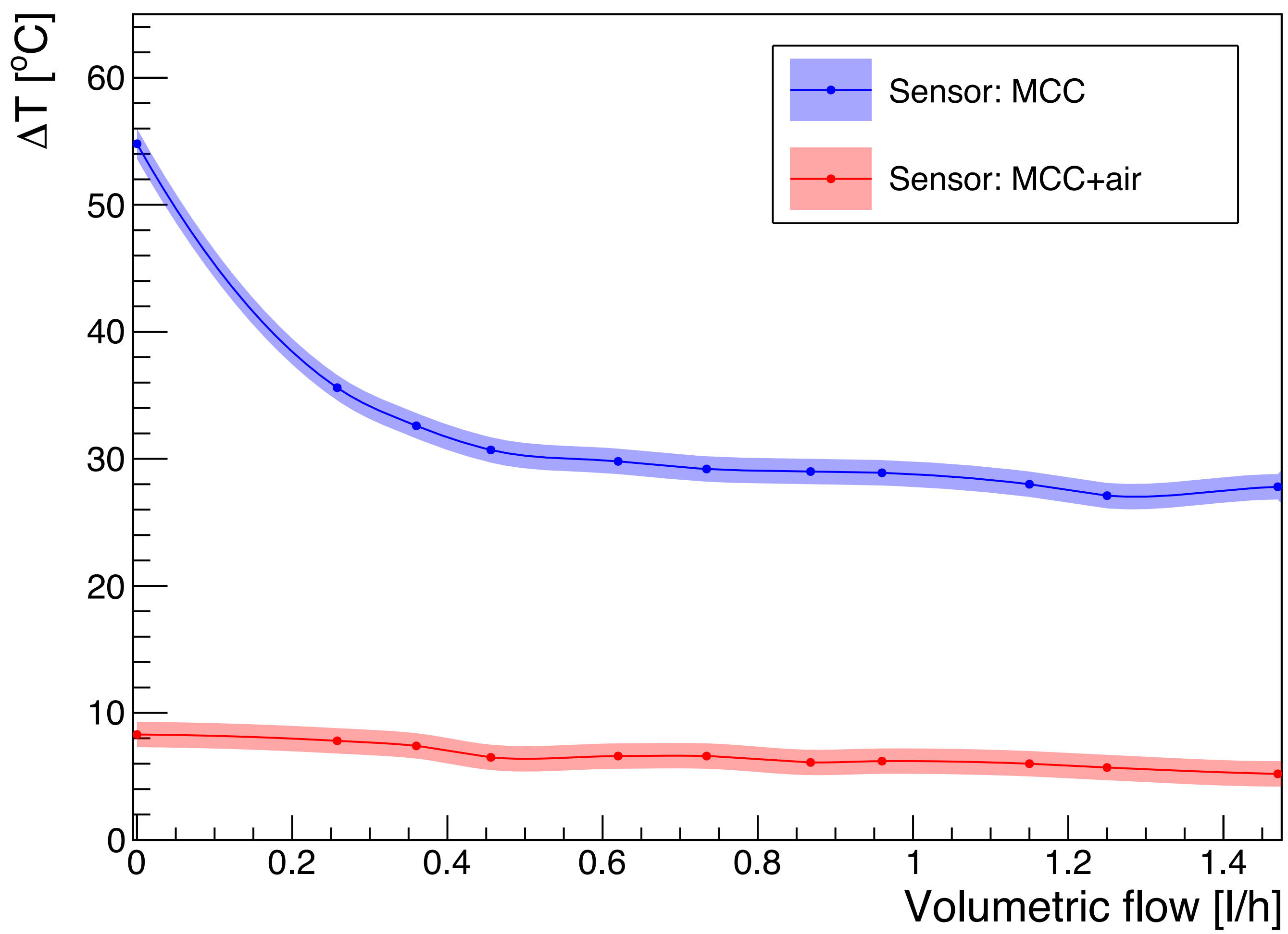


- **There is not big difference between MCC and MCC+air at the DCD hottest point**
- **Farthest regions to the air inlet are less affected**
- **Even with low volumetric water flow, high cooling**
- **93% of total heat removed by MCC**

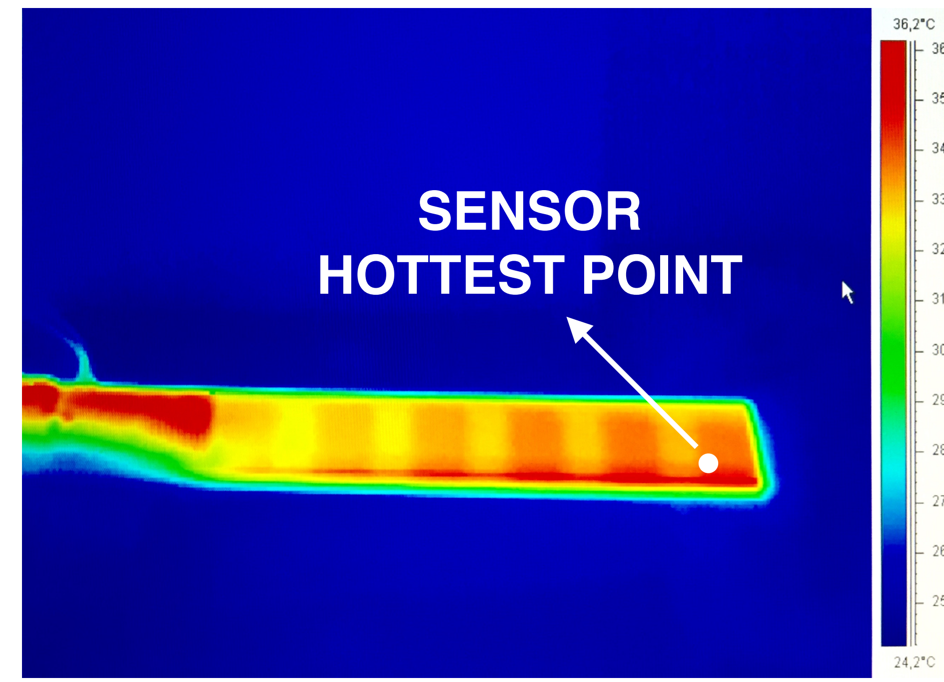
Cooling strategy: micro-channels running under the front end and gentle air flow on the sensor part

Thermal measurements: MCC + air



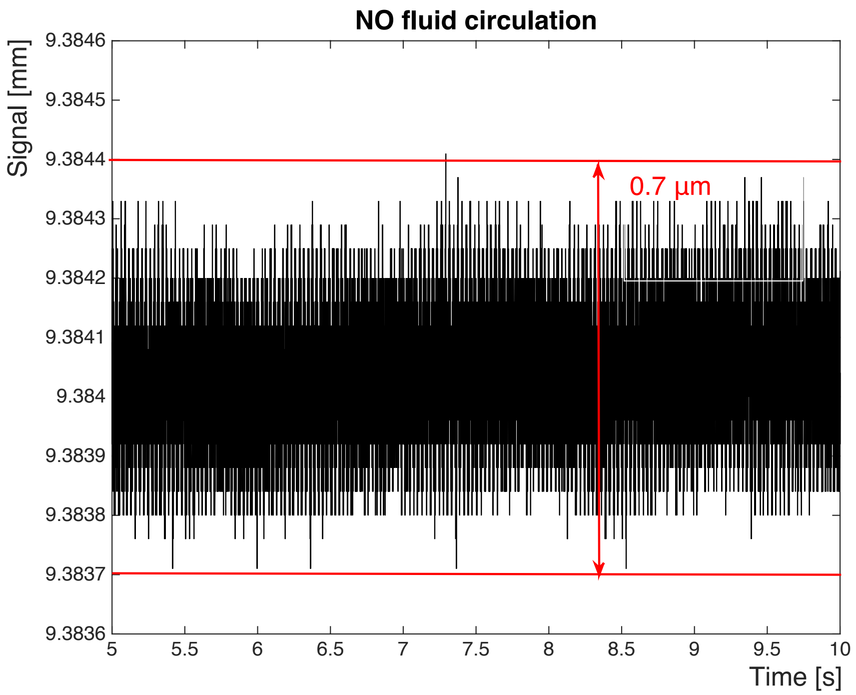


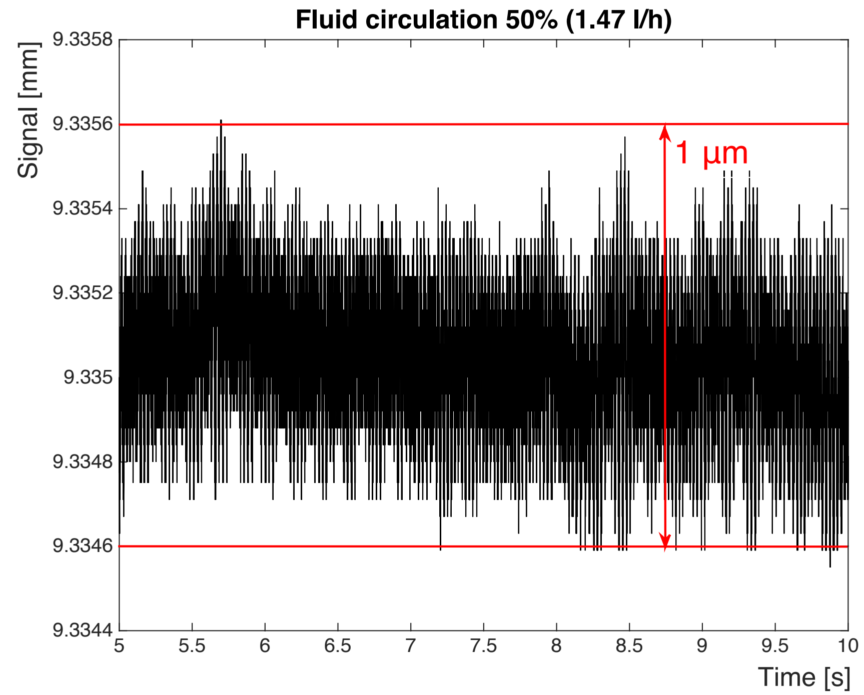
Cooling strategy: micro-channels running under the front end and gentle air flow on the sensor part

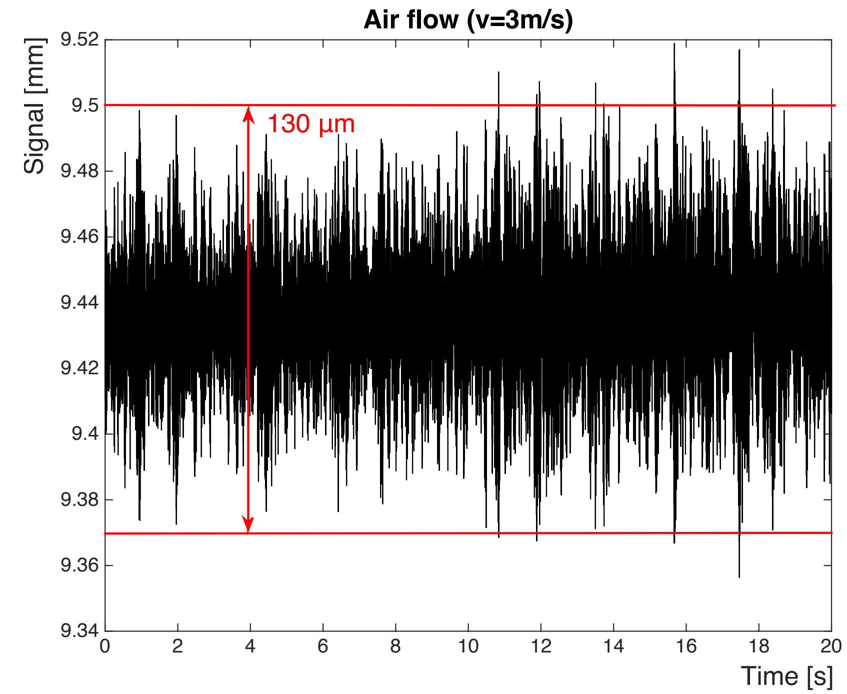


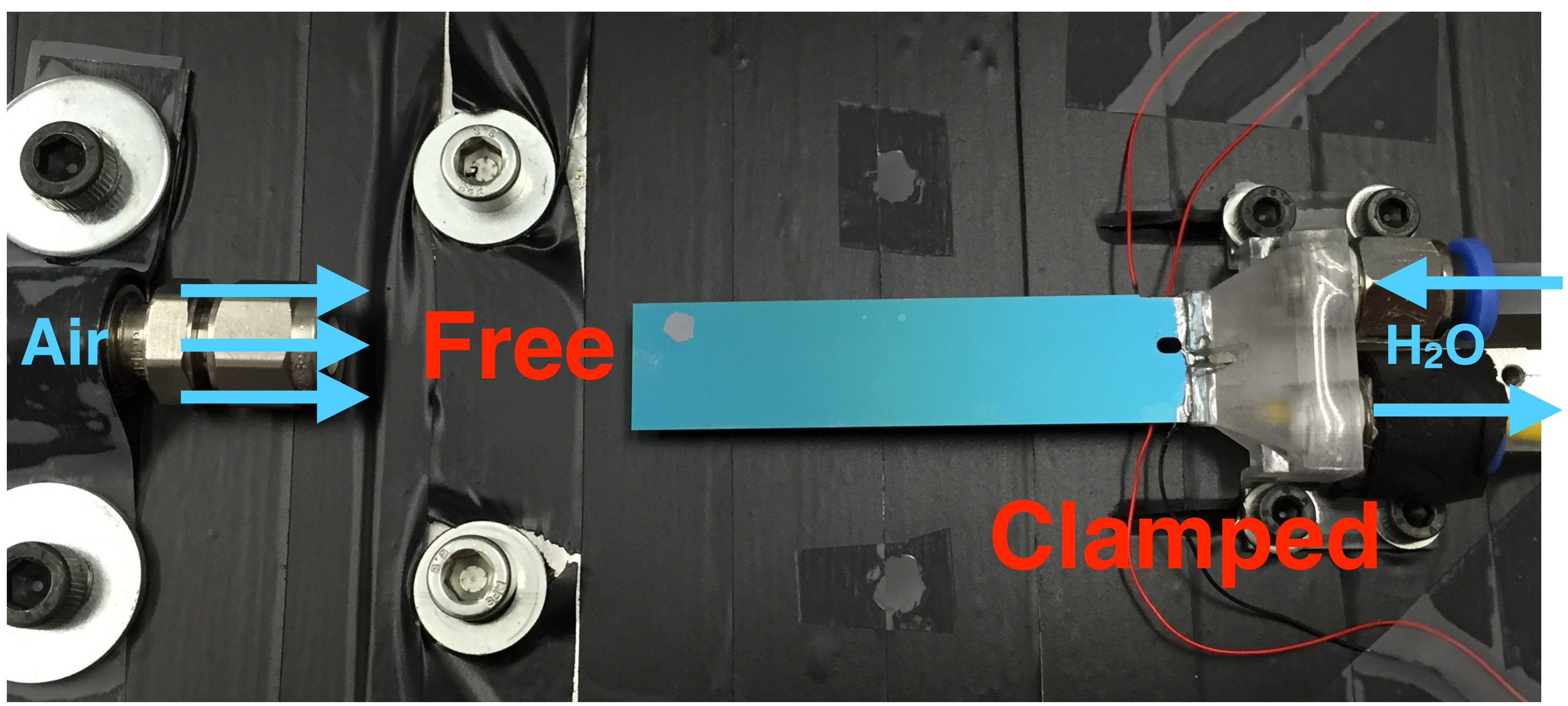
- **Big difference between MCC and MCC+air at the sensor area hottest point**
- **Nearest regions to air input are efficiently cooled even with low air flow**
- **MCC has less impact in away points as expected and great cooling locally**

Vibrations and deformations



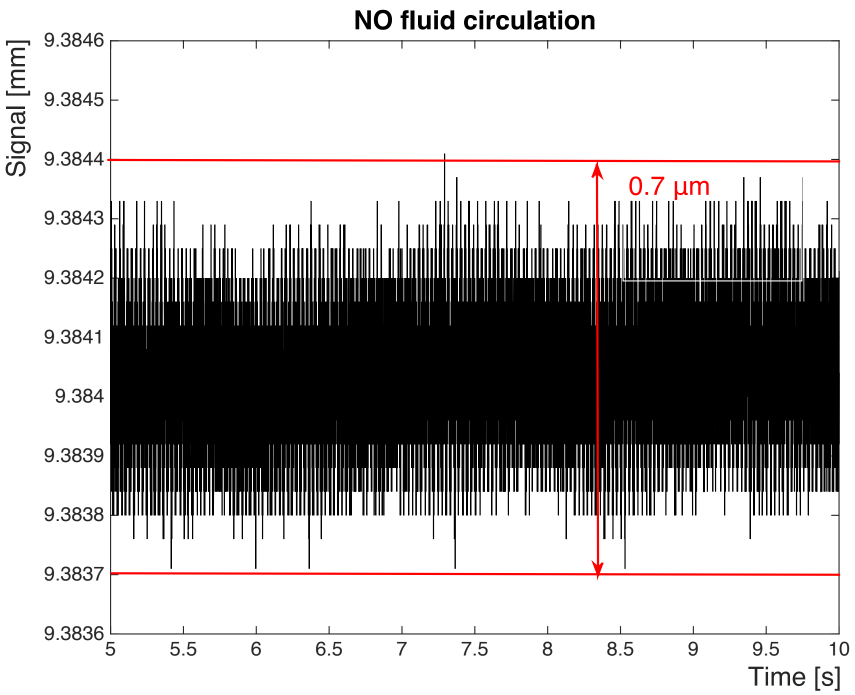


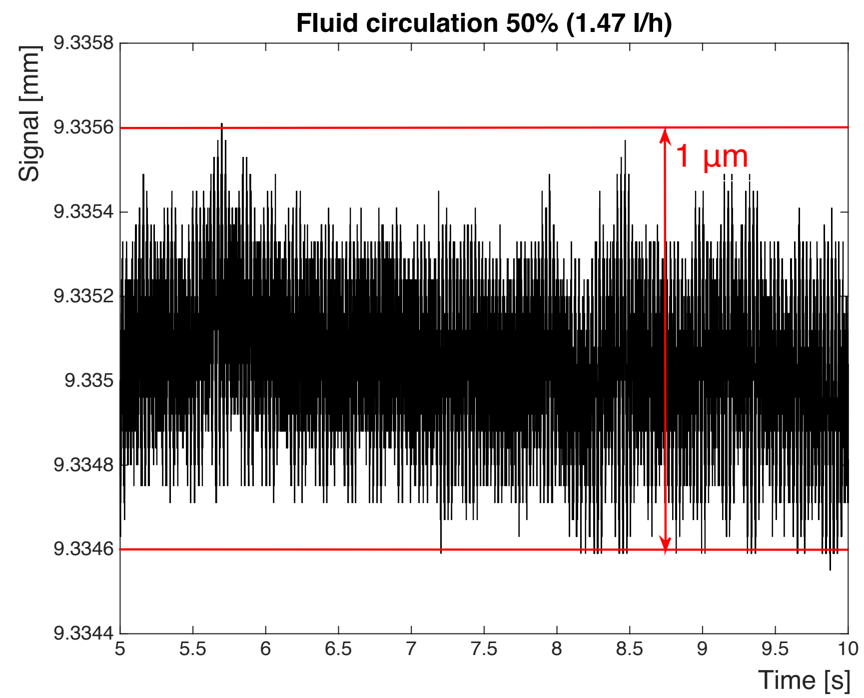


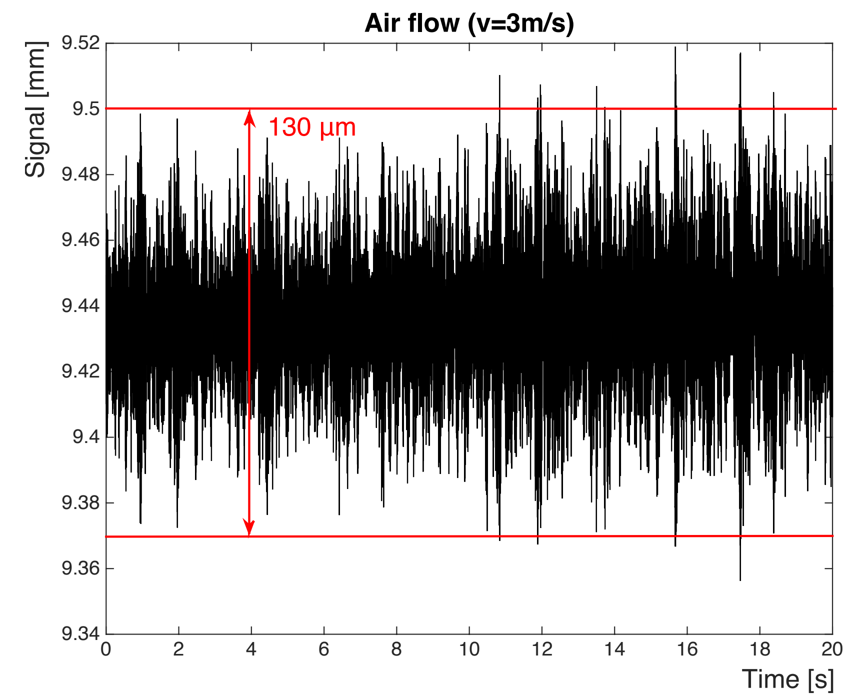


Clamped-free (CF) configuration: One extreme of the dummy is clamped to the 3D adaptor while the other is free of movement

Vibrations and deformations







No fluid circulation and no air flowing

Peak to peak of the signal ~0,7 µm

RMS ~0,3 µm

Fluid circulation 1,47 l/h

Peak to peak of the signal ~0,1 µm

RMS ~0,4 µm

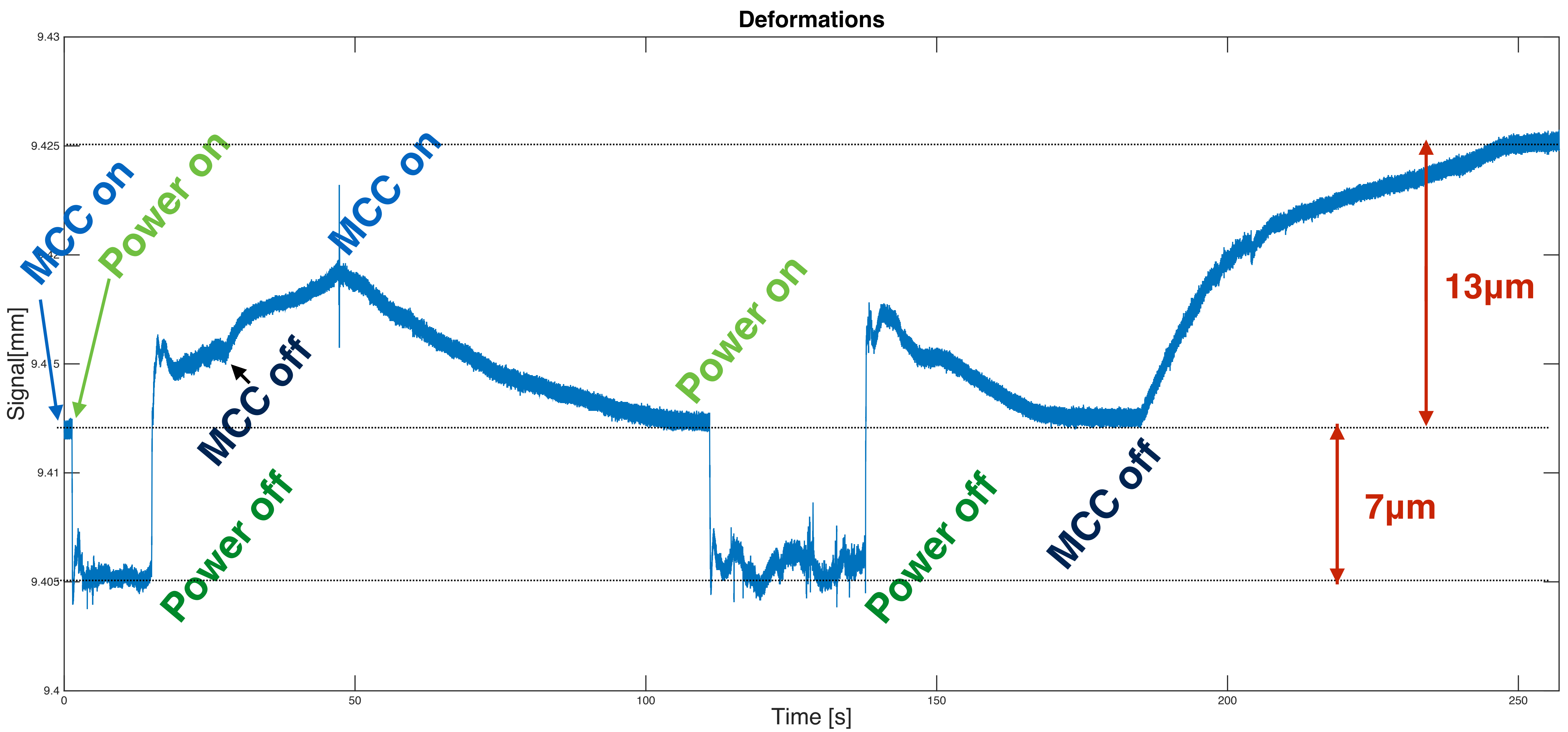
Air flowing 3 m/s

Peak to peak of the signal ~130 µm

RMS ~57 µm

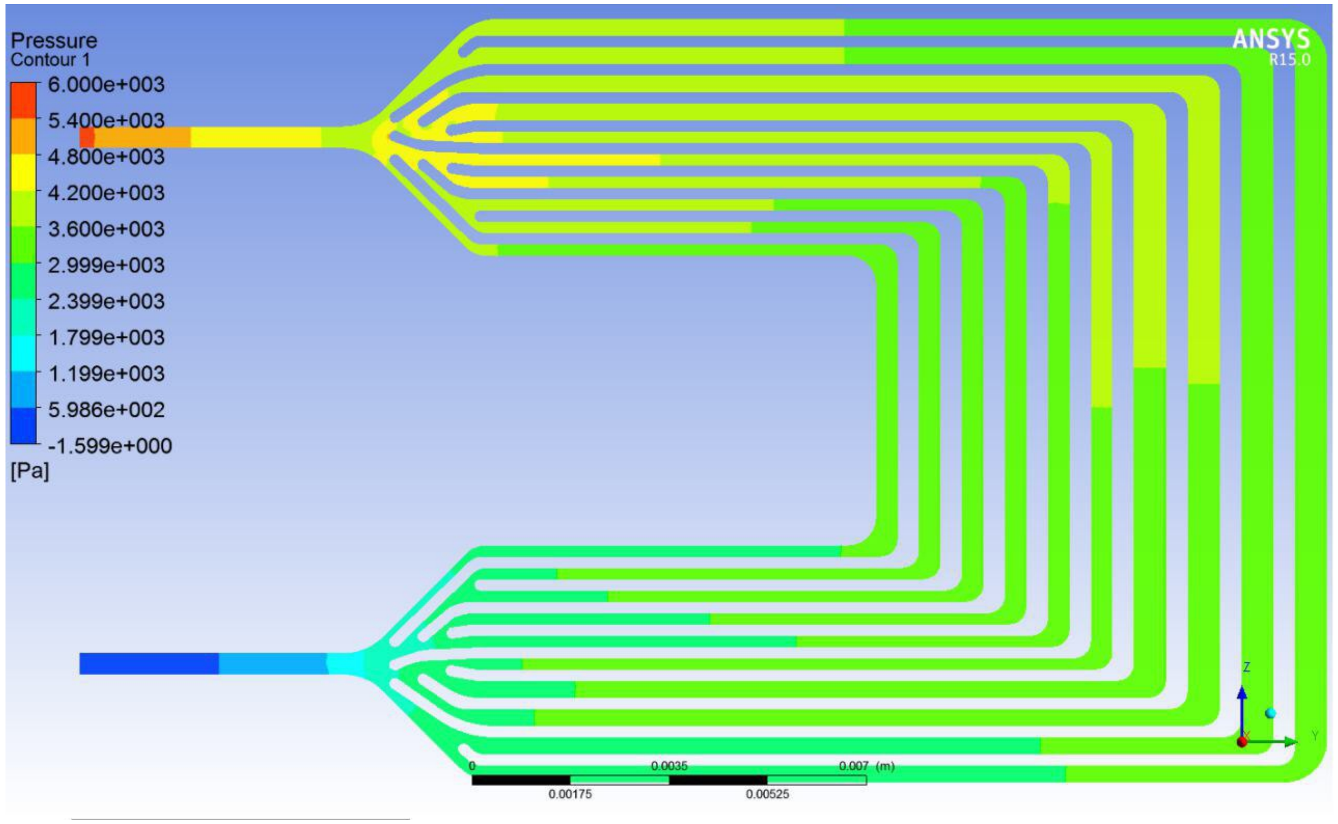
MCC has no significant impact on mechanical stability in the clamped-free configuration but air deformations are more than 100 µm if v=3m/s (could be reduced a factor 10 for velocities under ≤0.5m/s)

Vibrations and deformations

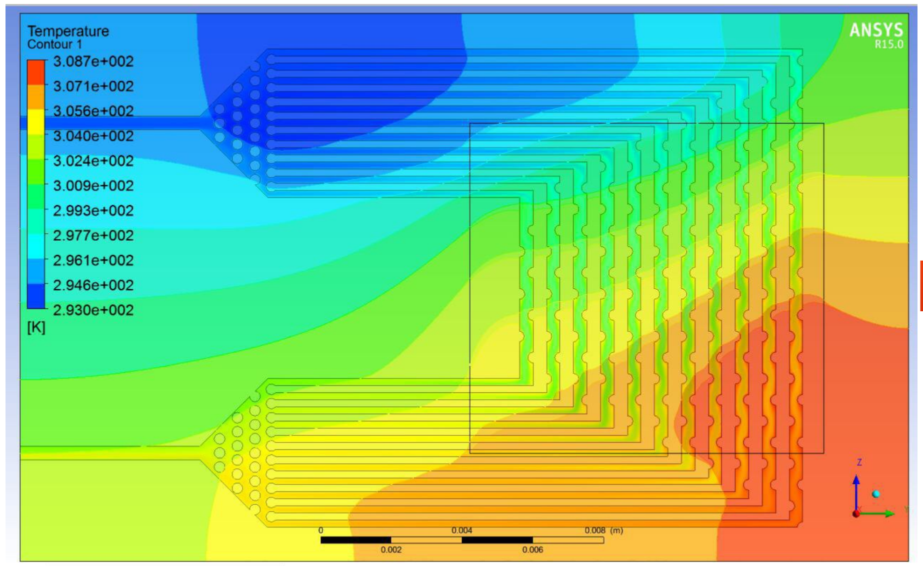


- Minor deformations observed in transitions regions
- Mechanical stability after cycles
- Maximum deformation ~20 μm

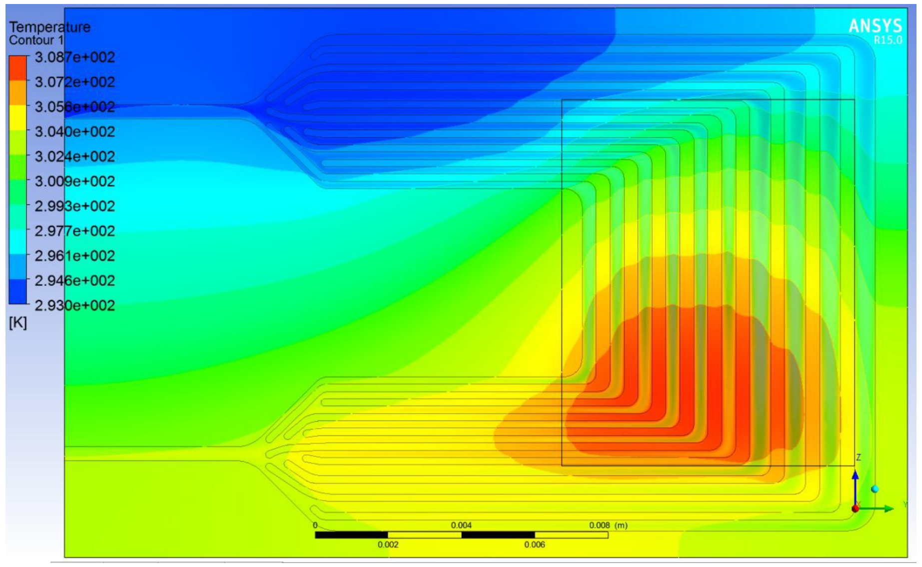
Optimized MCC geometry



- More homogenous flow
- Reduce pressure gradients
- Minimize and confine the heat spread



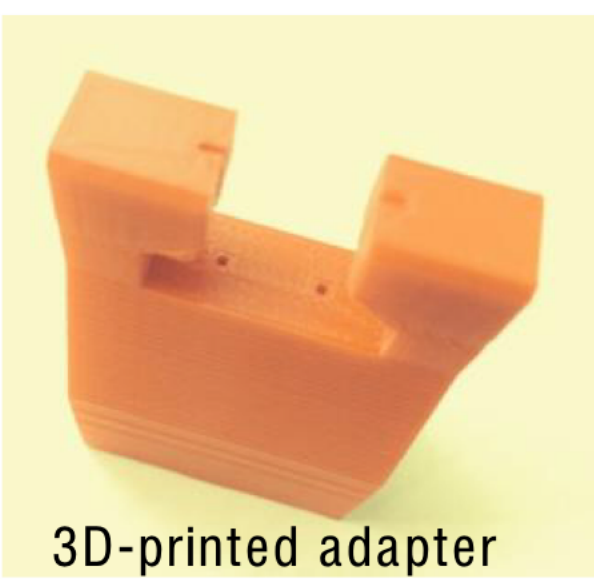
Recent geometry



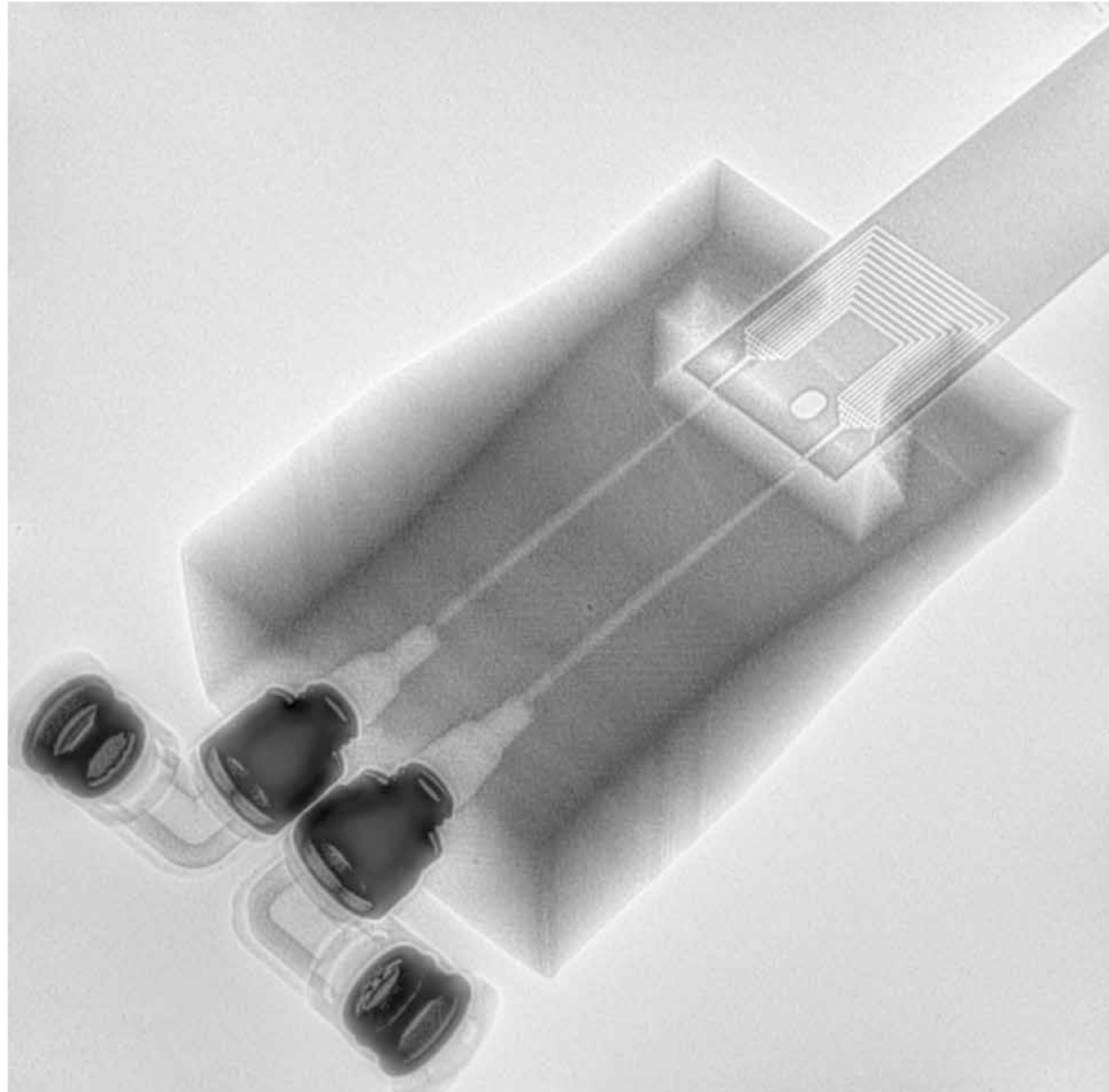
Optimized geometry

Towards a low mass interconnection

PEEK tubes with 360 µm OD



3D-printed adapter



Next steps

Built new samples with the **optimized geometry**

Redesign the 3D-printed adaptor (make it flat, use peek tubes...)

Simulate and measure **new fluids**

Conclusions

MCC shows very efficient cooling; **up to 25 W/cm^2** with minimal temperature increase (10^{o}C) even with a mono-phase fluid at low pressure

Thermal measurements are in good **agreement with the FE simulation**

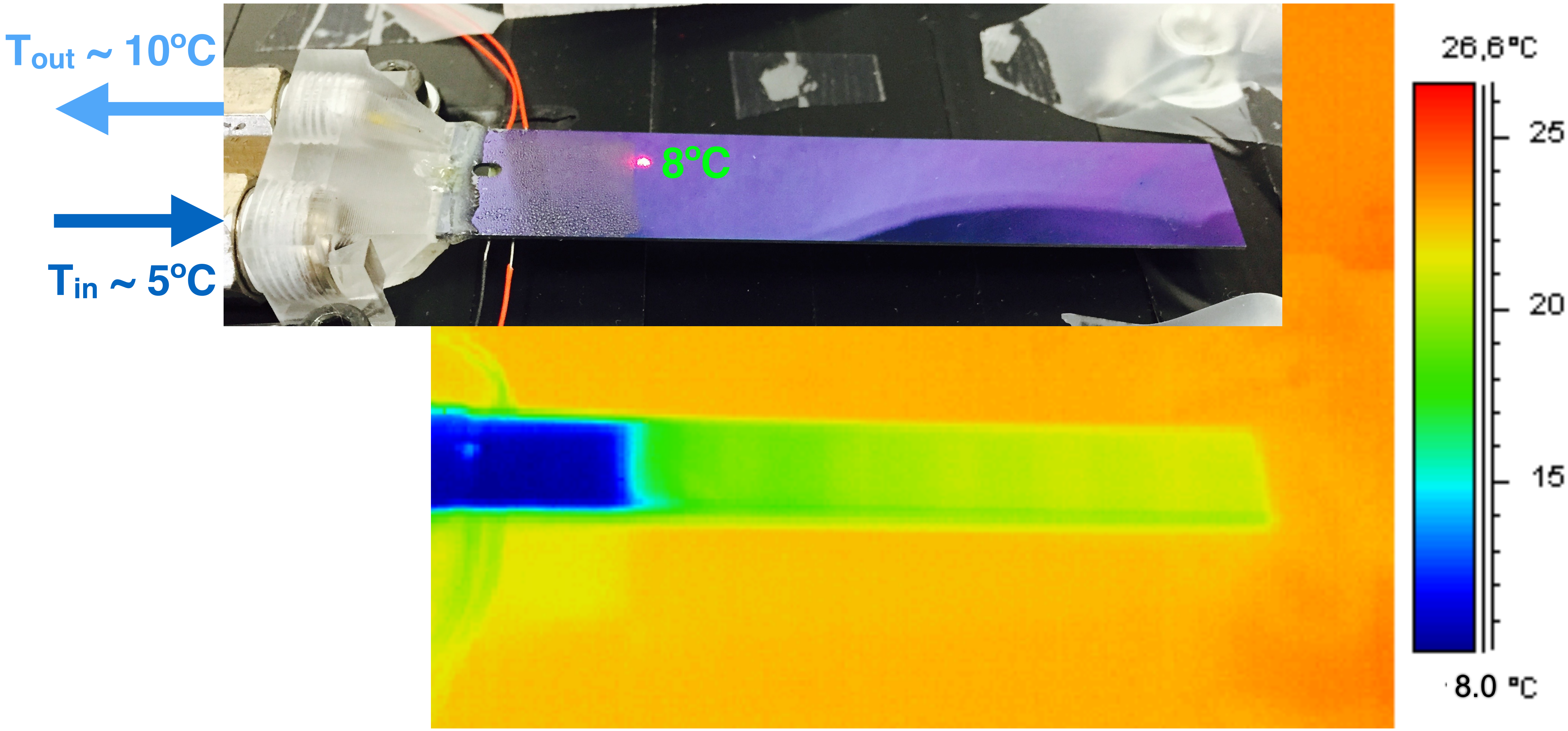
MCC has a **minimal impact on the mechanical stability**

The assembly with the 3D-printed adaptor was done **successfully in 3/3**

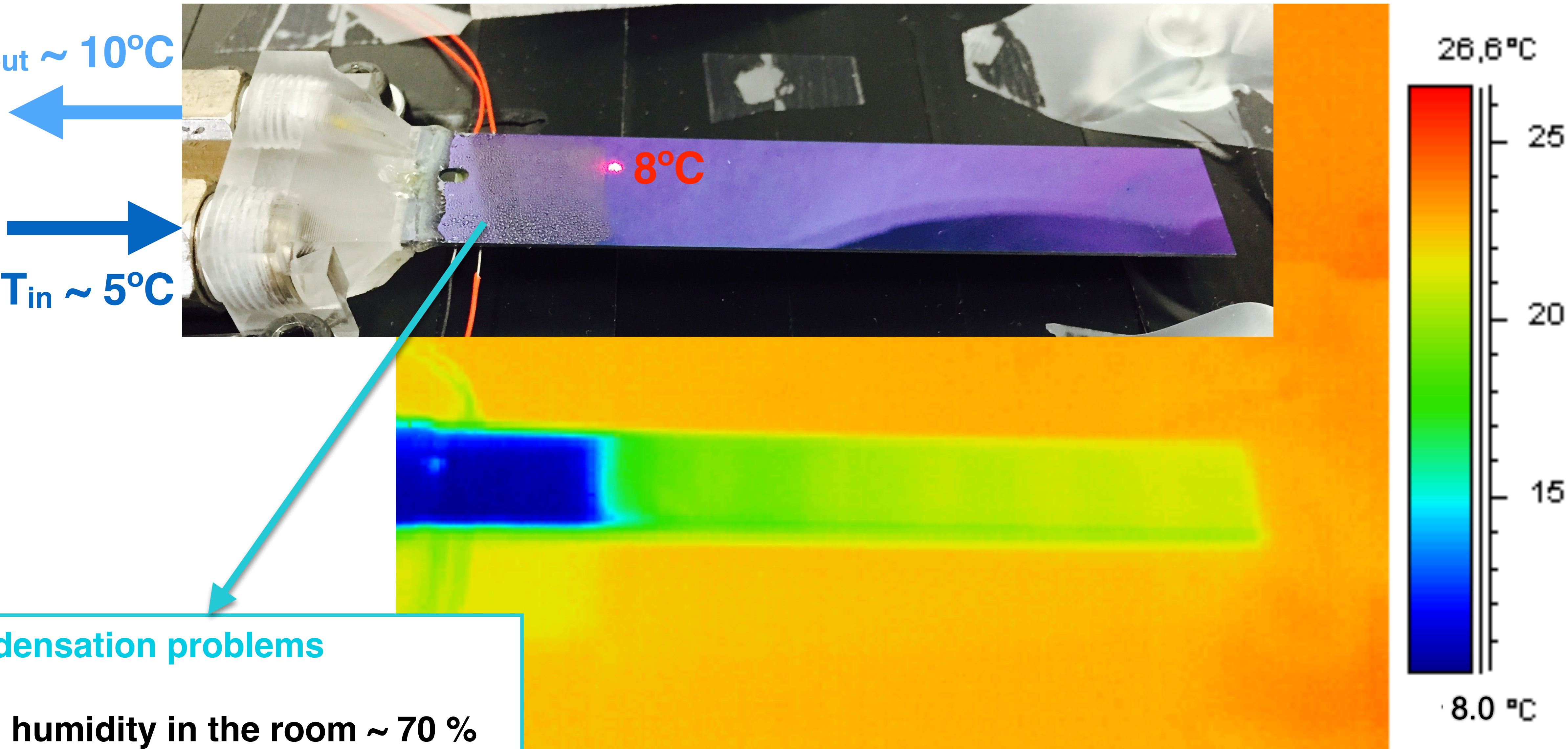
MCC embedded in all-silicon ladders is a real option

Thank you for your attention

Thermal measurements: cold water



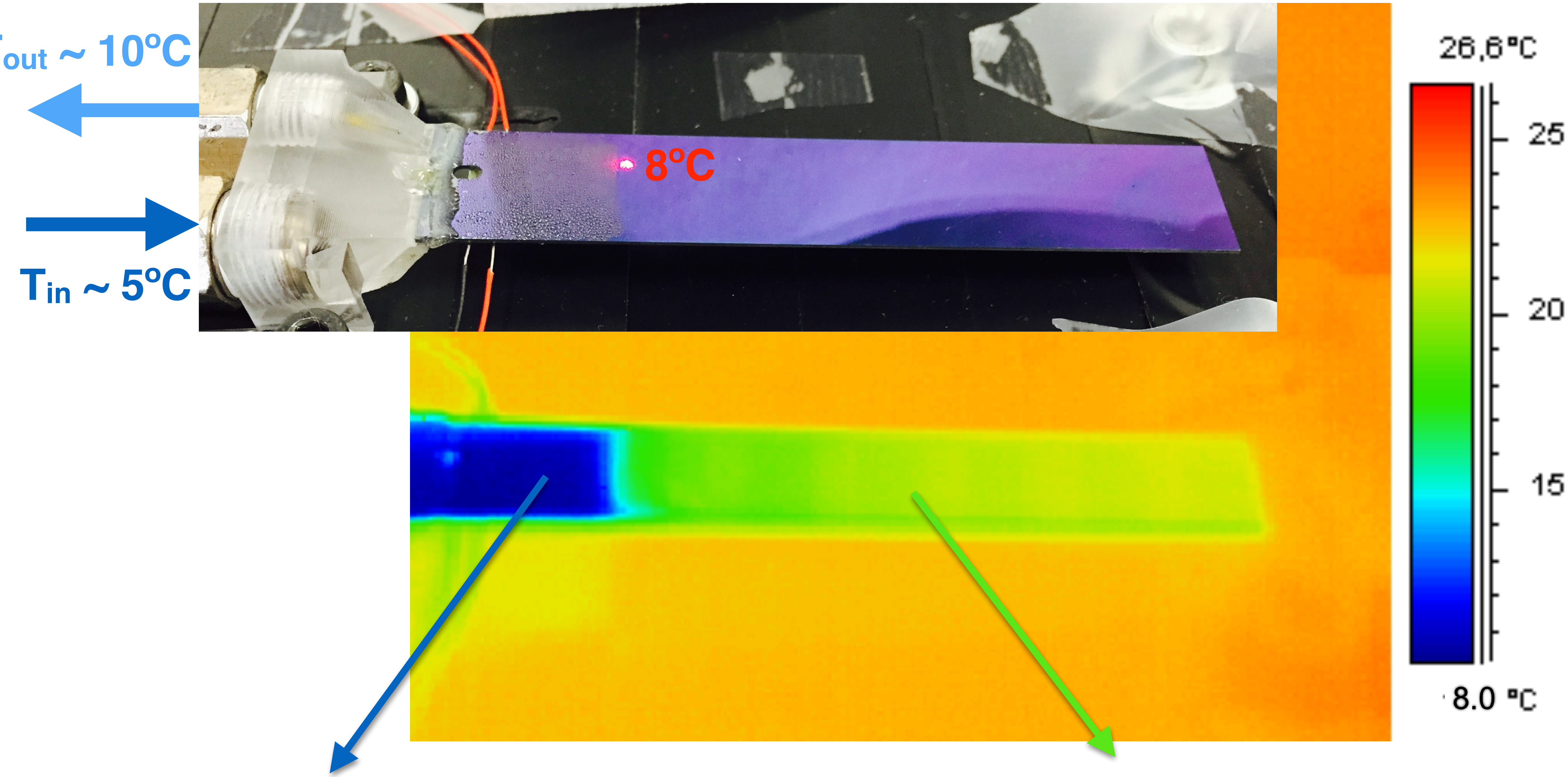
Thermal measurements: cold water



Condensation problems

High humidity in the room ~ 70 % impossible to power on the aluminum resistances (possible **short-circuit** due to the water on the soldering)

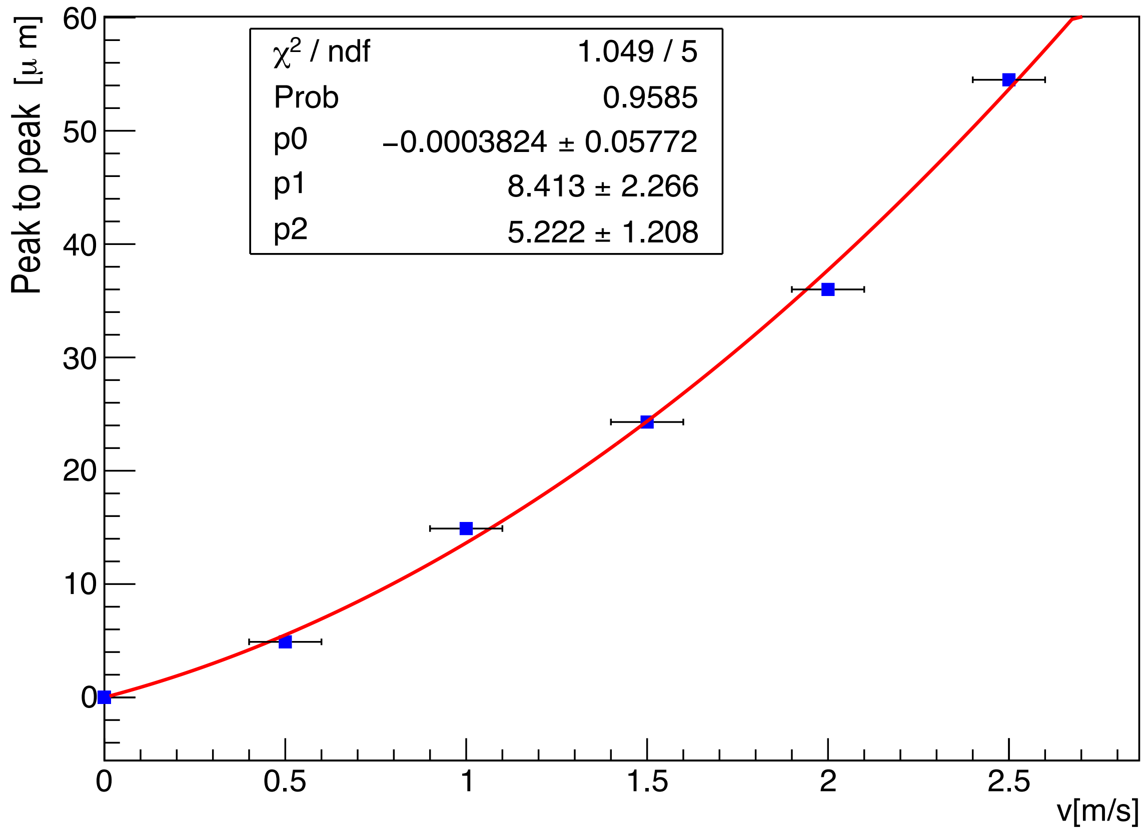
Thermal measurements: cold water



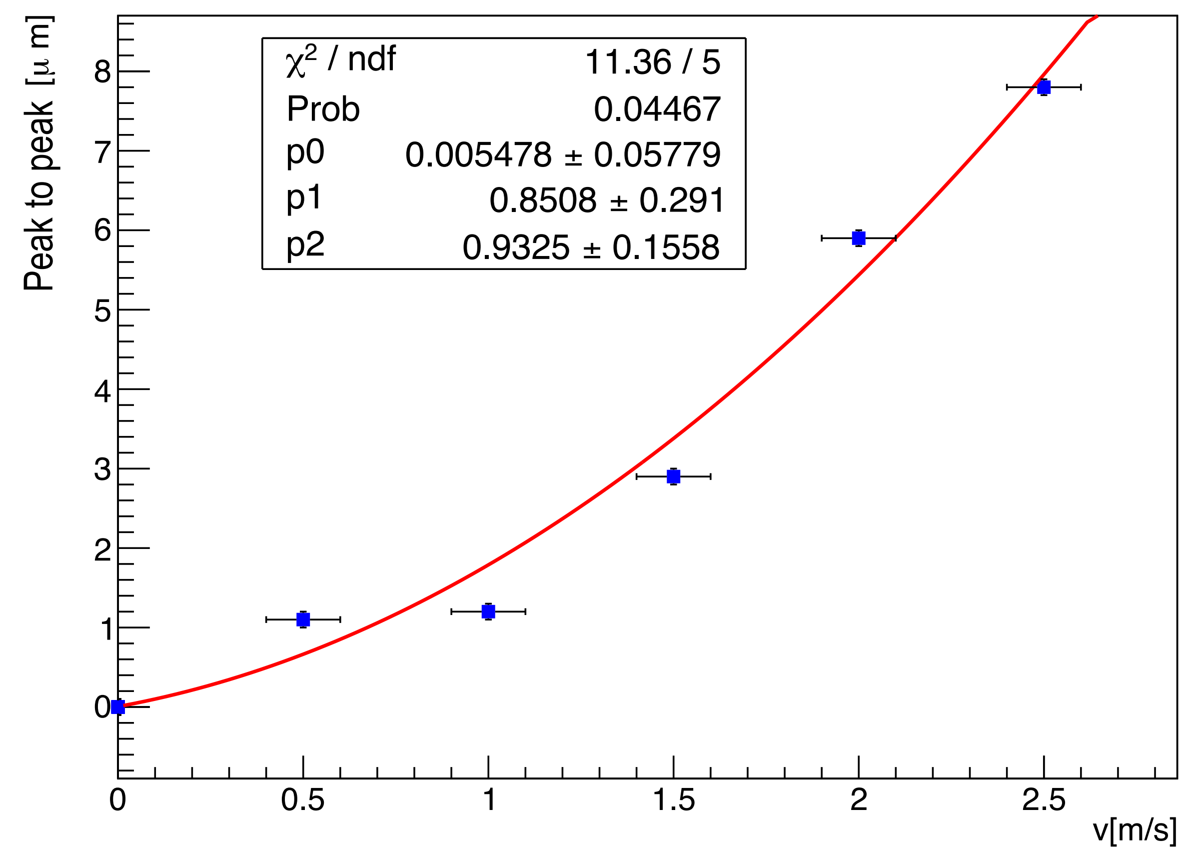
MCC region is cooled 18°C below T_{Room}

In this region the effect of the MCC is quite less pronounced 5-10 °C below

Amplitude vs v_{air}



Clamped-Free

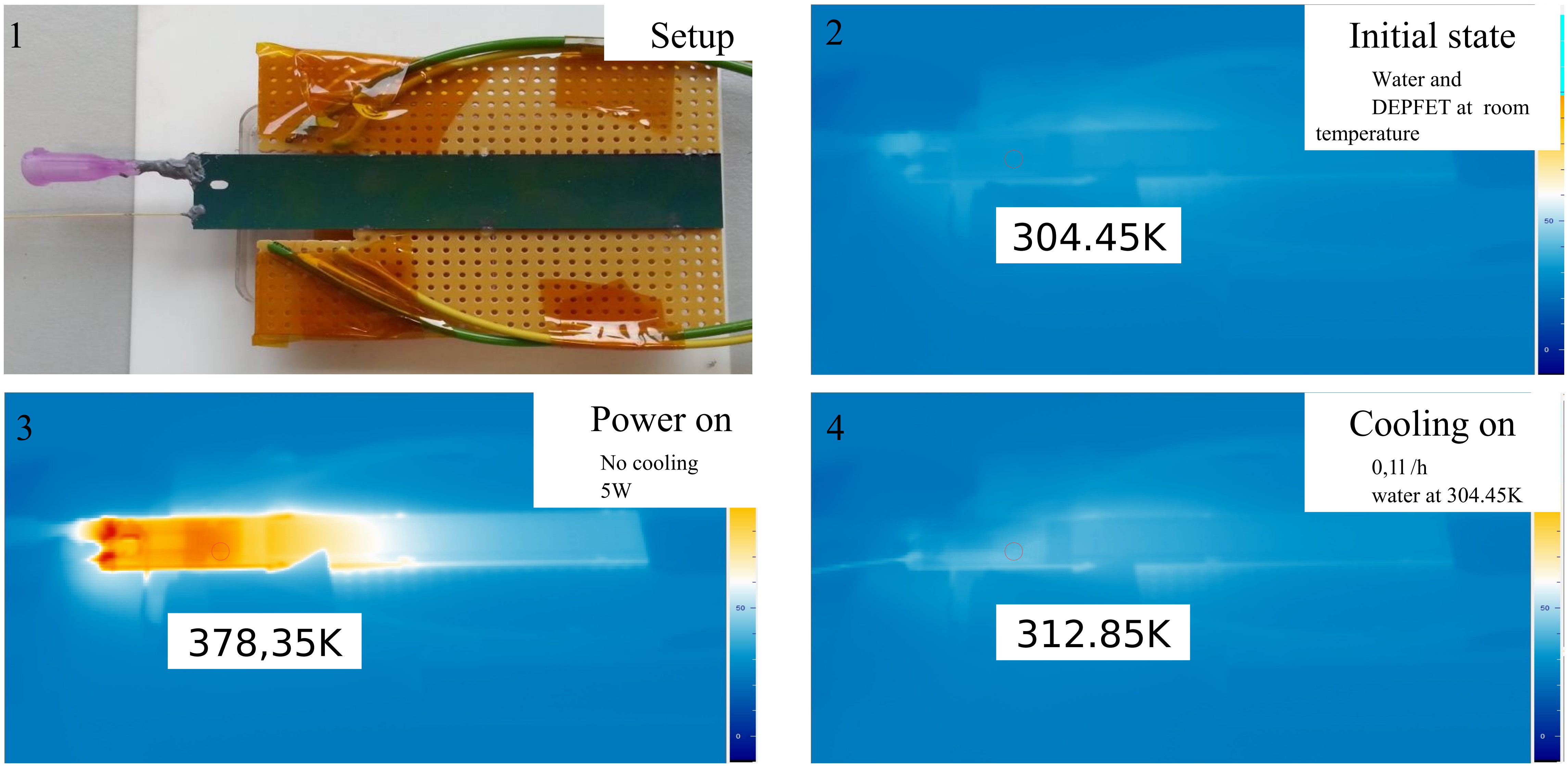


Clamped-Clamped

- *Peak-to-peak amplitude is the change between peak (highest amplitude value) and trough (lowest amplitude value)*
- RMS ≃ (PeaktoPeak/2) * 0.707 (approximation)
- For **v= 2.5 m/s** the amplitude of vibration is:
  - **~19 μm for clamped-free configuration**
  - **~2.8 μm for clamped-clamped configuration**

Micro-channel Cooling

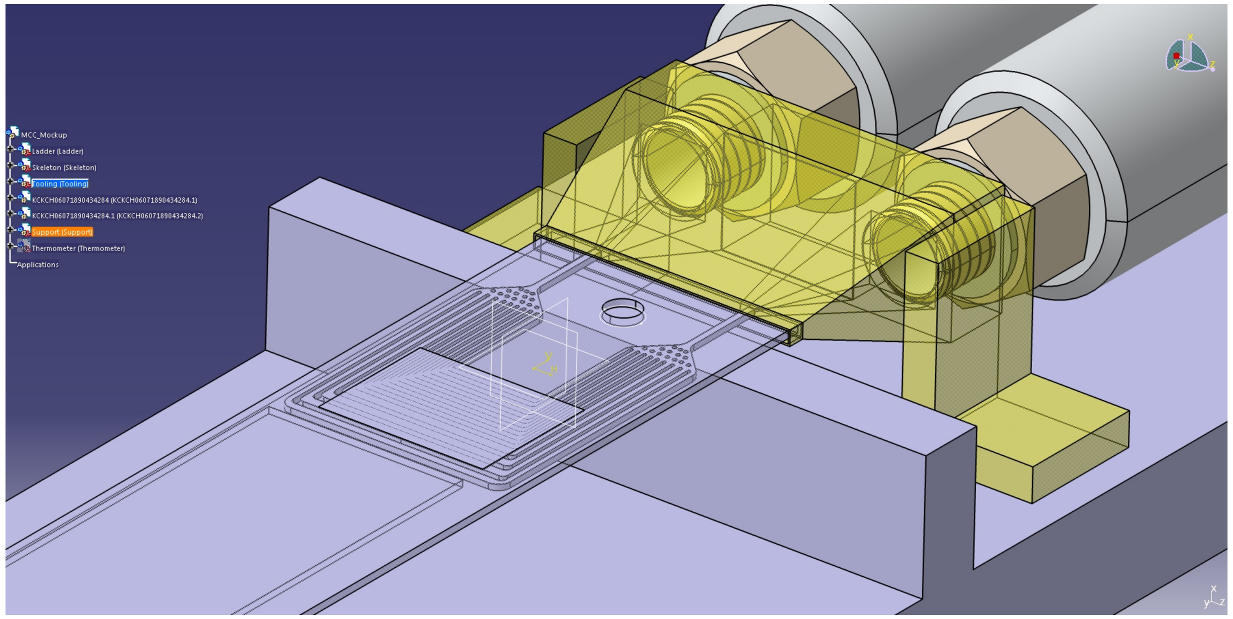
Tests made: 5W and water cooling

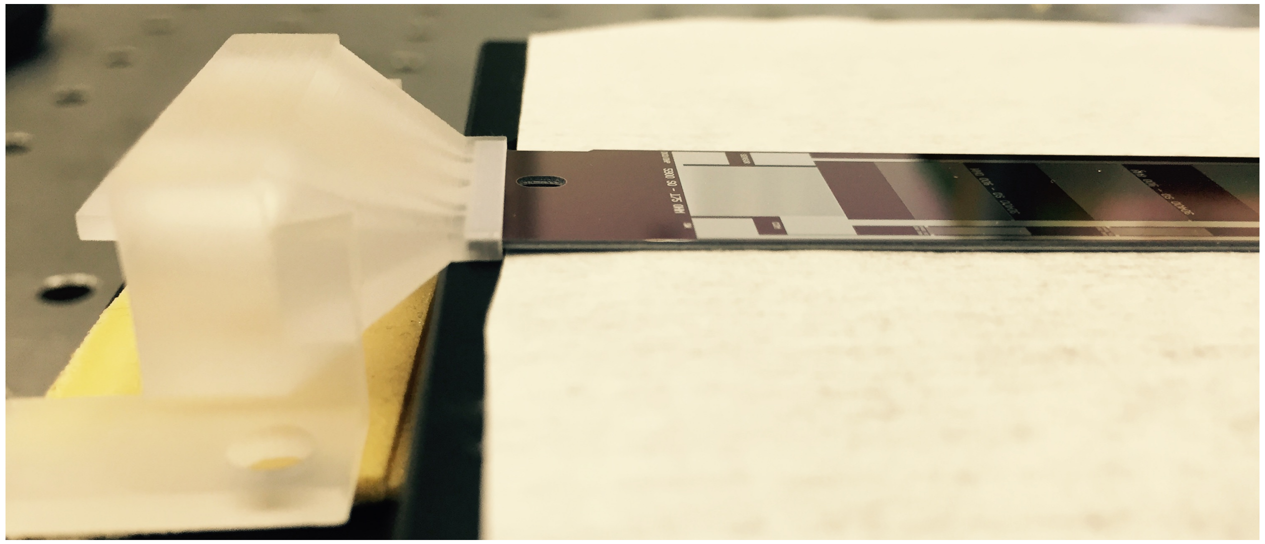


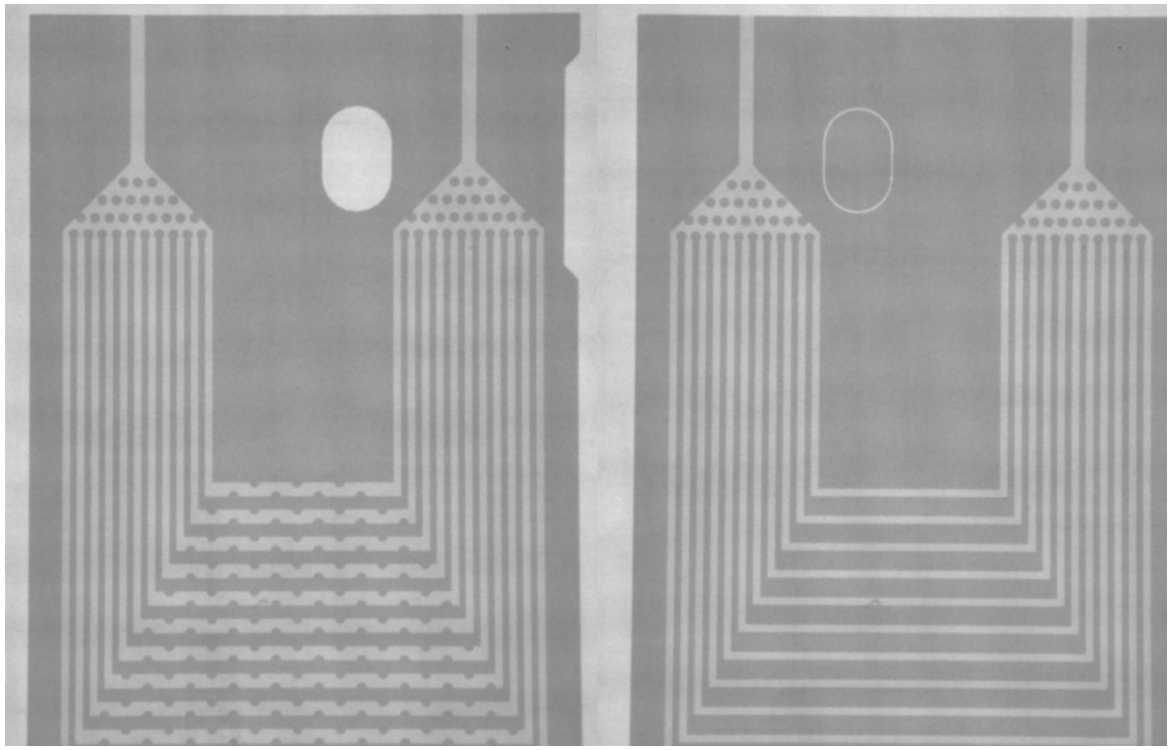
As shown first measurements, MCC with a flow of 0.1 l/h offers promising results

LCWS 2014 Belgrade: https://agenda.linearcollider.org/event/6389/session/4/contribution/172/material/slides/0.pdf

Micro-channel setup 2.0







X-ray images

New 3D printed piece
(with a precision of 15µm) to adapt the *swagelok* standard connexion to the micro-channel inlet/outlet

Different Micro-channels geometries
test: velocity of the fluid, cooling…

For the development of the new setup we have AIDA2020 funding