VELO module prototype 2

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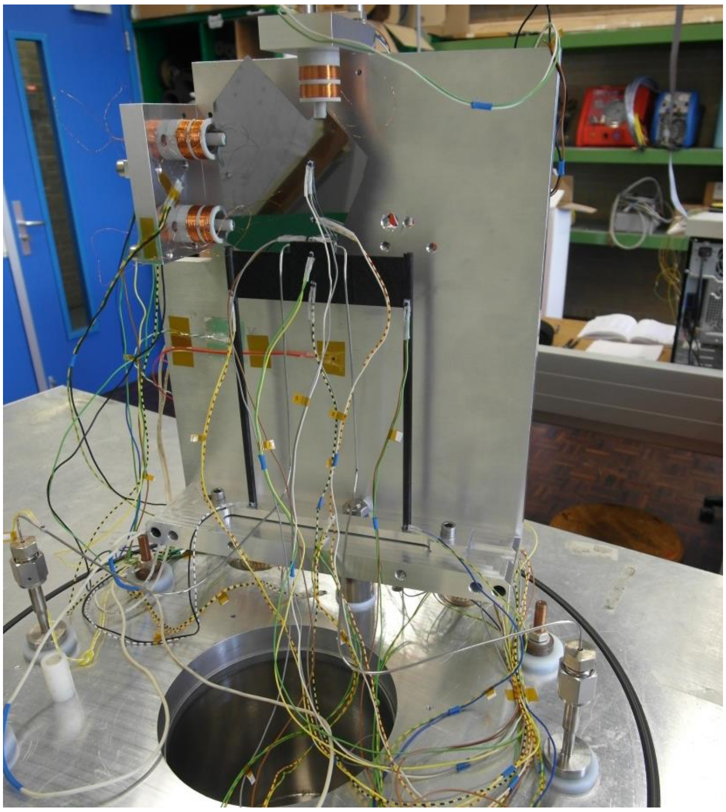

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1. Specifications VELO module prototype 2

The cooling block is soldered on the silicon for a better adhesion. In addition, a better adhesion increases the heat transfer compared to the module with the glue layer between the cooling block and the silicon.

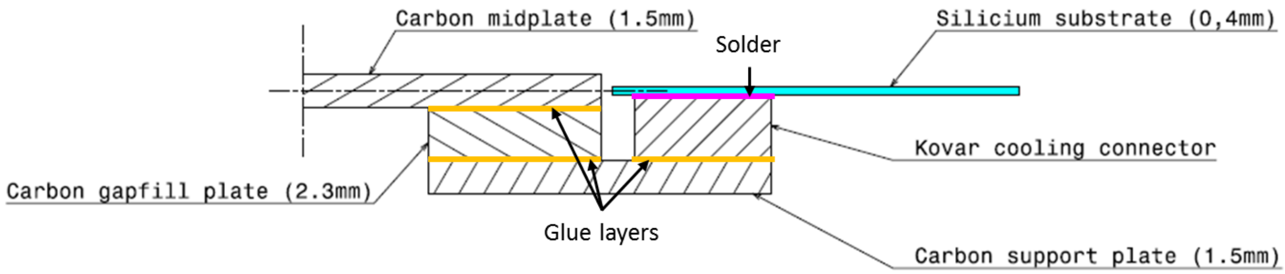


Figure 1: Section of VELO module II connection between the silicon and the carbon hurdle

In the cooling block a hole is drilled in which the two cooling capillaries are vacuum brazed. In the previous module, the capillaries were soldered in an angle, this time this instruction was forgotten and thus the capillaries were parallel to the cooling block surface.

The cooling block was soldered to the silicon in this configuration, causing them to touch the carbon hurdle. When bending the capillaries in the correct position too much stress was added to the silicon which caused a crack in the silicon.

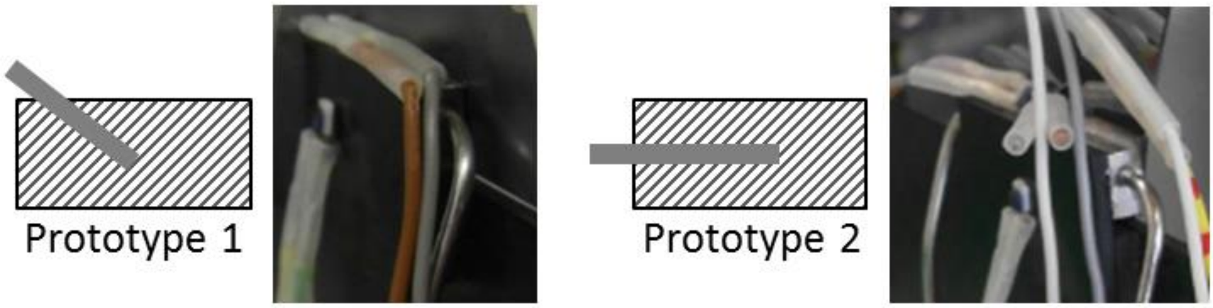
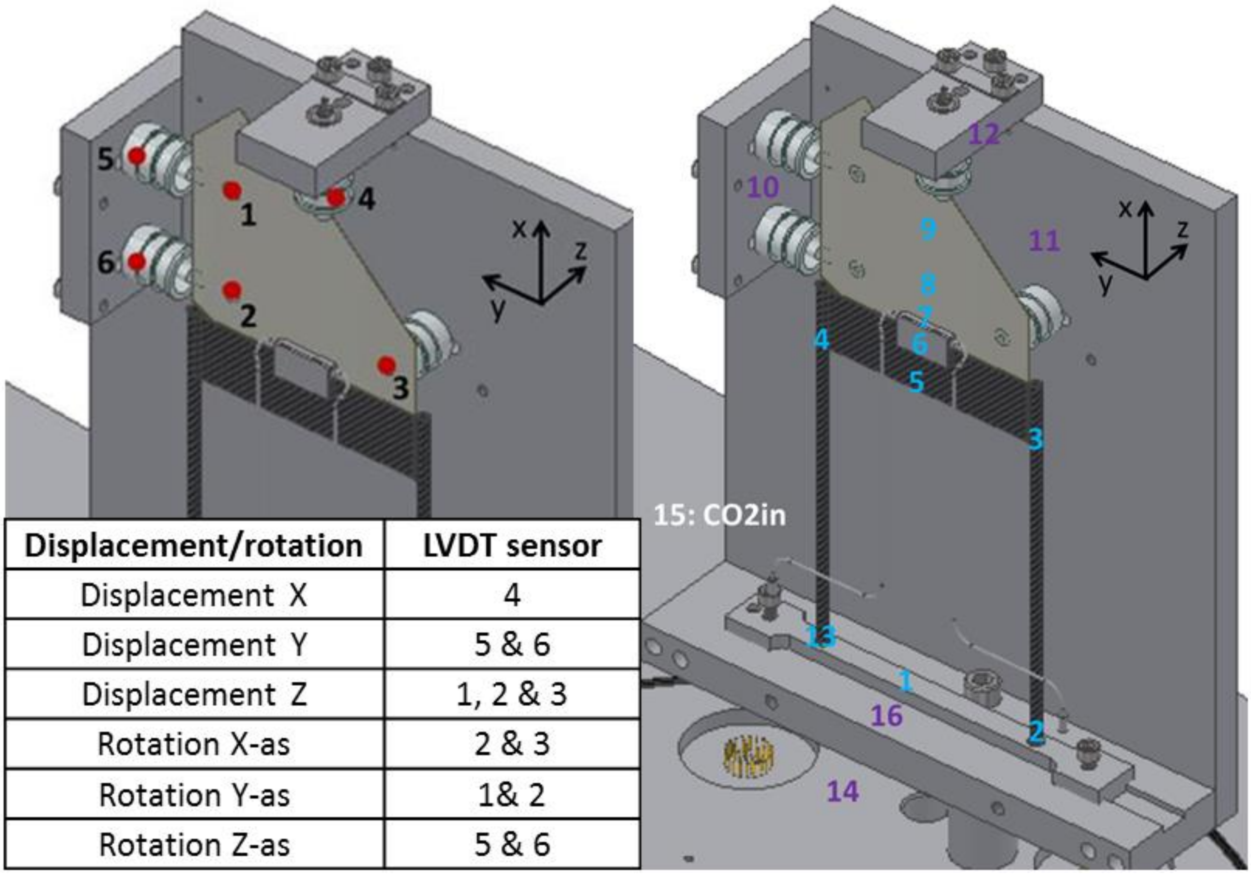


Figure 2: Capillaries in cooling block of VELO module prototype 1 and 2

Because the silicon lost a 'small' corner after handling the capillaries after bonding the silicon to the carbon hurdle, LVDT 3 cannot be used for the measurements.

2. Measuring set up

For these measurements, the same frame and LVDT sensors are used as the in the previous measurements with VELO module prototype 1. Figure 3 gives a view of the location of LVDT and temperature sensors.



Displacement/rotation	LVDT sensor
Displacement X	4
Displacement Y	5 & 6
Displacement Z	1, 2 & 3
Rotation X-as	2 & 3
Rotation Y-as	1& 2
Rotation Z-as	5 & 6

Figure 3: Location of the LVDT and temperature sensors

The coloured wires of the LVDT sensors are not connected exactly in the same way as before, therefore some pins are exchanged in the connector at the vacuum side.

Because it is difficult to test if the wires of LVDT 4 are connected properly, the system was started up by pumping down and turning the heater control on. The results show that LVDT 4 was connected in the wrong way, therefore the sign of calculation factor was changed in the Labview program.

The first results show that temperature T7 is warmer than expected, this is probably due to a thick glue layer between sensor 7 and the silicon. A view of the sensors from a cold temperature to warm is given below:

Module I	15	7	8	9	6	5
Module II	15	8	7	9	6	5

3. Results measurement 1: 22 April 2015

The following measurement is started with a frame temperature of 24 °C (Set Value 47) and under vacuum conditions. First the module is cooled down with liquid CO_2 with a temperature of approximately -24 °C. When the temperature is stable, the CO_2 is heated up in the following steps: -21, -18, -15, -11, -5, 1, and 7 °C. When the CO_2 flow through the module is stopped, the module heats up to almost 24 °C.

A summary of the settings of the cooling system follows:

- Temperature primary cooling = -50 °C
- Temperature Accumulator= 15 °C
- Cooling temperature CO2 = -24 °C
- Mass flow system = 5 g/s
- Mass flow module ≈ 2g/s
- Heater control: 24 °C

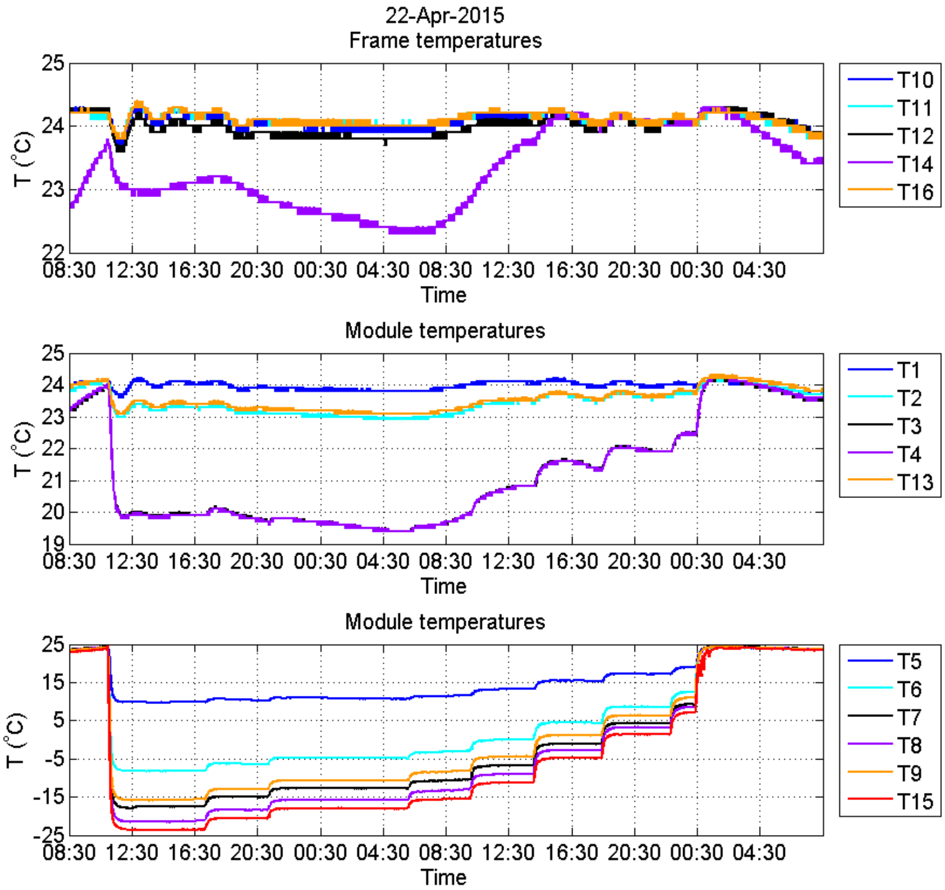


Figure 4: Temperature curve for cooling down and heating up the VELO module II

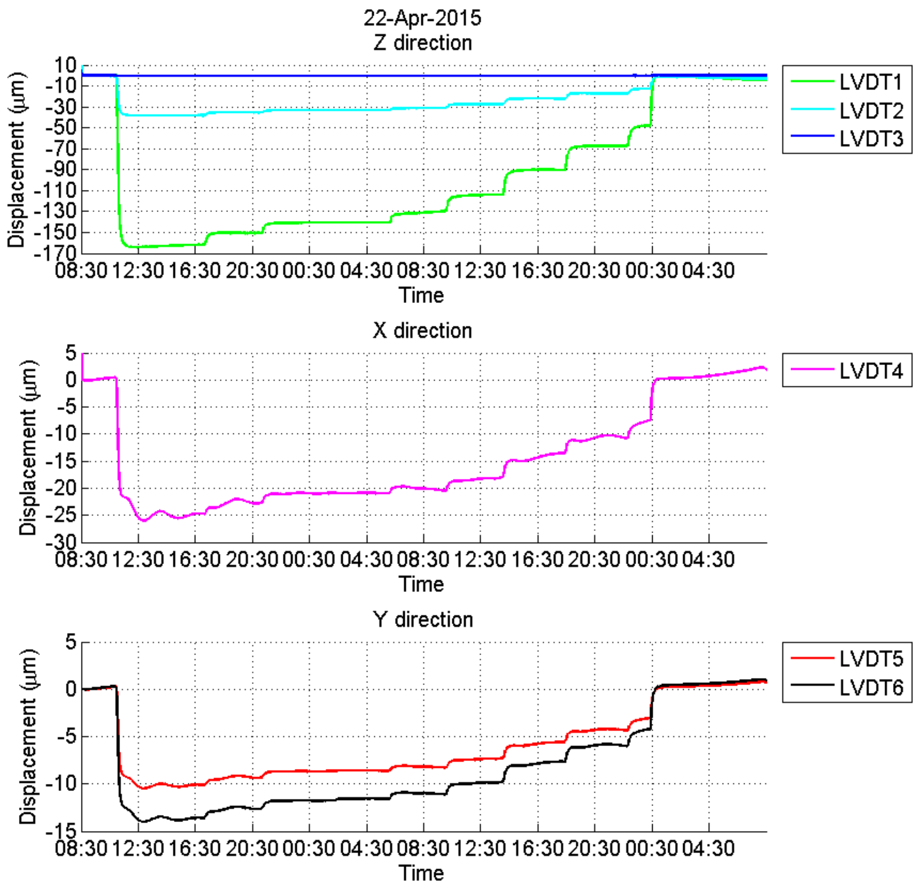


Figure 5: LVDT signal for cooling down and heating up the VELO module II

The displacement for the cooling down from 24 °C down to -24 °C per LVDT sensor is shown in the following table.

Table 1: Displacement for cool down from 24 °C down to -24 °C

Sensor	Displacement (µm)
LVDT 1	-162.1
LVDT 2	-38.2
LVDT 3	N/A
LVDT 4	-24.7
LVDT 5	-10.1
LVDT 6	-13.6

The displacement for different cooling temperatures is given in Figure 6. For each of the measuring points for each LVDT sensor a slope is calculated. With these slopes it is possible to extrapolate the displacement for a cooling temperature of -35 °C.

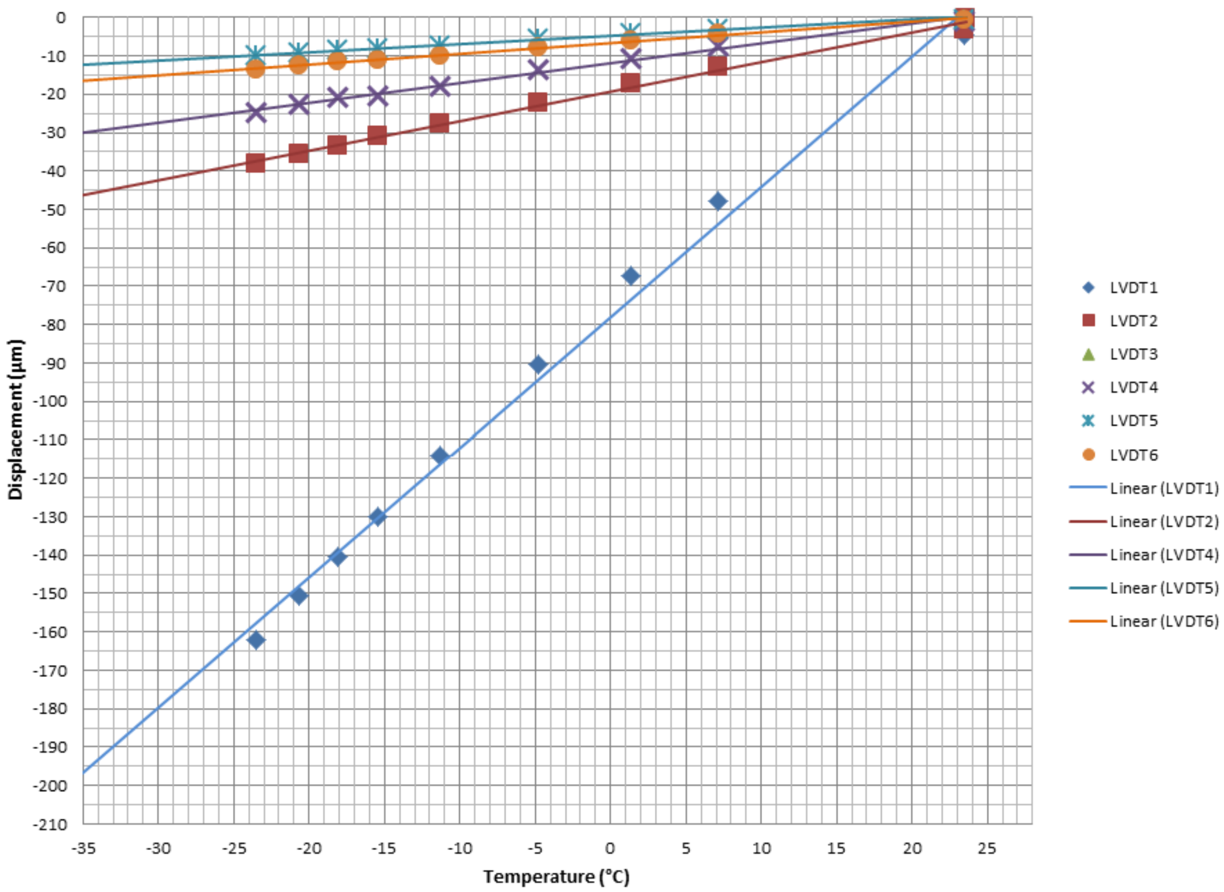


Figure 6: Displacement versus temperature for VELO module II

The extrapolated displacements for a temperature of -35 °C are given in the following table.

Table 2: Extrapolation of the displacement for cooling down to -35 °C

Sensor	Displacement (µm)
LVDT 1	-195
LVDT 2	-46
LVDT 3	N/A
LVDT 4	-30
LVDT 5	-12
LVDT 6	-16

To see if it is possible to reduce the time needed to perform a measurement, the linearity of the cool down from 24 °C down to -24 °C is determined. In order to do this, data points with a resolution of a minute are plotted and the slope is calculated.

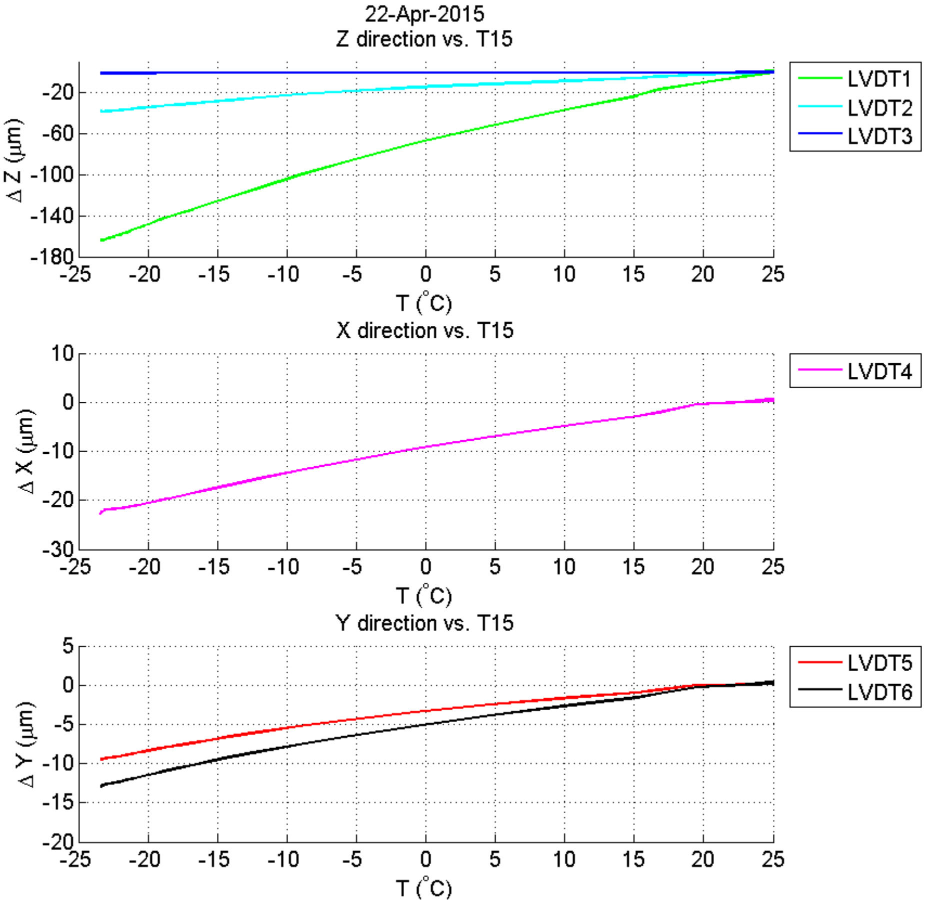


Figure 7: Displacement versus temperature sensor T15

Figure 7 shows that the displacement versus temperature is linear. The slopes of the measurement in steps and the cooling down from 24 °C down to -24 °C are given in Table 3. The values in this table show that the results of the cooling down give a good indication of the slope in μm/°C and thus these results can also be used for the extrapolation down to -35 °C.

Table 3: Slopes displacement versus temperature T15

LVDT	T15 (Figure 7)	T15 (Figure 6)
1	3.60	3.39
2	0.84	0.77
4	0.50	0.52
5	0.22	0.21
6	0.29	0.28

4. Results measurement 2: 24 April 2015

For this measurement an extra constraint for the capillaries is added to the setup (Figure 8). This constraint can influence the movement of the module, with this measurement it is possible to determine if this influence causes less displacement of the module.

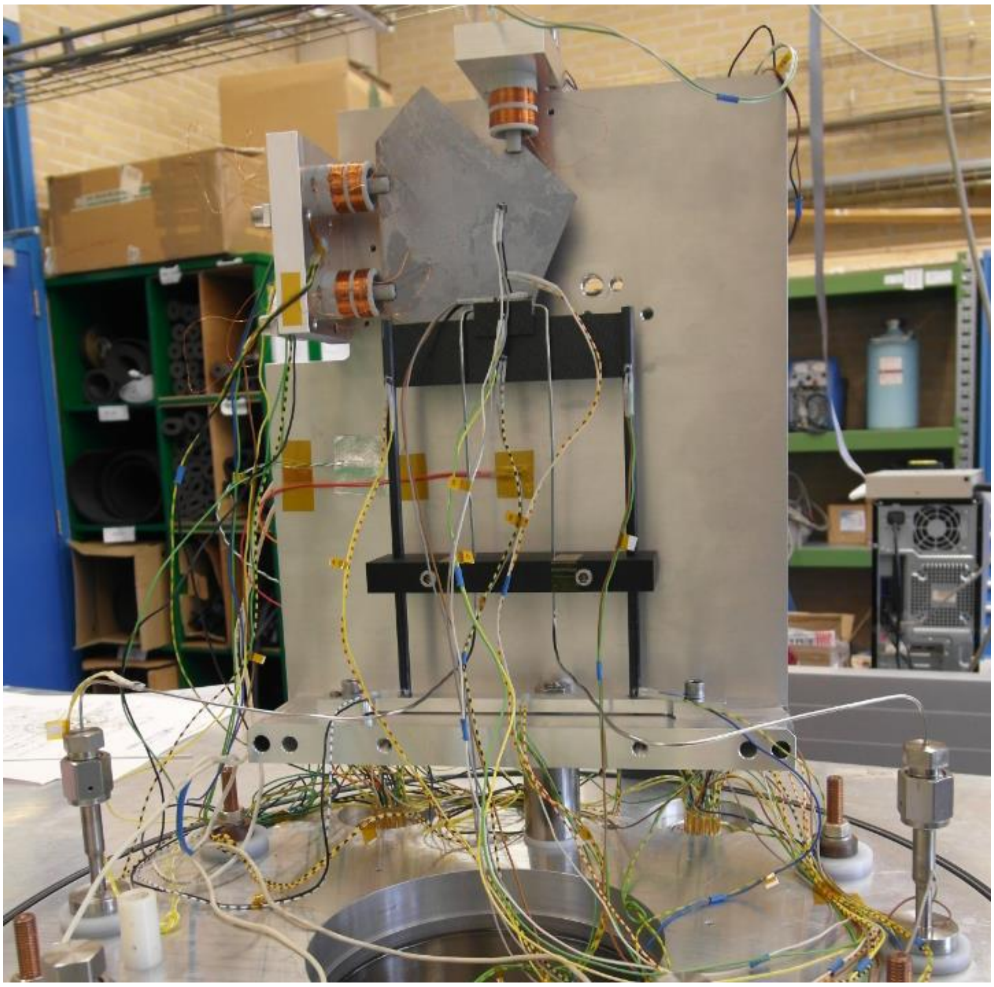


Figure 8: VELO module II with capillary constraint

Because there is not much CO2 left in the cooling system, he accumulator temperature is set to -5 °C. A lower accumulator temperature makes sure that the heater of the accumulator doesn't use much power and thus a low liquid CO2 level in the accumulator doesn't have to be a problem.

During this measurement the pumps cannot reach the mass flow of 5 g/s for the system and thus the mass flow in the module decreases and causes the temperature to rise. The CO2 in the inlet line is liquid and a decreased mass flow causes the liquid CO2 to pick up more heat from the environment and an increase in temperature.

A summary of the settings of the cooling system follows:

- Temperature primary cooling = -50 °C
- Temperature Accumulator= -5 °C
- Cooling temperature CO2 = -24 °C
- Mass flow system = 5 g/s
- Mass flow module ≈ 2g/s
- Heater control: 24 °C

First the module is cooled down with liquid CO_2 with a temperature of approximately -24 °C. When the temperature is stable, the CO_2 is heated up in the following steps: -18, -11 and -1. Next the liquid CO_2 is cooled down again by setting the temperature of the primary cooling back to -50 °C, this gives a CO_2 temperature of -16.4 °C. The expected CO_2 cooling temperature is not reached due to the low performance of the pumps and thus the cooling system is turned off.

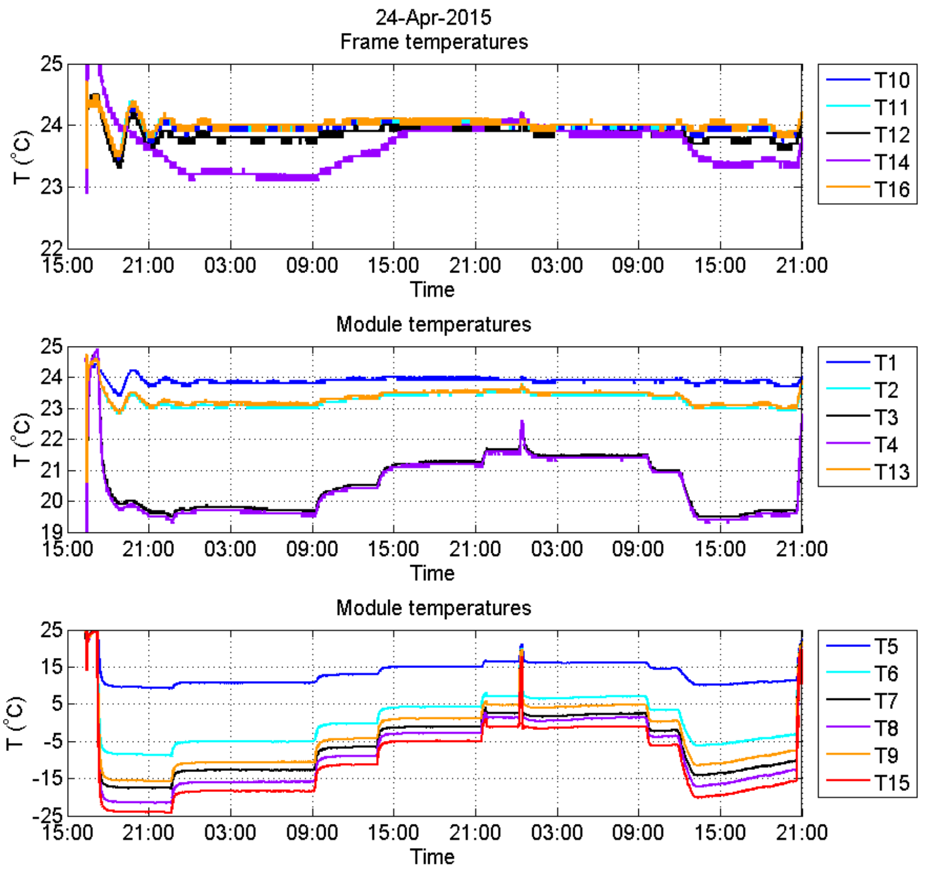


Figure 9: Temperature curve for cooling down and heating up the VELO module II with constraint

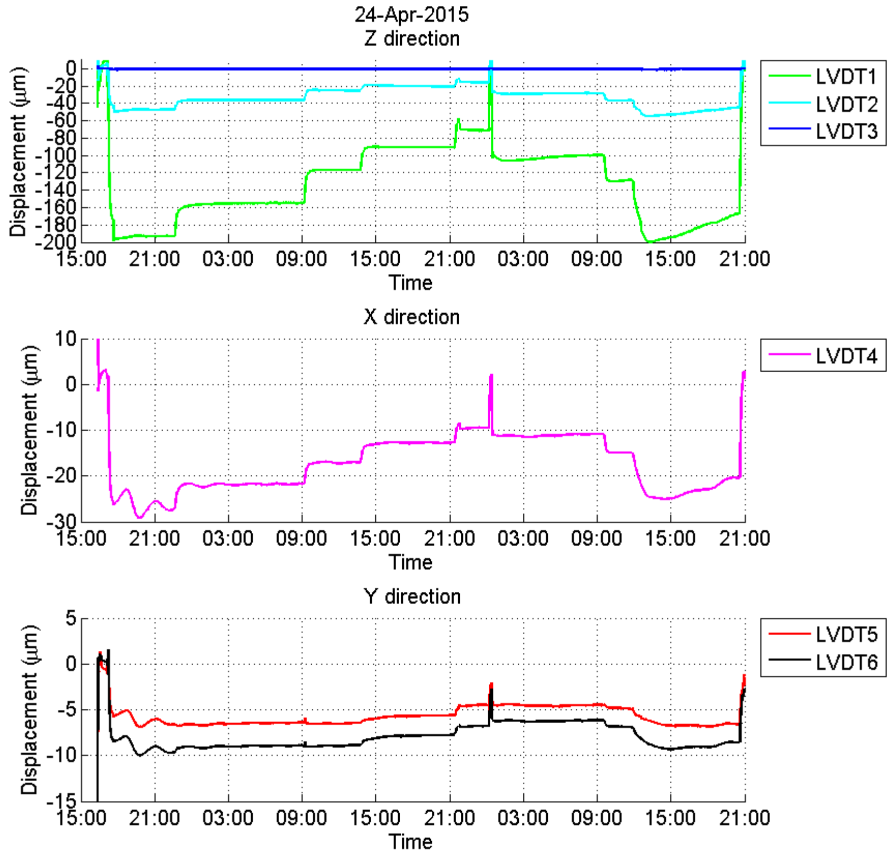


Figure 10: LVDT signal for cooling down and heating up the VELO module II with constraint

The displacement per LVDT signal for a cool down from 24 °C down to -24 °C is shown in Figure 11. This figure shows that the displacement versus temperature is more or less linear.

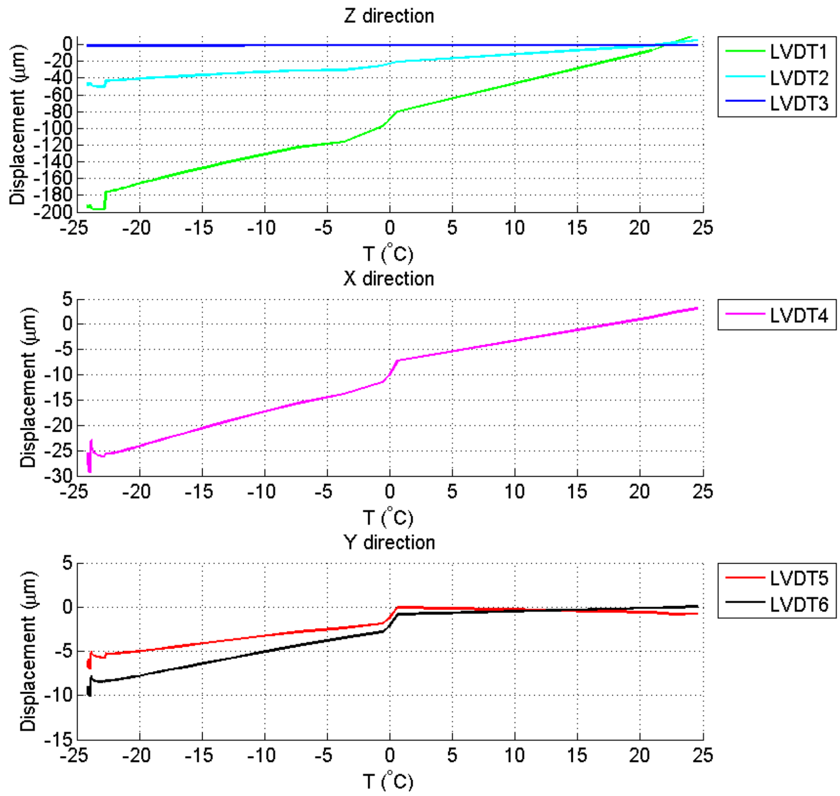


Figure 11: Displacement versus temperature sensor T15 for module II with constraint

The displacement for the cooling down from 24 °C down to -24 °C per LVDT sensor is shown in the following table. The displacement in the Z-direction, at -24 °C, is approximately 30 μm and 10 μm larger for LVDT 1 and LVDT 2,respectively, than for the module without constraint.

Table 4: Displacement for cool down from 24 °C down to -24 °C

Sensor	Displacement (μm)
LVDT 1	-193.2
LVDT 2	-47.2
LVDT 3	N/A
LVDT 4	-27.3
LVDT 5	-6.6
LVDT 6	-9.7

The last two measurements give an extreme value for LVDT 1, thus to make sure that this value is correct, LVDT 1 is calibrated in the test setup with a micrometer. The table below show the results of this calibration.

Table 5: Calibration of LVDT 1 in the test setup

Micrometer (a step is 10 μm)	LVDT 1 (μm)	LVDT 2 (μm)
-1	16.68	8.44
0	24.5	11.1
1	33.6	14.2
2	43.7	17.7
3	53.9	21.3
4	64.6	25.0
5	73.5	28.0
6	82.9	31.2
7	92.6	34.5
8	102.7	37.9
10	122.1	44.5
<-1	19.5	9.2
-1	17.5	9.0
0	25.2	11.5

From the table above can be derived that a step of 10 μm does give an increase of approximately 10 μm in the signal of LVDT 1 and thus that the values of LVDT 1 in the previous measurements are correct.

5. Results measurement 3: 29 April 2015

For this measurement a thin foil is added between the blocks of the constraint for the capillaries. This causes a constraint only in the Y- and Z-direction. The aim of this measurement is to see if this adjustment of the constraint gives a different displacement of the module.

Before starting this measurement, the filters of the cooling system are cleaned and the cooling system is filled with 8 kg CO_2. The mass flow is a little bit better after cleaning the filters, but a system mass flow of 5 g/s is barely reached.

A summary of the settings of the cooling system follows:

- Temperature primary cooling = -50 °C
- Temperature Accumulator= 15 °C
- Cooling temperature CO2 = -23 °C
- Mass flow system = 5 g/s
- Mass flow module ≈ 2g/s
- Heater control: 24 °C

First the module is cooled down with liquid CO_2 with a temperature of approximately -23 °C. When the temperature is stable, the CO_2 is heated up in the following steps: -18, -11, -4 and 2 °C.

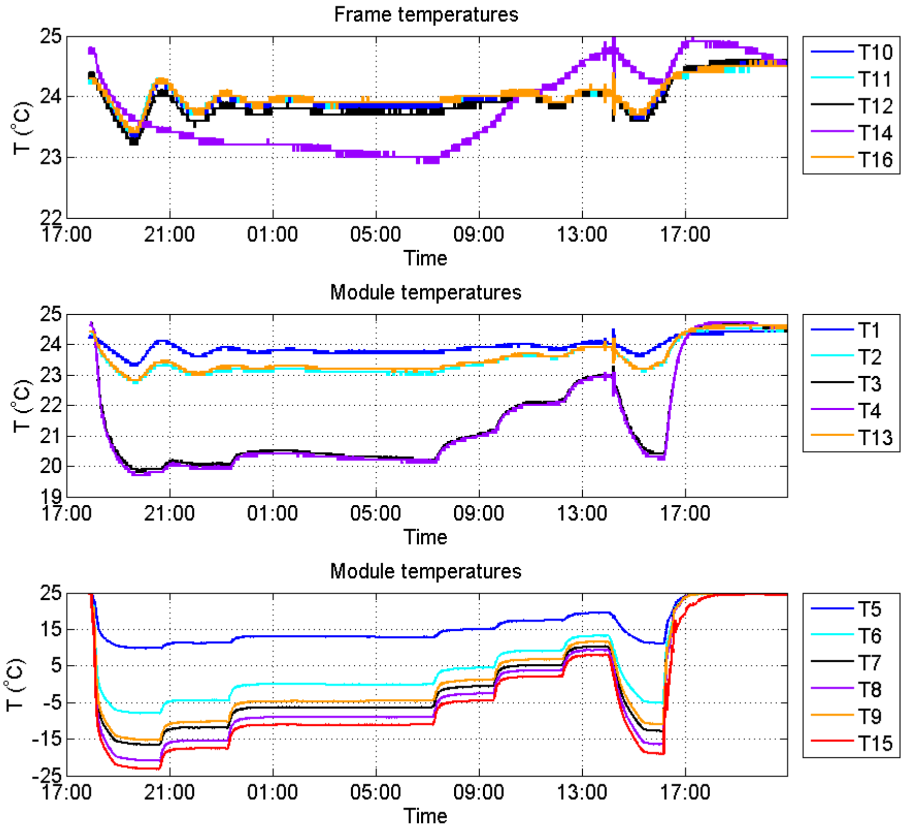


Figure 12: Temperature curve for cooling down and heating up the VELO module II with constraint 2

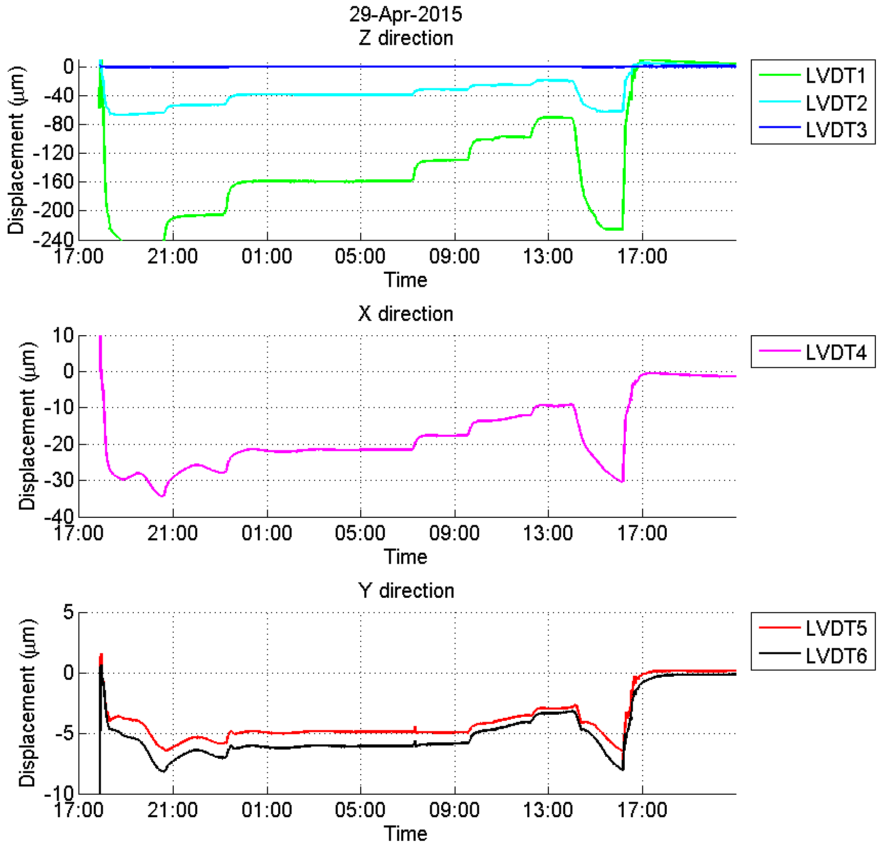


Figure 13: LVDT signal for cooling down and heating up the VELO module II with constraint 2

The displacement per LVDT signal for a cool down from 24 °C down to -23 °C is shown below.

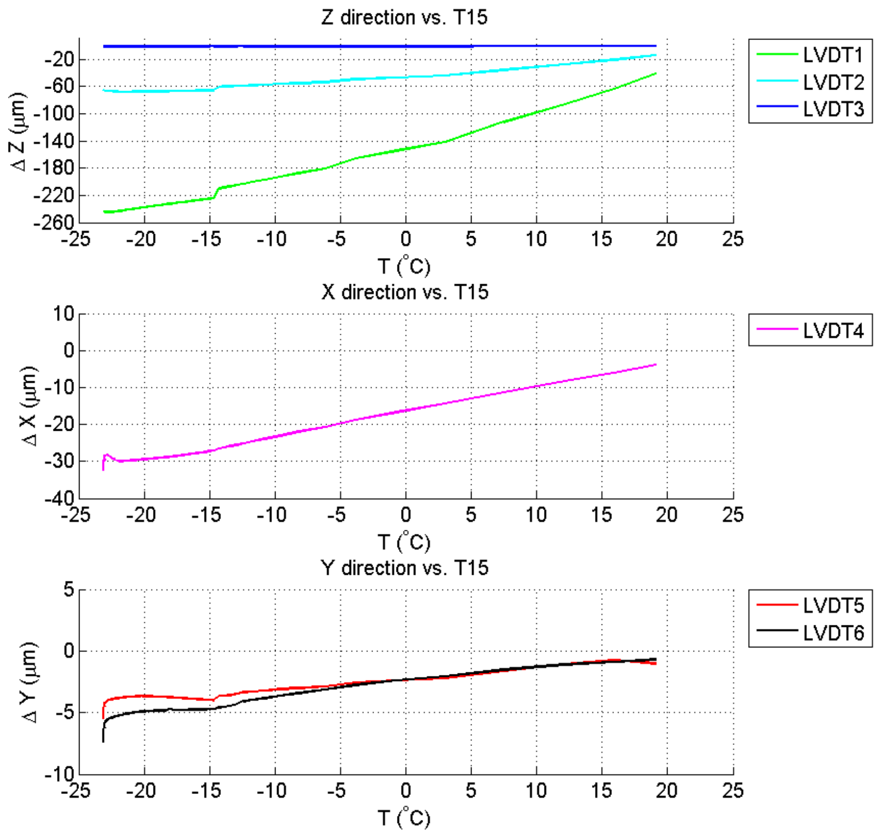


Figure 14: Displacement versus temperature sensor T15 for module II with constraint 2

The displacement for the cooling down from 24 °C down to -23 °C per LVDT sensor is shown in the following table. The displacement in the Z-direction, at -23 °C, is approximately 80 μm and 20 μm larger for LVDT 1 and LVDT 2,respectively, than for the module without constraint.

Table 6: Displacement for cool down from 24 °C down to -23 °C

Sensor	Displacement (μm)
LVDT 1	-242.7
LVDT 2	-64.4
LVDT 3	N/A
LVDT 4	-34.3
LVDT 5	-6.2
LVDT 6	-8.1

6. Results measurement 4: 04 May 2015

The last three measurements give extreme values for LVDT 1, thus to make sure that this value is correct, LVDT 1 is calibrated in the test setup with a micrometer. The table below show the results of this calibration.

Table 7: Calibration of LVDT 1 in the test setup

Micrometer (a step is 10 (μm)	LVDT 1 (μm)	LVDT 2 (μm)
-1	16.68	8.44
0	24.5	11.1
1	33.6	14.2
2	43.7	17.7
3	53.9	21.3
4	64.6	25.0
5	73.5	28.0
6	82.9	31.2
7	92.6	34.5
8	102.7	37.9
10	122.1	44.5
<-1	19.5	9.2
-1	17.5	9.0
0	25.2	11.5

From the table above can be derived that a step of 10 μm does give an increase of approximately 10 μm in the signal of LVDT 1 and thus that the values of LVDT 1 in the previous measurements are correct.

The aim of this measurement is to determine the repeatability of the measurements and to see that there is no significant change in the mechanical properties of the module due to the constraint used in the previous measurements.

A summary of the settings of the cooling system follows:

- Temperature primary cooling = -50 °C
- Temperature Accumulator= -5 °C
- Cooling temperature CO2 = -22 °C
- Mass flow system = 5 g/s
- Mass flow module ≈ 2g/s
- Heater control: 24 °C

First the module is cooled down with liquid CO_2 with a temperature of approximately -22 °C. When the temperature is stable, the CO_2 is heated up in the following steps: -17, -10 and -3.5 °C. The following figures only show the cool down to -22 °C.

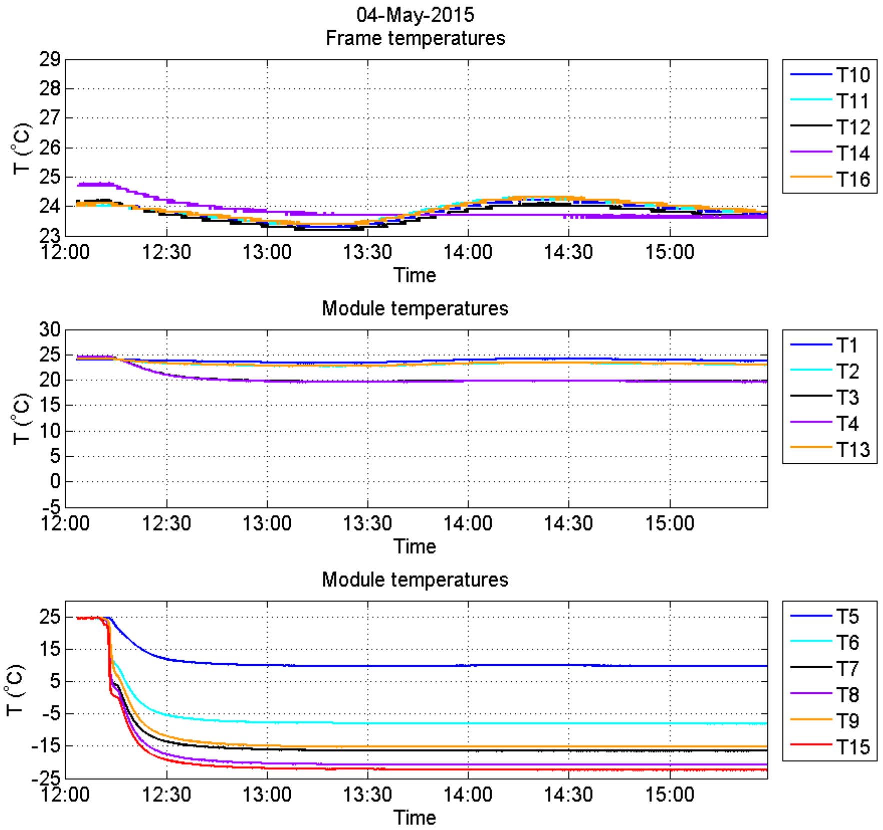


Figure 15: Temperature curve for cooling down of VELO module II

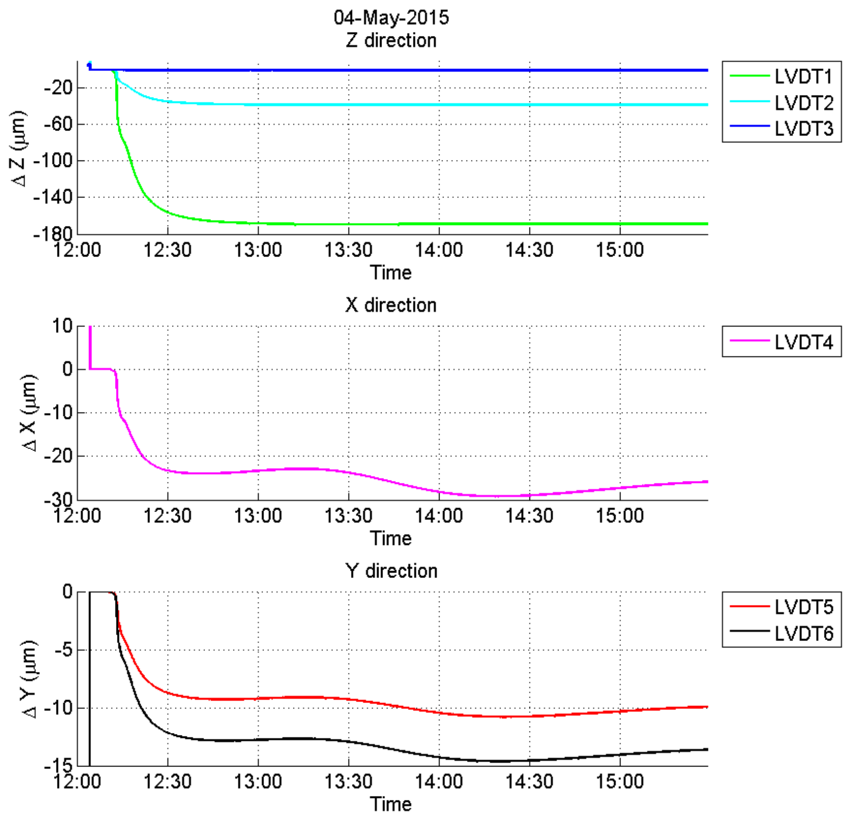


Figure 16: LVDT signal for cooling down of VELO module II

The displacement per LVDT signal for a cool down from 24 °C down to -22 °C is shown below.

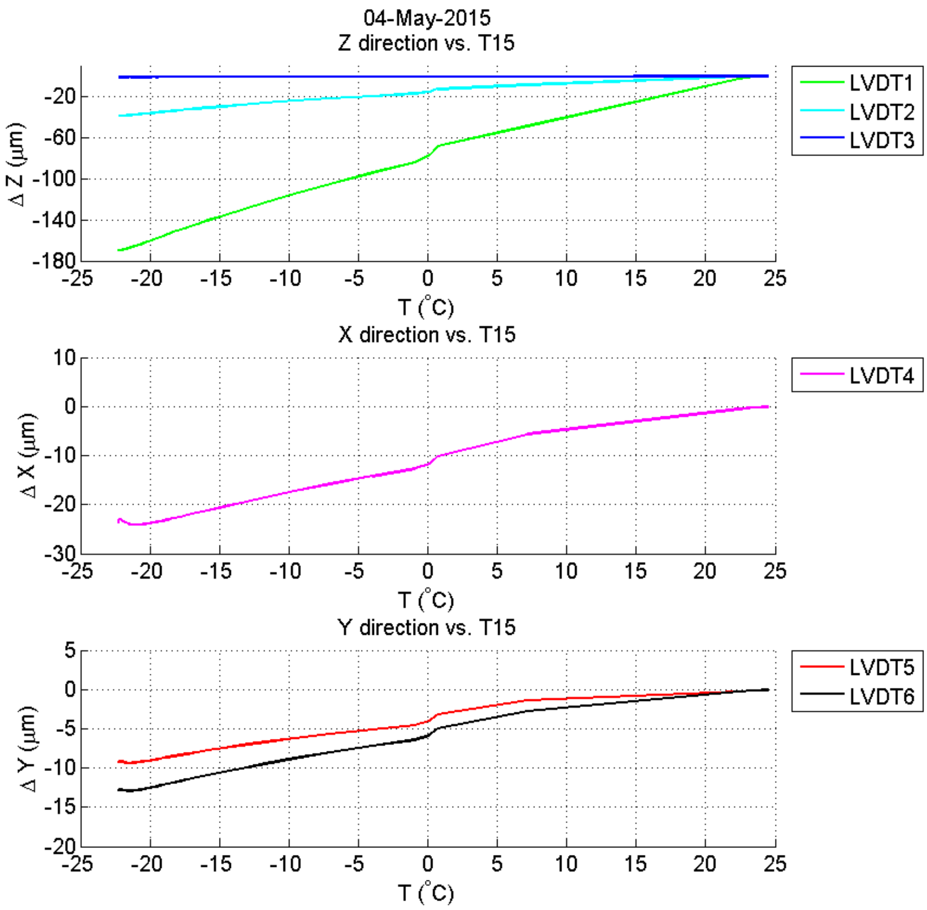


Figure 17: Displacement versus temperature sensor T15 for module II

The displacement for the cooling down from 24 °C down to -22 °C per LVDT sensor is shown in the following table. The results are quite similar to the results of the first measurement with module II.

Table 8: Displacement for cool down from 24 °C down to -22 °C

Sensor	Displacement (μm)
LVDT 1	-168.6
LVDT 2	-38.3
LVDT 3	N/A
LVDT 4	-26.3
LVDT 5	-10.0
LVDT 6	-13.8

7. Conclusion

The repeatability of the displacement of the module is good, the difference between the first measurement and the repeated measurement is 6 μm for LVDT 1 and approximately 1 μm for the remaining LVDT sensors. The cooling temperature for the first and repeated measurement is different, -24 °C and -22 °C, respectively.

Due to the missing LVDT 3, the rotation of interaction point P cannot be calculated with the transformation matrix. An estimation of the displacement of point P at a CO_2 temperature of -24 °C is given below:

Displacement in X	-25 μm
Displacement in Y	~ -12 μm
Displacement in Z	~ -170 μm

The measured displacement versus temperature is linear, thus extrapolation of the results give a reliable view of the displacement at lower temperatures.
De extrapolated displacement of interaction point P at a CO_2 temperature of -35 °C is:

Displacement in X	-30 μm
Displacement in Y	~ -14 μm
Displacement in Z	~ -200 μm

Adding a constraint for the capillaries gives a larger displacement of the module when cooling down. This is possibly caused by moving the capillaries, relative to the cooling block, when placing them in the constraint. Another cause can be that the capillaries are not perfectly straight and therefore the don't have sufficient space to move in the length direction.