R&D on CO_2 Cooling using a Silicon Microchannel Substrate for the LHCb VELO Upgrade

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The VELO Upgrade

The new Vertex Locator (VELO) detector (Figure 1) will replace the silicon micro-strip detector currently operating around the interaction point in the LHCb Experiment. It will use hybrid pixel detectors composed of silicon sensors bump-bonded to new VeloPix CMOS readout chips designed for the new 40MHz readout rate of the LHCb Upgrade.

Each VELO module will have 4 sensors, each one being readout by 3 VeloPix ASICs, mounted in a mechanical frame capable of moving the sensors away from the beams when LHC is not in stable colliding beam mode.

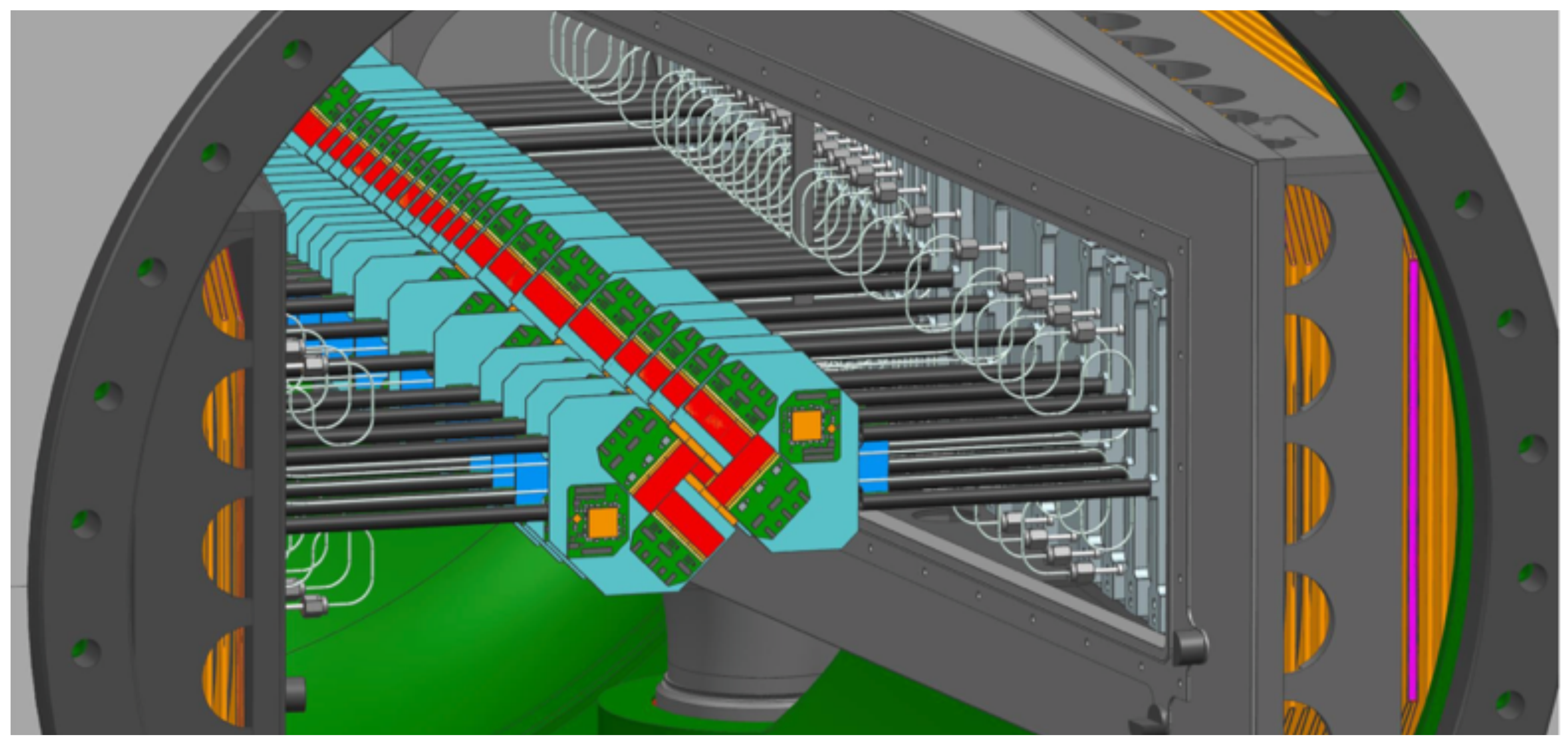


Figure 1: The VELO Upgrade. Each module has four sensors (in red) on a microchannel cooling silicon substrate (blue).

VELO Upgrade Cooling

The VELO Upgrade will use a cooling technique similar to the current VELO: circulating dual-phase CO_2. The cooling is essential to guarantee the operation of the VELO in vacuum and avoid thermal runaway. The requirements for the cooling are:

- Achieve a temperature of -20°C at the tip of the sensors.
- Operate under the secondary vacuum of the VELO.
- Maximum power dissipation (end of life) of 30W per module.
- Minimize amount of material: substrate will be retracted by 5mm on the innermost sensors.

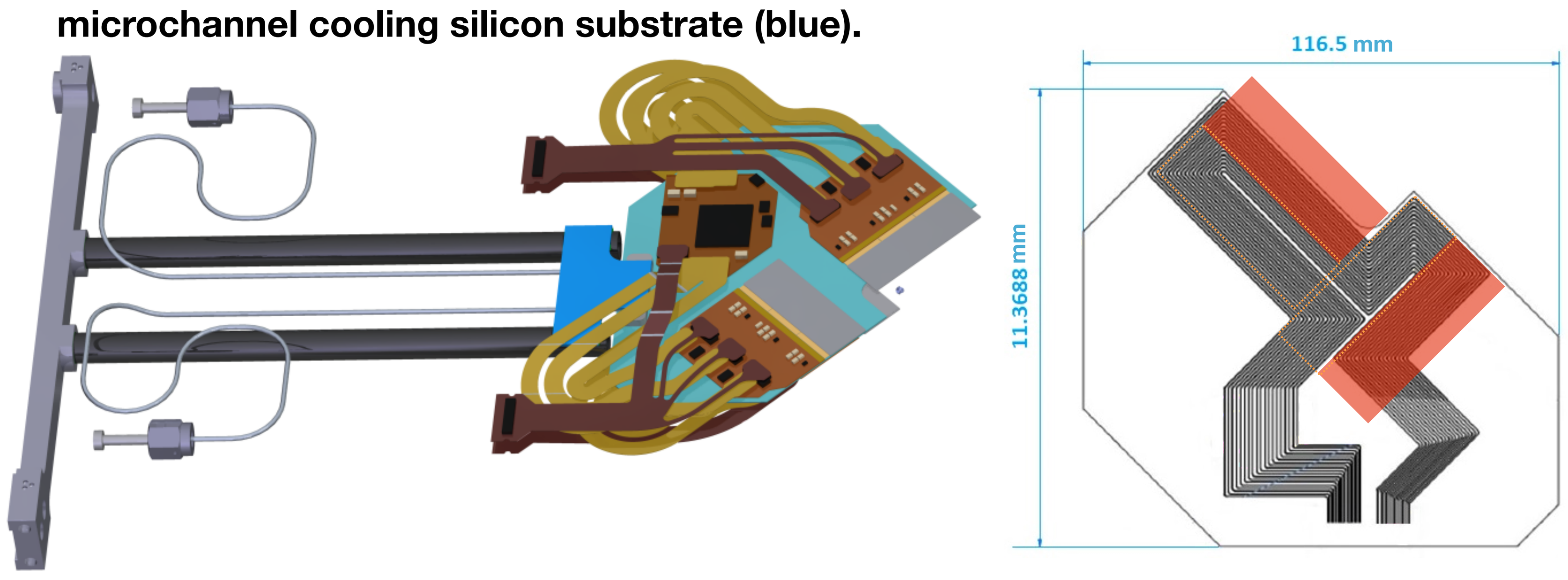


Figure 2: The VELO Upgrade Module. The design including all of the electronic element (left). On the right the microchannel design marked with the sensor positions (red).

Microchannel Cooling

In order to achieve the desired goals, the VELO Upgrade has opted to implement a silicon microchannel technology. Using silicon as substrate has the added benefit of matching the thermal expansion of sensor and readout ASICs. This cooling scheme will involve channels that are 120µm x 200µm going through the silicon under the electronic elements that produce heat in the module (Figure 2).

The microchannels are produced by etching channels on the surface of a silicon wafer which is then bonded to a second "cover" wafer, adding to a total substrate thickness of 500µm. The first 40mm in length of the channels have a 60µm x 60µm size which then changes to the nominal size, triggering the CO_2 boiling, preventing instabilities and ensuring even flow.

High Pressure and Reliability Tests

Extensive tests were performed to determine the pressure resistance of microchannels to rupture. At room temperature the CO_2 saturation pressure is 65 bar, and for safety reasons high pressure tests were performed by using silicon microchannels of varying width bonded to a 2mm thick glass layer (Figure 3). The microchannels were tested by use of a high pressured water pump (Figure 3), nominal LHCb samples did not fail up to 700 bar (pump limited).

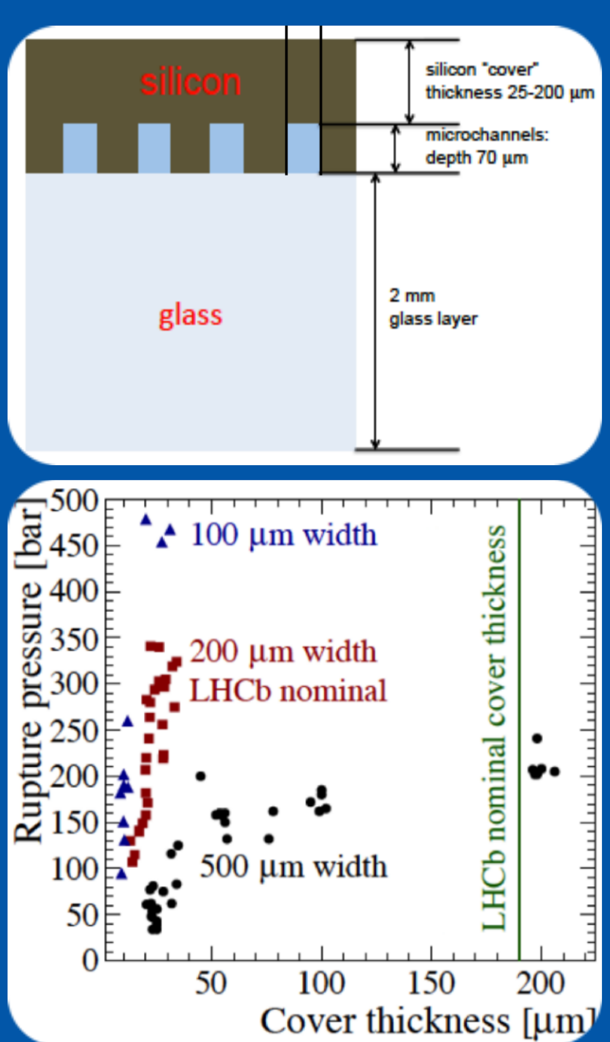


Figure 3: Scheme of samples for rupture test (top) and results of observed ruptures (bottom). No ruptures were observed in nominal LHCb samples.

Creep is defined as the plastic deformation of a material at very low mechanical stress, and usually happens over very long times (years). Samples were tested at 120°C under 60 bar CO_2 pressure, which speeds up the creep effect by a factor of ~10^4 (1h equivalent of 1 year).

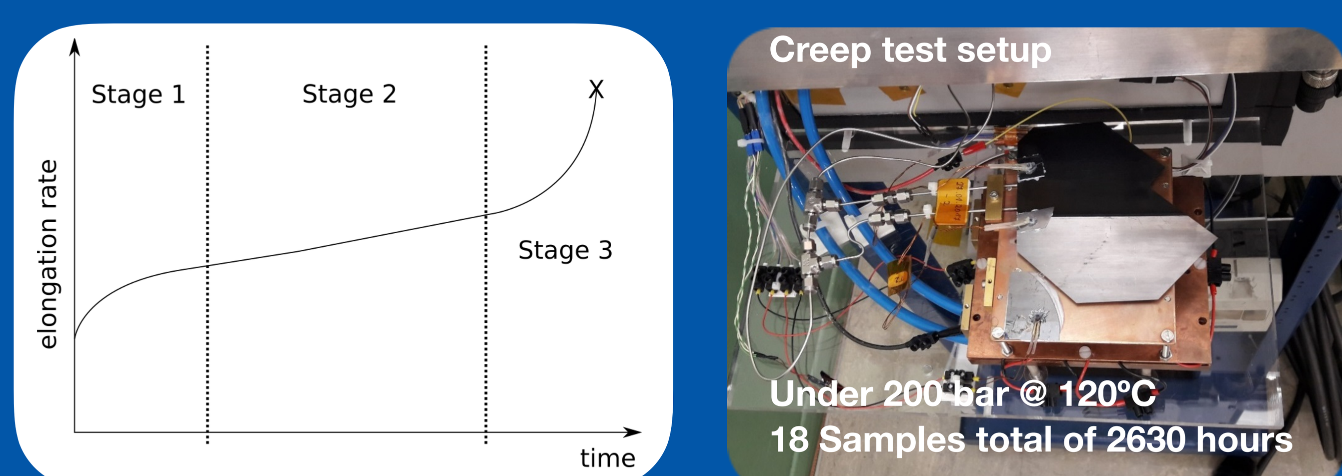


Figure 4: Plastic deformation due to low mechanical stress (creep) and the setup used to test both creep effect and fatigue.

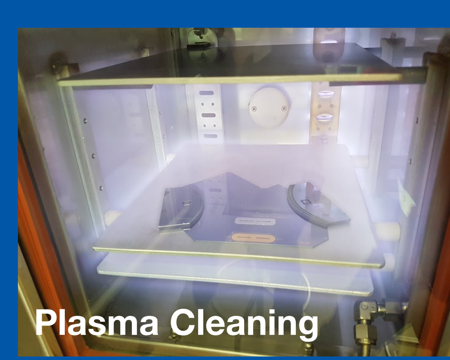
The solder joint was also probed for fatigue, which is the onset of mechanical damage due to repeated temperature cycles. Nine small soldered samples have been temperature (-40°C to 60°C) and pressure (1bar up to 200bar) cycled. During each temperature cycle 6 pressure cycles were performed. **In a total of 5232 cycles no failure was observed.**

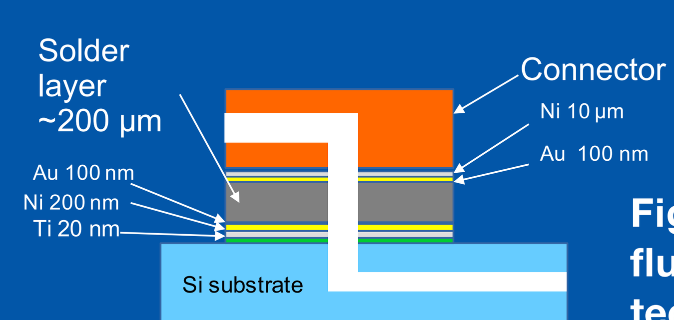
Fluidic Connector Attachement

The fluidic connector needs to be soldered to the silicon substrate inlets and outlets:

- Leak tight and resist to a pressure of up to 186 bar.
- High level of planarity.
- No voids in the solder layer, while using no flux.

Great care is taken in removing contamination from all surfaces that would stop the flow of solder. A vacuum setup was built to perform the soldering procedure to the required precision of alignment between connector and substrate. The obtained substrate connections have been tested up to 186 bar and are aligned with a precision of ~40µm.





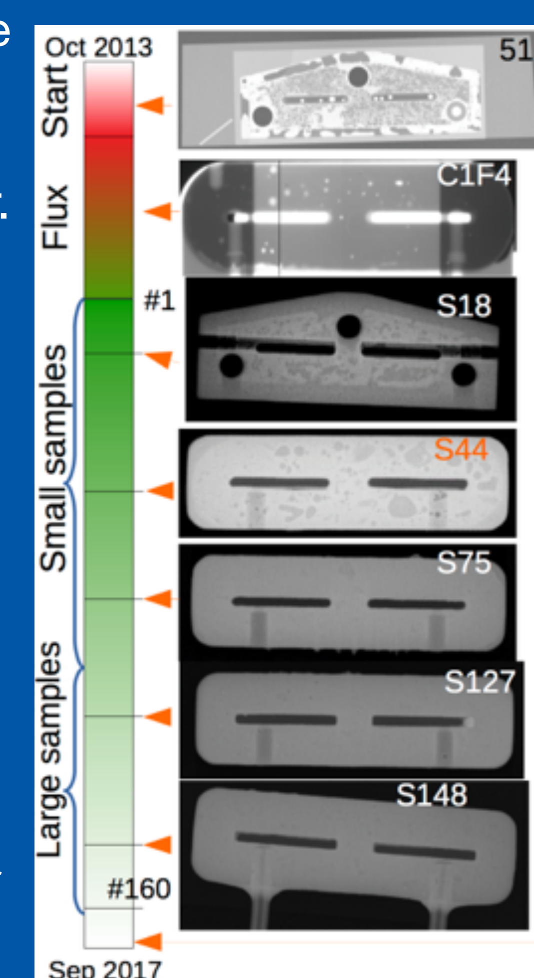


Figure 5: Evolution of the fluidic connector soldering technique.

Cooling Performance

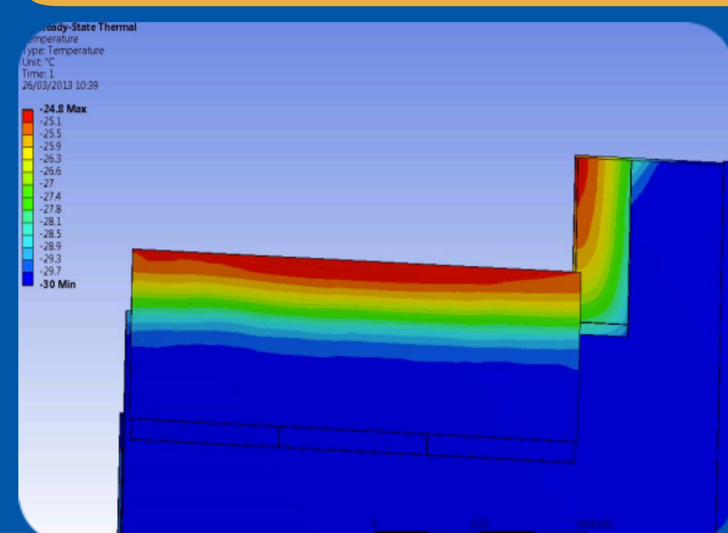
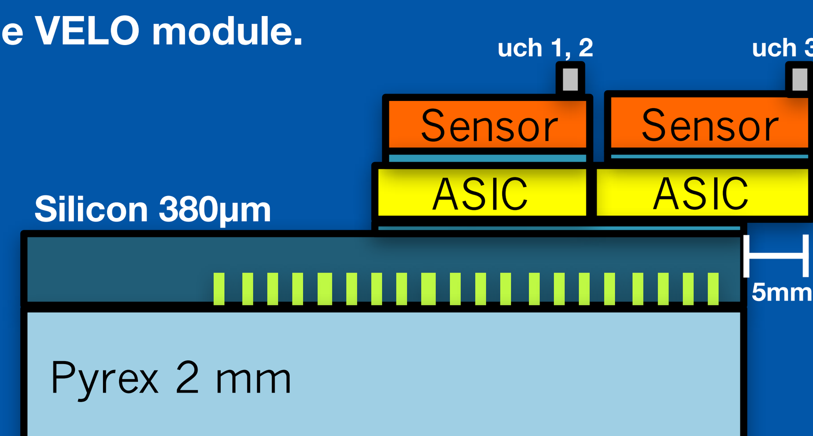
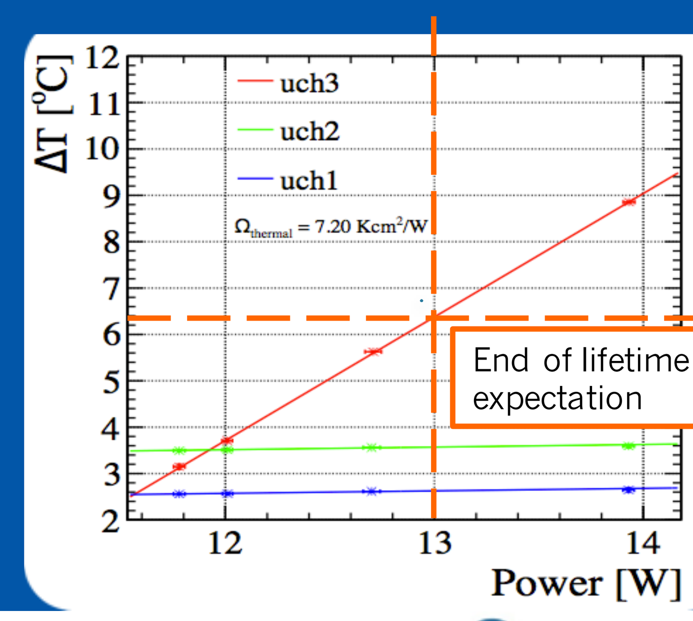


Figure 6: Thermal simulation of the VELO module.

An ANSYS thermal simulation was performed and a ΔT of 5°C was found between the tip of the sensor on the overhang and the substrate.

Tests were performed with pyrex microchannel samples in which heaters that mimic the power distribution of ASICs and sensors were glued.





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