LIEBE offline tests report:

Tests and actions performed without LBE, 30/08/2018:

- Thermocouples and heating elements position:

In a first instance, the position of the heating element + thermocouple pairs was confirmed by activating one single heating element at a time and an external thermocouple.

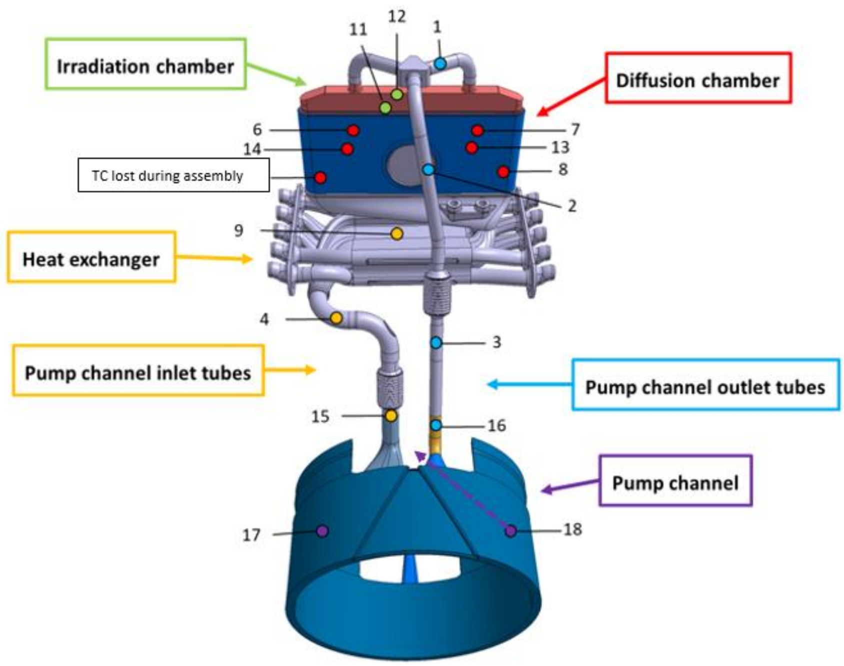


Figure 1: Schematic of the LIEBE loop with the 18 positions of the heating element + thermocouple pairs

All the pairs were in good place except TC18 that was found to be close to the positions 15 and 16. The heating element was still heating the zone 18.

- Level sensors:

The level sensor controllers were checked to work properly with external cables before starting the tests. When connected to LIEBE, the high-level sensor was on, indicating contact with a conducting material, while the low level was off, which is unreasonable. No LBE could be present at that moment; consequently, the cable was already malfunctioning or in contact with the steel due to the vibration of the multiple operations performed on the target.

- Pressure sensor:

The sensor was tested to give the right readout at atmospheric pressure and under vacuum. Afterwards used to put the second envelope under 200mbar of Argon. The pressure readouts were stable between 200mbar and 350mbar during all tests depending on the temperatures of the loop, figure.2 as example.

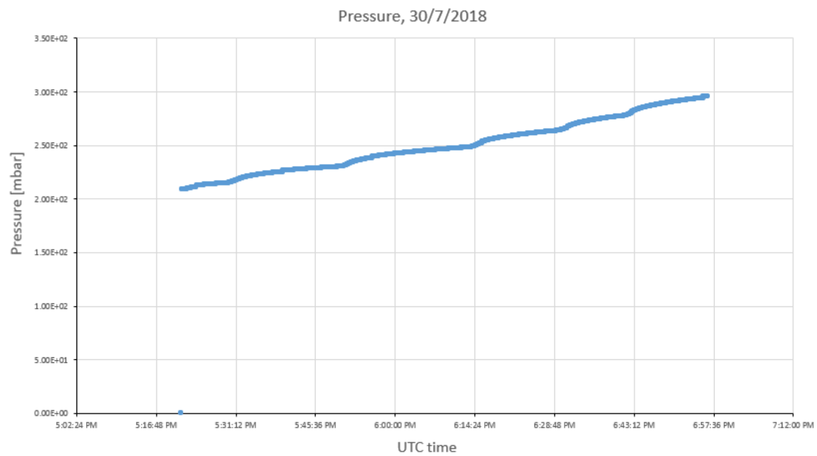


Figure 2: Pressure in 2nd envelope during outgassing of the loop.

The pressure sensor stopped working after 4 days of tests. Considering that the previous sensor bought for LIEBE was never operational, probably the model chosen is just unreliable. However, the constant power cuts during the tests and the temperatures reached at the connection with the sensor (≈100ºC), close to the maximum allowed by the manufacturer might have helped to reduce the lifetime of the device.

- Outgassing of the loop:

The ion source was heated at 1800ºC, **without leak confirming the new design**, and then the loop was heated up to 300ºC where possible, see figure.3. The pressure went up to 2.7e-5mbar in the front-end with loop and source hot and it was reduced to 1e-6mbar after a night with the loop at 250ºC. No water cooling was used.

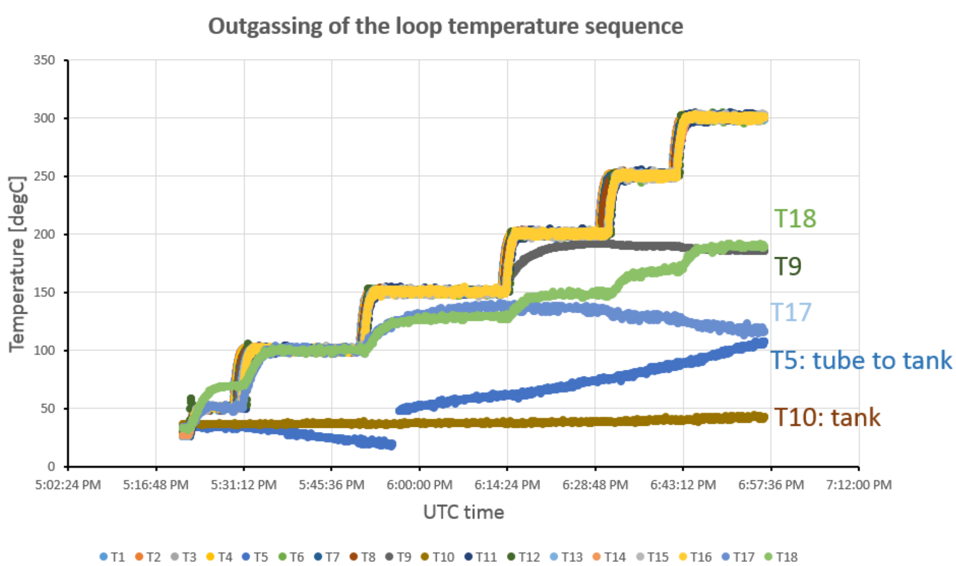
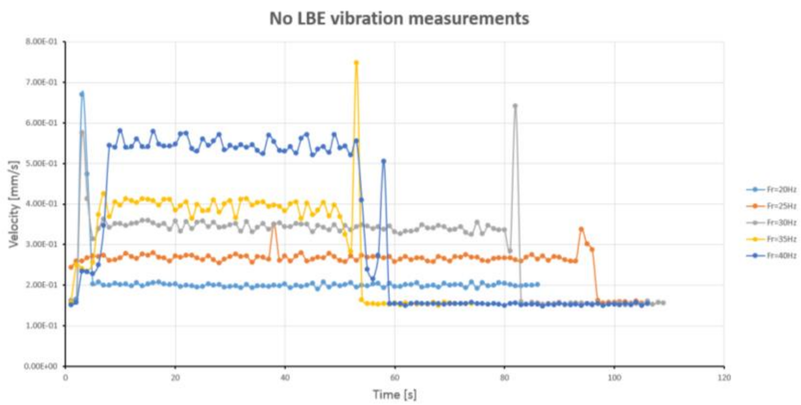


Figure 3: Temperature sequence during outgassing of the LIEBE loop, note that TC5 connection was inverted.

During the outgassing sequence, it was already seen that positions 9, 17 and 18 could not reach the lowest operational temperature, 200°C, by themselves. Moreover, the bottom of the pump channel was cold, close to room temperature, since there is no heating element in that position.

- Vibration tests with the loop under vacuum:

Vibration levels without LBE were checked for every pump operational frequency for comparison with previous tests, to have a baseline for the rest of the offline tests and to check the accelerometer behavior, figure.4.



Pump Fr [Hz]/[rev/min]	Velocity average on target [mm/s]
0/0	0.17
20/165	0.2
25/206	0.26
30/247	0.34
35/288	0.4
40/330	0.54

Figure 4: Vibration levels at the start of the tests without LBE

The velocities found are similar to previous tests and within the acceptable levels defined by ISO10816 (Evaluation of machine vibration by measurements on non-rotating parts). Vibration peaks were detected while changing the pump speed but within the margins.

During the vibration tests the low level sensor turned on. This would mean that most of the LBE was molten even if the tank heating was not used. The tube to the tank showed close values to the melting point but without reaching the fusion temperature, figure.6. The tank thermocouple was showing values lower than 50ºC but it was seen afterwards, during the LBE melting phase, that this value was probably inaccurate due to a bad contact with the tank. However, it can be assumed that the tank was much colder than the tube or at least that just a few droplets from the bottom could melt. No cavitation due to a partially filled loop was detected.

	PUMP			LIEBE_SIDE (Uncoupled)			LIEBE_SIDE (Coupled)		
	+X	+Y	+Z	+X	+Y	+Z	+X	+Y	+Z
Baseline	0.20	0.19	0.19	0.06	0.05	0.04	0.05	0.05	0.04
10Hz	0.83	0.54	0.47	0.05	0.05	0.04	0.52	0.17	0.22
20Hz	0.54	0.39	0.64	0.06	0.05	0.04	0.24	0.85	1.27
30Hz	0.88	0.79	1.13	0.06	0.05	0.04	0.45	0.39	0.19
40Hz	1.44	0.92	1.19	0.07	0.05	0.04	0.48	0.22	0.25
50Hz	4.28	1.76	1.41	0.05	0.05	0.05	0.73	0.27	0.25

Figure 5: Vibration tests from October 2017, the values are in mm/s

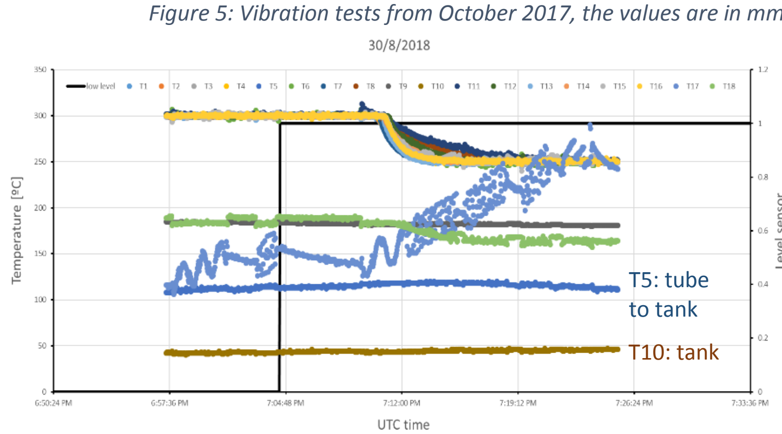


Figure 6: Temperatures on the loop while vibration tests under vacuum.

Later on during the tests, it was seen that some insulating material from the level sensor cable melted during operation. Unexpected readouts could come from here, figure.7.

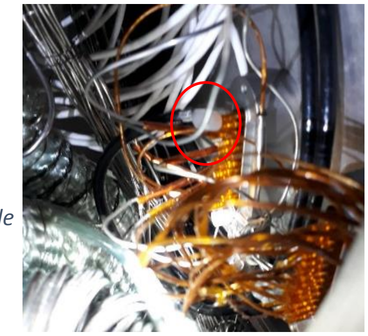


Figure 7: Picture of the LIEBE inside connections for TC and level sensors.

Melting of the LBE 31/07/2018

After a night outgassing, the standard target heating was used to heat the LBE tank and the tube linking the tank with the loop. The pump was used to heat up the channel to values close to 200ºC, see T17 temperatures and the parasitic currents caused by the pump in figure.8. Vibration values were equal to previous tests under vacuum.

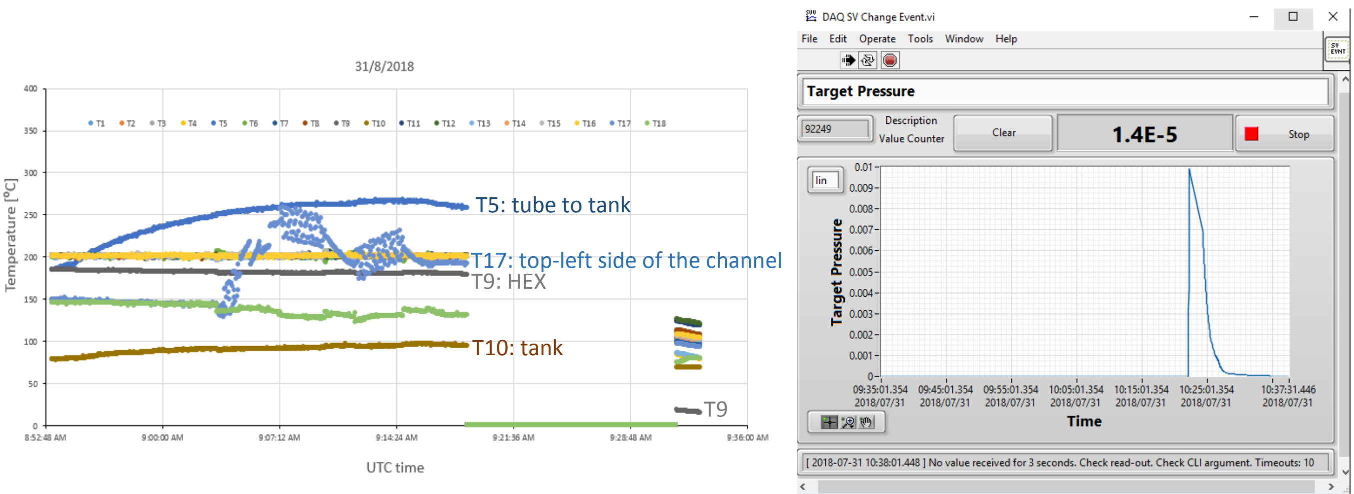


Figure 8: Loop temperatures while heating the LBE tank and target pressure during the melting process (UTC time in LIEBE data acquisition is 1h delayed from the pressure readout UTC time).

Temperatures from TC10 were quite low (<100ºC); it was assumed that the thermocouple was not very well placed in contact with the tank. The tube (T5) was well warmed up to 250ºC with only 1 heating element. Meanwhile, the tank has 4HE attached, that are powered electrically in parallel with the HE5 of the tube to the loop. While opening the second envelope to check the tank temperature with an external thermocouple, a pressure leak triggered the interlock, figure.6 pressure readout, which cut the power of all systems. The pressure peak was expected due to the remaining argon in the tank from the process of LBE filling. The sharp increase of pressure and the fast recovery of the vacuum are in well agreement with that hypothesis. Moreover, the remaining argon was forcefully on the top of the tank, so most of the LBE had to be molten for this event to occur. In figure.8 it can also be seen the rapidly loose of temperature in the heat exchanger, T9 is at room temperature after 15min without heating elements, which could induce non-controlled LBE solidification in that zone. The level sensors were both on, as before, during all the process.

The LIEBE loop was set to 200ºC and the pump to 247rev/min (30Hz) to heat up the channel and start the flow of liquid metal. Meanwhile the LBE tank was again heated to ensure that all the LBE was molten into the loop. The HEX temperature was expected to increase once a flow would be developed. However, T9 decreased from 180degC to 160degC without any water-cooling being used. The loop temperature was increased to 300ºC and afterwards to 400ºC trying to see an effect on T9 without success, figure.9.

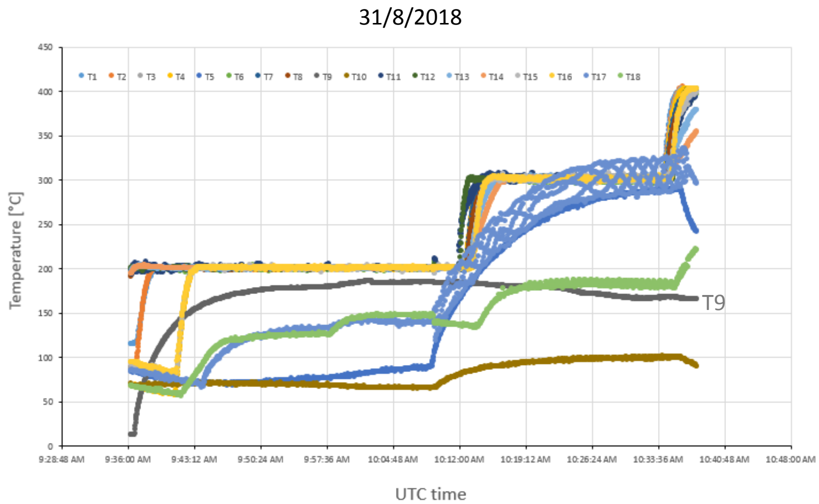


Figure 9: LIEBE loop temperatures after LBE melt, from 10:36am to 11:40am

Vibration levels were similar to the ones measured under vacuum. At 247rev/min an average of 0.3mm/s slowly decreasing was detected, compared to 0.34mm/s under vacuum, figure.10. No cavitation was detected in a first instance although a friction noise could be heard coming from the channel, which indicated flow. Unfortunately, there is no clear evidence that a flow of LBE was developed since the level sensors were proven unreliable and no evident effect was seen on the accelerometer. The only hints are the temperature effect on T9, the previous pressure leak and a soft friction noise from the channel. It was then tried to heat up the rest of elements in the loop to see an effect on T9.

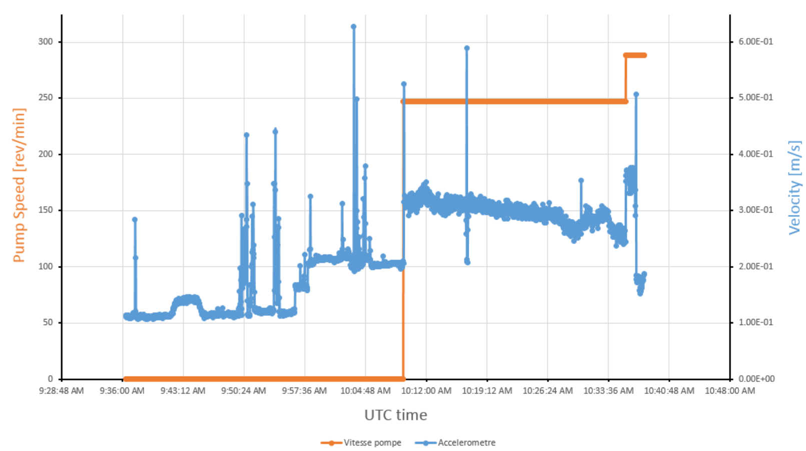


Figure 10: Vibration after LBE melting, from 10:36am to 11:40am

The PLC controlling the LIEBE stopped at 11:40am (10:40am in LIEBE's data acquisition), while heating up the loop to 400ºC and coinciding with a pressure increase in the target, figure.11 first circle. The pressure interlock did not trigger and resetting of the PLC brought the elements to work again. There is no link between the PLC and the pressure sensor apart from the interlock cutting the power. However, the pump was stopping from time to time and its current control was giving errors "torque program limit, acceleration program limit, deceleration program limit". It was considered a problem with the control system to be fixed later on. In addition, to be noted for the rest of the report, the acquisition data system just checks the pump velocity input. It does not take into account if the pump is on or not. Luckily, the vibration levels show clearly when the pump is working, figure.13.

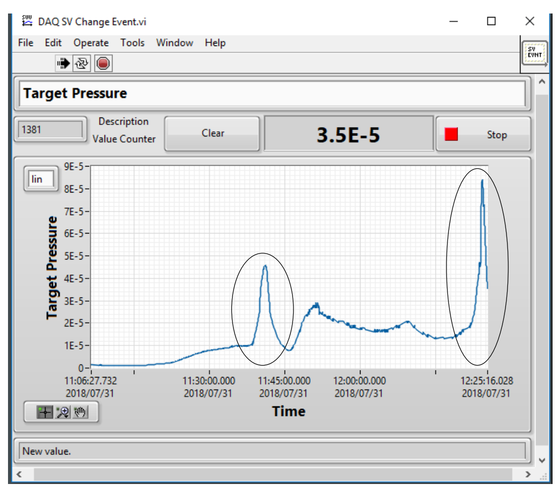


Figure 11: Target pressure from 11:06am to 12:25pm

After reset of the PLC system all the elements were fully functional again. The loop parameters were set to the previous status (400degC and 247rev/min on the pump, figure.12 and figure.13). LIEBE seemed stable at that point, with some increase on the pressure following an increase on temperature or pump speed, following figure.11.

At 12:24pm, another pressure peak triggered this time the pressure interlock, second circle on figure.11. Both peaks shown don't have a sharp start as seen in the previous leak at 10:20am. T9 temperatures were around 160ºC, above the 125ºC melting point of the LBE. Even if other parts of the HEX could be colder due to the low thermal conductivity seen (no effect on T9 from the hot diffusion chamber at 400ºC), the accelerometer would detect higher vibration levels due to cavitation in the channel, as it will be seen later in this analysis. Moreover, after the first melt of LBE inside LIEBE some outgassing could be expected, triggered by both the temperature and the flow. Following that hypothesis, the pressure peak coincides with an increase on temperature up to 450ºC of the loop, figure.12. This effect would confirm the presence of LBE in the loop. The ion source couldn't be used to check the extracted beam because of the constant power cuts.

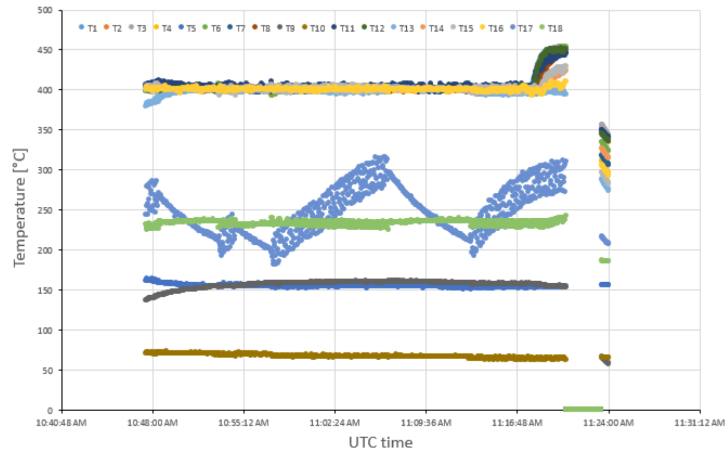


Figure 12: Loop temperatures from 11:48am to 12:24pm

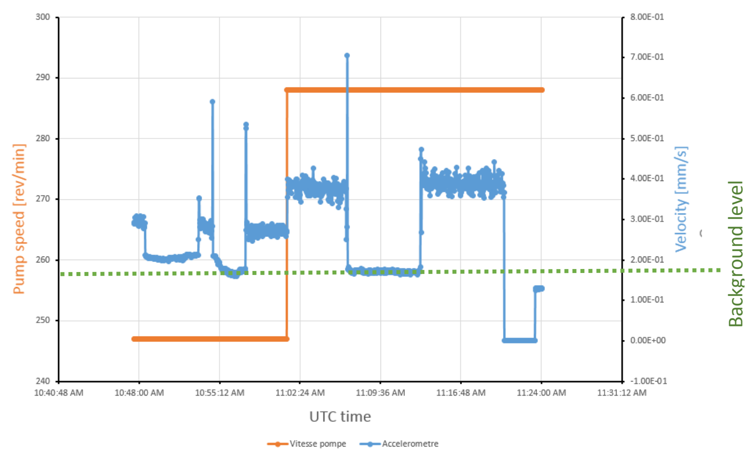


Figure 13: Pump speed and vibration from 11:48 to 12:24

Broken heating elements 31/07/2018 afternoon and 1/08/2018

After the power cut at 12:24pm triggered by the pressure interlock, 3 heating elements stopped working, HE2, HE4, and HE12. HE4 was found completely broken, figure.14. In addition, the broken HE4 caused a short-circuit damaging the relay for control. The consequence was that control of the HE was lost and 21 Amps were sent constantly to the target through the broken cable. This unforeseen effect misled the cause of the problem until replacement of the relays, which showed no positive effect. The damage seems to come from a mechanical defect first that led to a higher resistance of the wire which finally melted. It must be highlighted that the miss functioning of the controls was seen offline due to the proximity of the power supply. It would not have been seen online. The damage on HE2 and HE12 is still not assessed.

Figure 14: Heating element 4 broken.

Restart of the tests. 2/07/2018

The tests restarted with the damaged heating elements disconnected from the control system. The loop was set to 200°C to warm up overnight, previously the LBE was solid in the loop, then heated up to 300°C, figure.15. The loss of the heating elements was not very problematic in the case of HE2 and HE12, temperatures on their zones followed quite well the overall temperature set in the loop. On the contrary, not having a heating element at the exit of the heat exchanger was more worrying considering the low temperatures in the HEX. It was also noted that the low-level sensor was off and stayed off the rest of the tests.

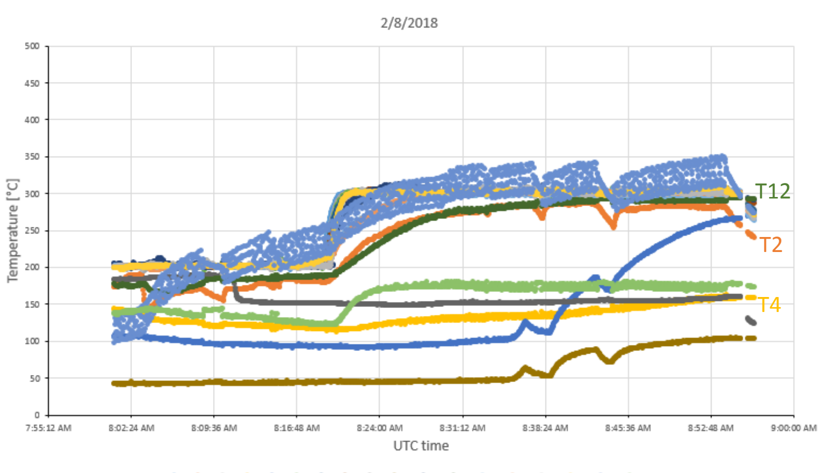


Figure 15: Temperatures in the loop from 9:00am to 10:00am

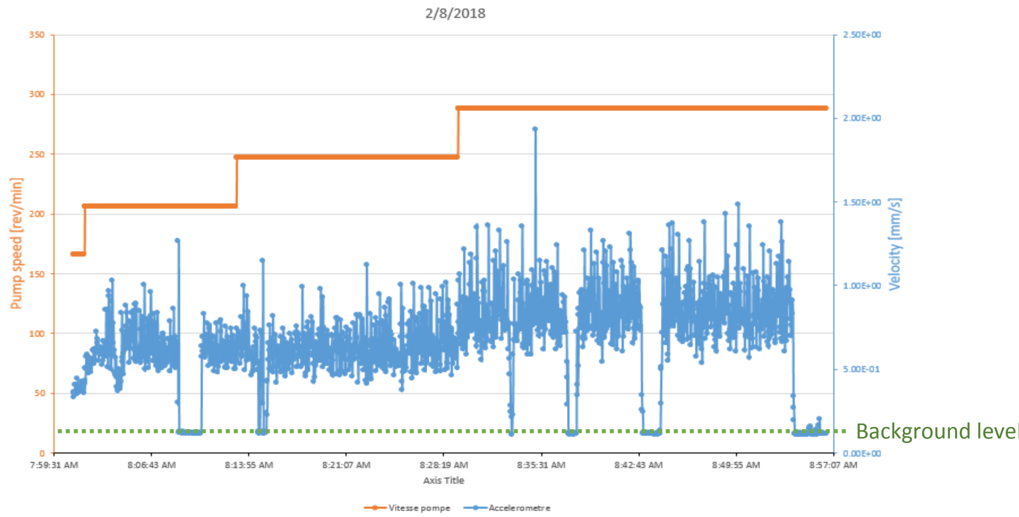


Figure 16: Vibration and pump speed from 9:00am to 10:00am

At the start of the EM pump, higher vibration levels were detected indicating cavitation, figure.16, 206rev/min - 0.26mm/s under vacuum compared to 0.75mm/s on average with cavitation. Cavitation issues could be explained by having a partially filled channel. That would mean that LBE was in a solid state somewhere in the loop, probably at the heat exchanger, or that a plug was stopping the flow. It has to be noted again that, even after a night warming up the loop, the LBE in the channel is cold since little heating power is placed there, as seen previously during the outgassing tests. Consequently, cavitation in a first instance was expected.

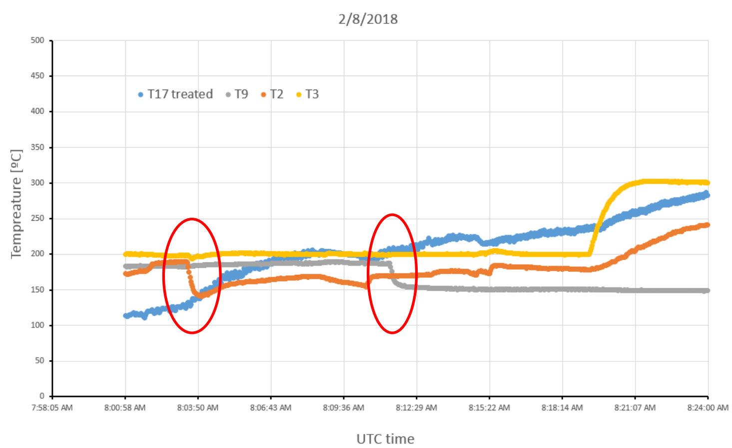


Figure 17: Temperatures after restart of the tests. 'T17 treated' is a 10s average of the raw data for clarity.

Having a closer look to the temperatures, the HEX temperature lowered drastically from 180°C to 150°C (8:10am). T2, positioned at the tube exiting the pump channel, also suffers a drastic decrease on temperature but earlier in time, at the start of the EM pump. Since the HE element was not working there, the zone is highly influenced by the temperature of the LBE flowing. The decrease in temperature could be explained by the flow of relatively cold LBE, just molten, coming from the channel (T17 and T2 cross in time there). In that case, the following drop on T9 would mean the unclogging of the HEX and the start of the flow on that zone. Just molten LBE, 125^{o}C, could cool down the weakly heated HEX. The consequence then is that the loop was clogged while the EM pump was working and developing a flow for roughly 10min. Moreover, it proves a difference between the temperature readouts from TCs, very close to the heating elements, and the actual temperature of the LBE inside. Comparing with, for example TC3 (just underneath TC2), it shows just a very small drop at the start of the flow. The effect is hidden by the HE element maintaining almost constant 200^{o}C on the surface. The heating elements of the tank were used trying to compensate the loss of HE4 (from 8:38am onwards), without much effect on T9 that stayed around 150°C, but a reasonable increase on T4, figure.15.

From figure.16 vibration levels stayed very high even after the temperature effect seen in figure.17. From the overall temperature plot in figure.15 it could be argued that the low temperature in zone 4 could be causing a plug at the exit of the HEX. In that case there is not enough LBE in the loop to cause a leak through the ion source, no effect on the pressure inside the front-end was seen either.

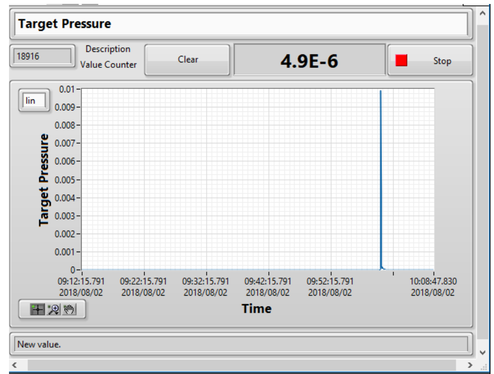


Figure 18: Pressure leak.

The vacuum interlock triggered at 10:00am, figure.18. A very sharp and narrow peak, which agrees with the hypothesis of still having some argon bubbles trapped in the loop. It also coincides with the heating up of the tube to the tank trying to release zone 4. Melting of LBE on the linking tube entrance could liberate remaining argon.

The recovery of the controls was quick but the acquisition system has to be restarted every time. Unfortunately, there is some data missing from the restart of the loop after the vacuum leak. In addition, from the OneNote logbook, the transformer tripped during recovery from an unknown cause right after. These events led to a prolonged time without HEs (≈20min).

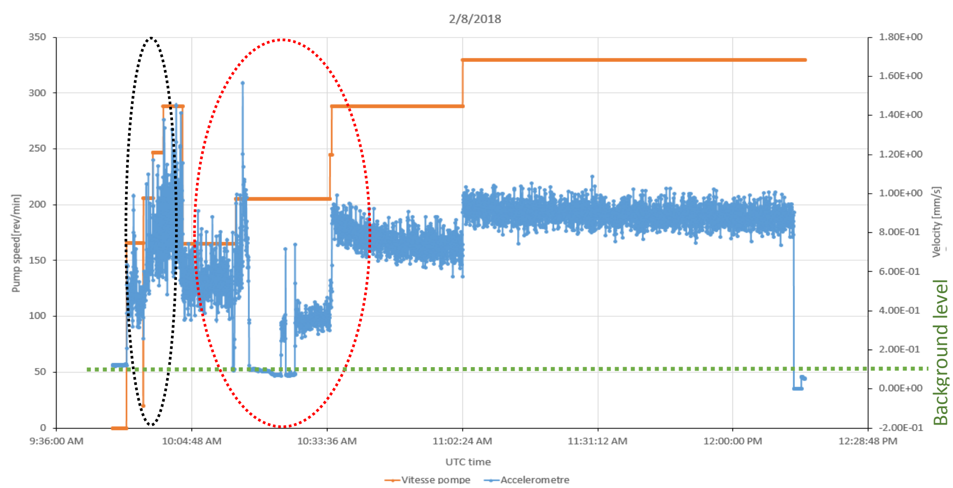


Figure 19: Vibration and pump speeds from 10:45am to 13:20pm

The EM pump was used to recover the temperature in the channel once thermal equilibrium was reached on the HEX (150ºC) and most of the loop, figure.19 and figure.20 first circle in black. High vibration was detected by the accelerometer, similar to figure.16. A closer look to the temperatures at the restart of the loop show similar phenomena seen previously in figure.17, figure.21.

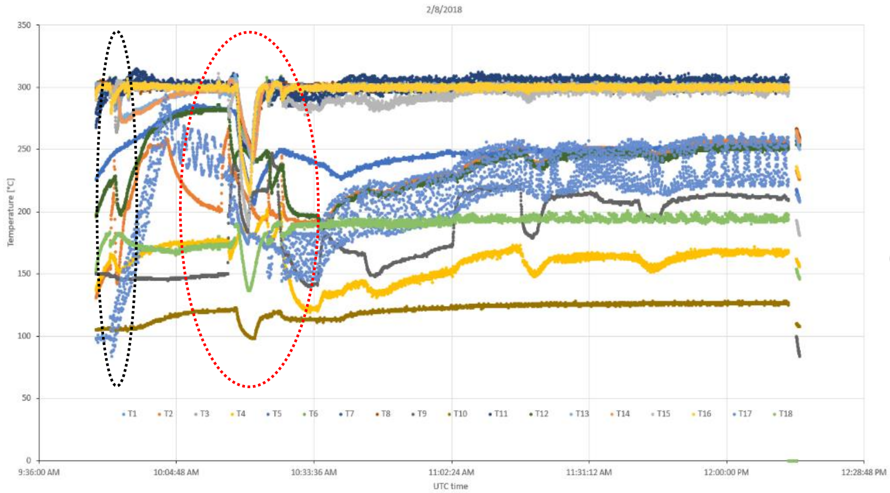


Figure 20: Loop temperatures from 10:40am to 13:10pm

It seems from the temperature data that zone 2 was blocked for 1 minute, following figure.21. When the pump starts T16 reacts immediately with a slight decrease in temperature from the colder LBE coming from the channel. Instead, T2 increases temperature quite drastically until presumably the LBE melts in that zone releasing the flow, when the temperature quickly lowers to the channel temperature T17. At the same time T1 and T3, on top and underneath respectively from zone2, react to the flow.

So, even if TC2 was showing temperatures above 150ºC, the LBE inside was not molten, which induces to think that the same thing happened in the HEX but with a much bigger section of LBE. T9 was stable at 150ºC, the HE could not heat up more. Around 11:10am a sudden increase of pressure was seen, figure.22. The pressure increase is rather slow with the ion source ramping up at that moment. Considering the hypothesis that a plug existed on the HEX and even if the pump speed was reduced to low values, 165rev/min (20Hz) since there was concern about the vibration levels, probably at that stage the LBE was filling the diffusion chamber. Moreover, at that time the ion source was hot for the extraction of stable beam, which would evaporate the LBE getting close to it. It was decided to stop the pump and heating elements for precaution, second circle in red in figure.19 and figure.20, and the pressure stabilized, figure.23.

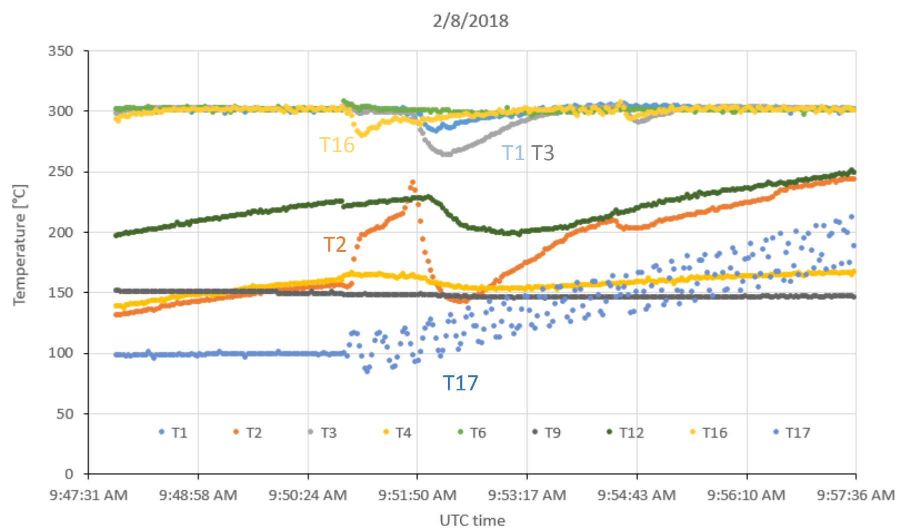


Figure 21: Closer look to temperatures in the first circle in black from figure.20, from 10:47am to 10:57am

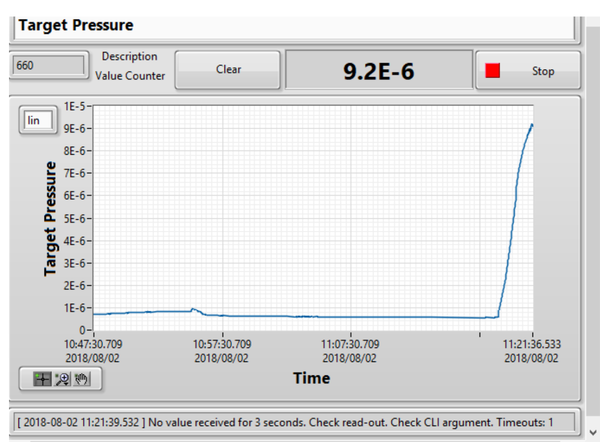


Figure 22: Sudden pressure increase

Following closely the temperatures in this period, figure.24, after reducing the pump speed around 10:05am T2 temperature slowly decreases following the LBE temperature from the channel. At 10:12am, coinciding with the pressure increase in the target, T2 temperature increases showing a possible plug. As soon as the flow seems to be restored, from T2, T9 temperature increases drastically matching T12 (irradiation chamber temperature in green) and then lowers following the tendency of all other temperatures because of the HEs being down for precaution, circle in red, figure.24.

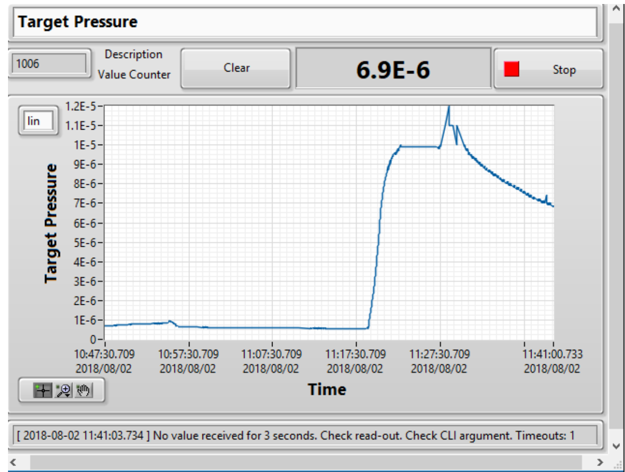


Figure 23: Pressure in front-end

After stabilization of the pressure, lower vibration values were detected, figure.19 10:30am. It seemed that a full flow was then developed. For the first time during the tests, T9 reached higher values than 200ºC, figure.25. Temperature effects of increasing the pump speed could be seen and even the water cooling was tested. Different temperature equilibriums, between 150ºC and 250ºC, could be reached using different water channels. Unfortunately, electro valve 1 was not reacting to the controls. The reason is still unknown.

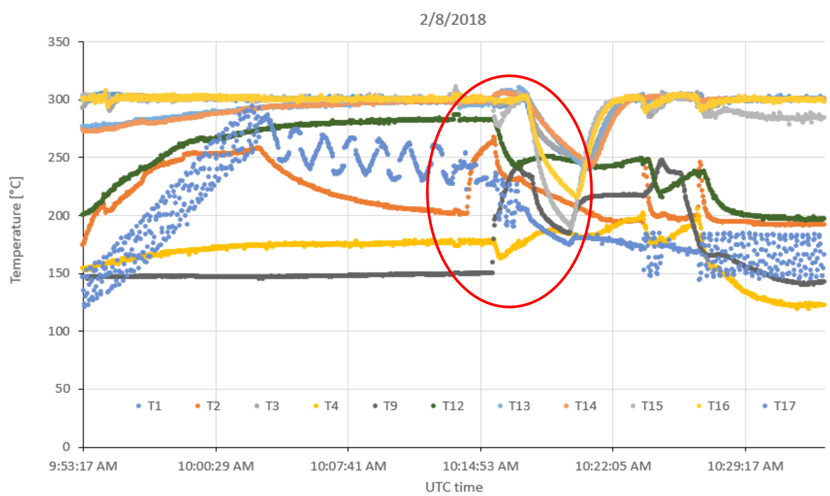


Figure 24: Closer look to the temperatures in the second circle in red from figure.20, from 10:53am to 11:36am

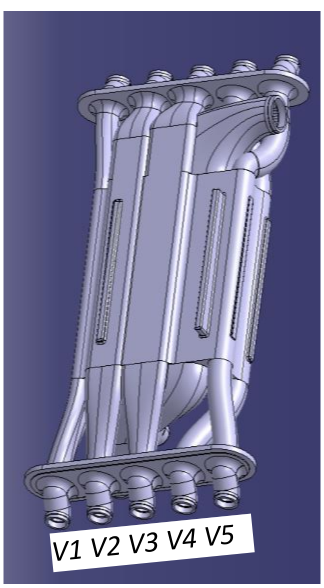


Figure 26: HEX water channels

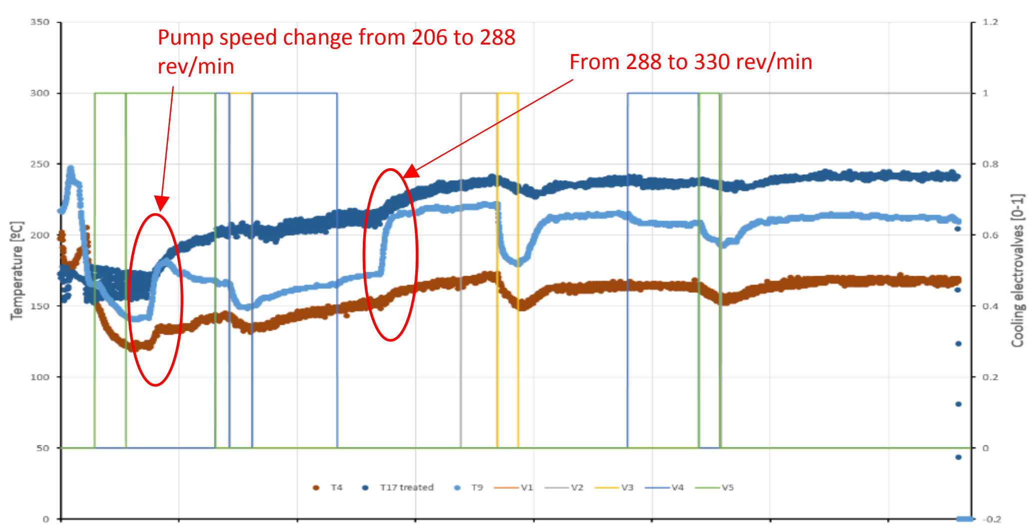


Figure 25: Temperatures and EV used from 10:23am to 12:10pm

After one hour operating in these conditions the source reached 300A (1800C) the transfer line was at 190ºC and the chimney connecting the diffusion chamber and the transfer line at 145ºC. While preparing the mass scan, another sharp pressure leak, as figure.18, is reported to bring down all the elements. The HEX loses 100ºC in some minutes and the target is unable to quickly recover afterwards, end of figure.20.

It was tried to quickly recover the flow bringing up the HEs as fast as possible and using the pump to heat the channel. High cavitation was detected once more, figure.26. The HEX temperature lowered very rapidly and only reached back 120ºC after some minutes. It seems clear that the loop was plugged again. The ion source was quickly recovered and a mass scan was attempted. However, the anode showed short-circuit when putting any voltage. A clear sign that the source was coated with LBE. Nevertheless, in a first instance the ion source was ramped down to see if it was a dilatation problem from the cathode. From the target pressure, similar behavior as figure.11 was seen. The pressure was reacting to the increases in pump speed and loop temperatures. Then, again, the pressure interlock triggered, figure.28.

It was attempted one more time to recover the loop after this event, this time being more patient and leaving the loop warm up for 1h until stabilization. Similar effects as in figure.25 were then seen but another pressure leak stopped operation after 20min. It was then decided to try a mass scan with the loop cold.

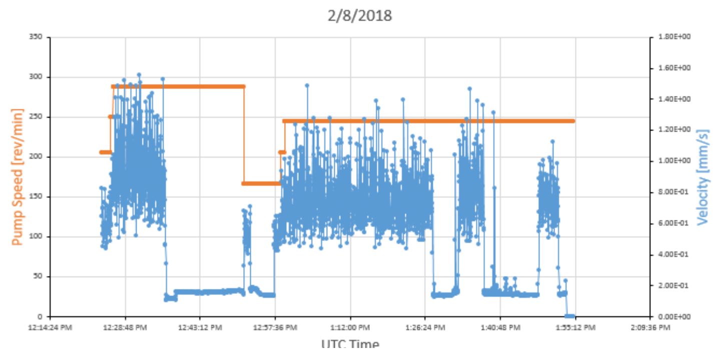


Figure 26: Vibration and pump speed from 12:20pm to 2pm

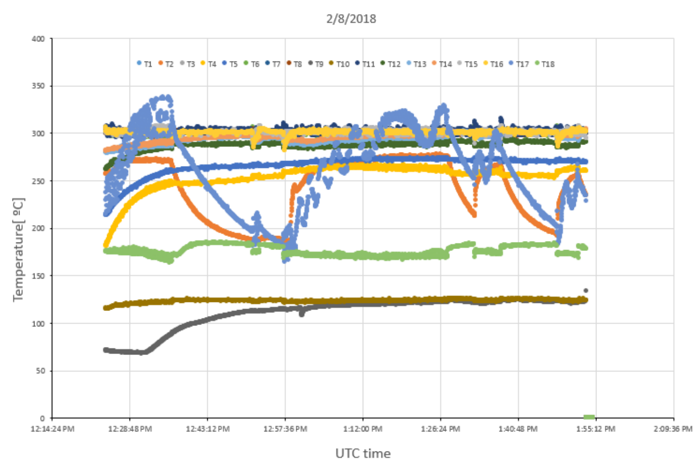


Figure 27: Temperatures from 12:20pm to 2pm

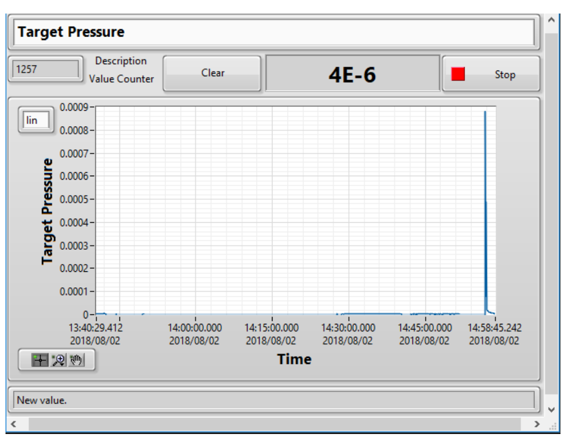


Figure 28: Another pressure leak, this event occurred 4 times in the same day of tests.

Mass scans solid LBE 2/8/2018

With the LBE cold it was possible to use the anode and a mass scan was done. It was noted that the current drawn by the high voltage power supply was high. The transfer line heating was tested and the temperature reached was 340ºC with oven at 15A. The parameters of the source and the results are in the following figure.29.

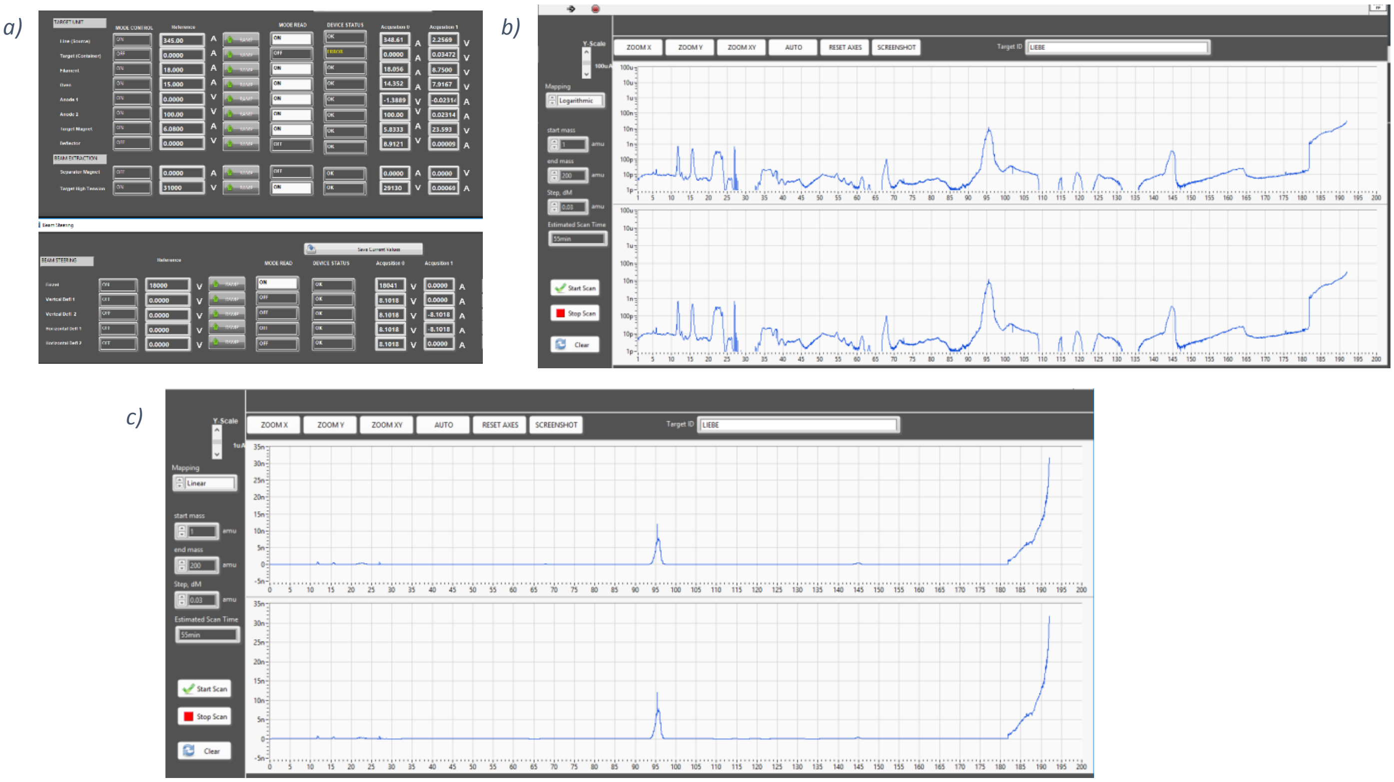


Figure.29: a) Parameters of the ion source b) Mass scan in logarithmic scale, c) Mass scan in linear scale

The mass scan didn't reach the final mass set to see the lead and bismuth contamination in the beam. However, it can be seen from the mass spectra that the current increases drastically when getting close to 200 mass. Manually setting the magnet to 208Pb the current value found was 170nA. After the scan, the loop was left overnight warm, 200ºC on all HE, and the ion source also at nominal temperature to try do a mass scan with a flow of LBE next day.

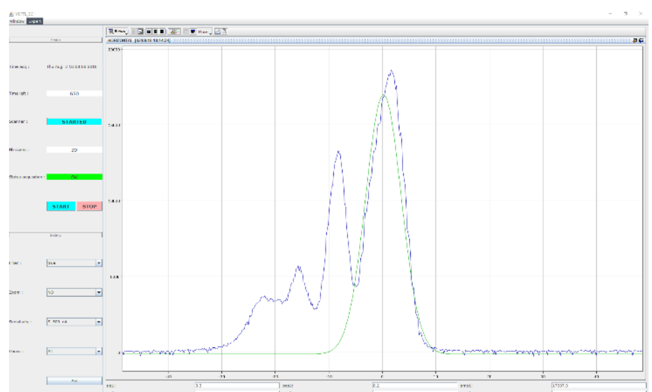


Figure.29: Scan done on the Pb mass showing the Pb stable isotopes shape

Mass scans 3/8/2018 with molten LBE

After a night with the target warm, it was possible to put voltage on the anode. The pump was set to 206rev/min and a mass scan was started with the loop conditions that can be seen in figure.30 and figure.31. It was tried to keep the same conditions throughout the mass scan, figure.32. Again, the mass scan did not reach the Pb and Bi masses. Centering manually on mass 208Pb, 2µA of current were seen.

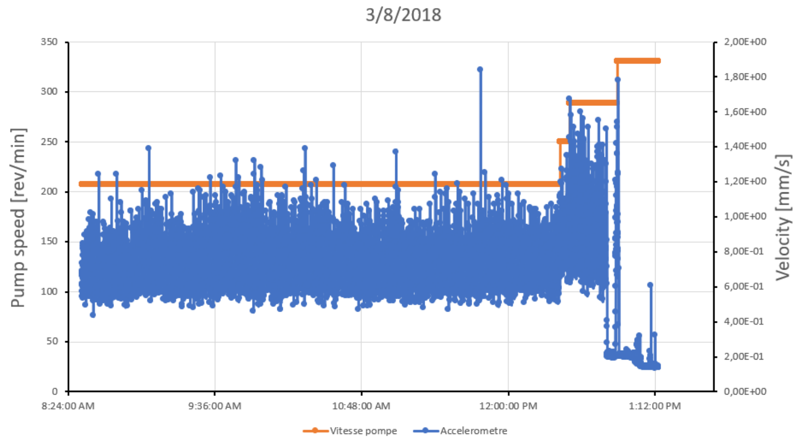


Figure.30: Vibration and pump speed during the mass scan

High vibration was detected, which could indicate a plug from what has been analyzed previously. The only particular effect that can be seen in figure.31 is the slow loose of temperature in T9, once more, no water-cooling was being used. Consequently, it could be argued that the loop was not unplugged during all this time. However, the vacuum is reported to be good during all the scan. Moreover, it was possible to operate the loop for almost 5h straight for the first time, but this could be explained by the loop not getting unplugged. The fact that the pump was set to a slow speed, can be also a factor to unplug the loop and to affect the pressure in the front-end.

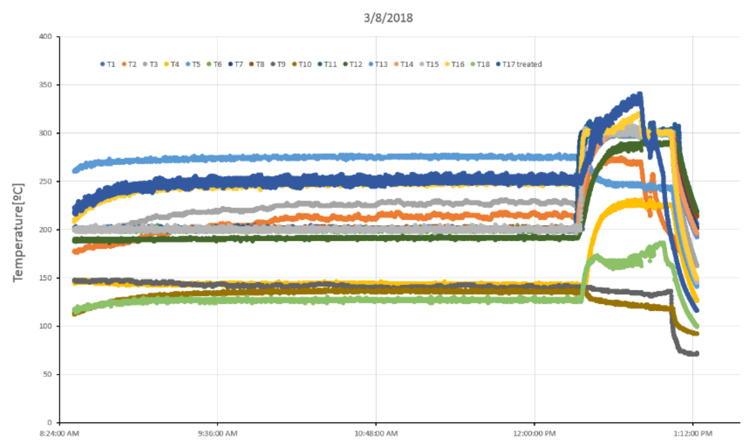


Figure.31: Temperatures in the loop during the mass scan

After the first mass scan with the loop temperatures at 200ºC it was tried to go to 300ºC to do another scan. The anode then was showing shortcircuit and it was decided to stop the tests.

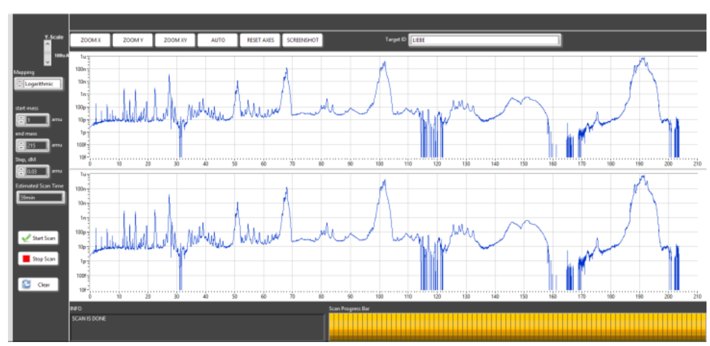


Figure.32: Mass scan on the 3/8/2018

Diagnostic after the offline tests:

Uncoupling of the LIEBE target from offline separator showed that macroscopic amounts of LBE escaped the loop entering the ion source and front-end. The extraction electrode and the insulator ceramic were completely coated with LBE.

Figure.32: Extraction electrode coated with LBE

Figure.33: Macroscopic quantities of LBE underneath the ion source

The LIEBE base was open to check the interior of the ion source and the transfer-line connecting the loop to the ion source, figure.34. The base was completely coated with LBE, showing condensation on the cold parts of the assembly and bigger quantities on the path of the liquid through the ion source. A partially filled transfer-line was found, figure.35, indicating that the liquid LBE reached that zone. It is clear from the post-analysis that LBE in liquid phase from the loop reached the transfer line level. Consequently, the ion source vacuum chamber was filled with LBE that was being evaporated while the ion source was hot. That can explain the short-circuited anode and the high levels of Lead contamination seen in the faraday cup.

Figure.35: Picture of the transfer line filled with solid LBE

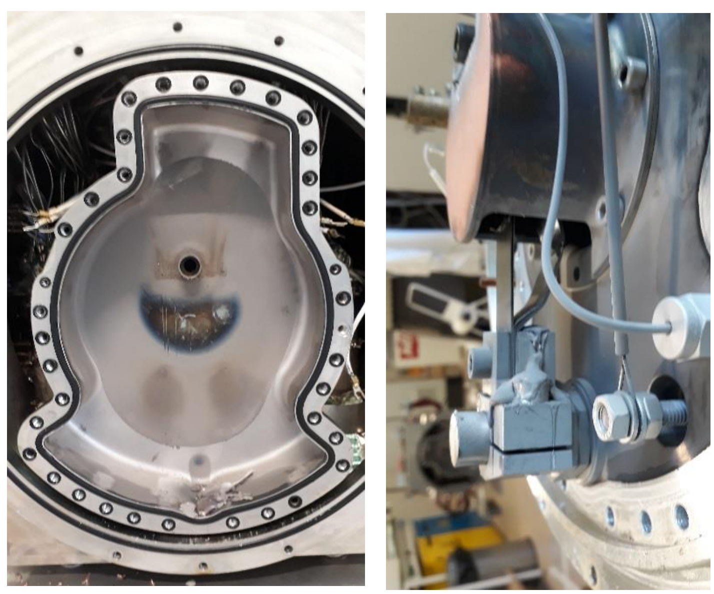


Figure.34: Pictures of ion source vacuum vessel and the line connection underneath the source

Conclusions:

The LIEBE target was not designed to have solid LBE in the loop. The pump channel and the heat exchanger heating elements are not designed to melt LBE. Moreover, heat loses around the loop are high, especially on these places. Consequently, any problem encountered that stopped the heating and the circulation of the LBE in LIEBE caused solidification very rapidly. Recovery of the flow cannot be done statically with the present heating elements in the loop; it needs the use of the electromagnetic pump in a first instance to melt the LBE in the channel and just then, the heat exchanger can be reheated by incoming LBE from the hot diffusion chamber. Therefore, in order to restart the target, it has to be operated partially developing a flow while plugged. Moreover, there is no clear signal of a flow in the loop nor of the presence of LBE. The level sensors did not give any valuable information during the tests; the accelerometer was useful to detect cavitation, which is forced to happen to re-melt the LBE, but not the consequences of it. Temperature effects of the LBE melting have been detected during this analysis but are difficult to see during operation. In addition, thermocouples were installed too close to the heating elements, consequently not reading the real temperature of the LBE in most zones of the loop. The risks of attempting the re-melting of the LBE in these conditions have been found, LBE leaked towards the front-end through the ion source. Nothing impedes the LBE to reach the ion source while the heat exchanger is being reheated. At the same time, there is no reliable sensor detecting a possible LBE leak before it is too late.

Difficulties on the operation of the targets occur often. Even more probable in the case of a complex prototype like LIEBE. The offline tests had to be stopped and solidification of the LBE happened multiple times for different causes. Particularly, the filling procedure of the LBE tank was conceived so possible remaining LBE oxides stayed on top, not entering the loop and not clogging the grids. The unforeseen effect was that the trapped gas on top of the LBE tank was not released at once during melting of the LBE. Instead, gas bubbles were unpredictably escaping the loop throughout the tests, which triggered the pressure interlock numerous times impeding continuous operation of the target. More importantly, heating elements broke during operation losing their functionality and damaging the present control configuration. The power supply delivered 21Amps to the target through a broken heating element, uncontrollable and undetectable for the present PLC control system. This effect would not have been seen during online operation.

The safest solution to avoid the LBE leak would be to make impossible the passage of the molten liquid independently of the thermal equilibrium in LIEBE. Unfortunately, it is not clear if this is possible yet. The fact that the path from the LIEBE loop to the ion source has to be conditioned for the isotope effusion, together with the pressure developed by the EM pump, might make this option impossible or at least far from being developed. Nevertheless, LIEBE's heating system must be redesigned to take into account re-melting of the LBE; it cannot rely on operating with only the liquid phase. As well, it should be considered to install thermocouples in zones were the real temperature of the flowing LBE can be detected. If these elements are added and therefore a homogeneous and sufficient heating of the loop is achieved, the vibration velocity could be the reliable signal to evaluate the status of the flow in LIEBE. During the offline tests it has been seen that plugs and cavitation in the loop are detected by the accelerometer.

Overall, the LIEBE offline tests showed the difficulties of operating a much more complex target. Several elements were proven to be unreliable even without a highly radioactive environment. Moreover, the design showed inability to safely restart operation with solid LBE. Simplicity and flexibility in the target design and operation should be considered to improve in reliability and be able to provide more experimental data.

Resume of the problems encountered:

- Insufficient heating element power to heat up the loop to 200ºC to safely start the operation or re-melt the LBE:
    - Top of the pump channel slightly above 100ºC.
    - Bottom of the pump channel close to room temperature.
    - Heat exchanger maximum temperature about 180ºC on TC. Clearly seen from the tests that other parts of the HEX were colder.
- The LBE leaked through the ion source:
    - A plug was developed presumably at the entrance of the HEX due to the low temperatures + operation breaks caused by other problems.
    - Attempting to re-melt the LBE in the HEX increased the liquid level inside the diffusion chamber reaching the ion source. This effect was visually confirmed during post-tests analysis.
- Damage on heating elements:
    - HE have shown to be less reliable than expected.
    - Broken HE cause short-circuits damaging control components. 21A were sent to the target with an unknown path. To note that this effect was seen offline due to close proximity of the power supply. Only unexpected temperature readouts could be seen from the controlling system.
- Pressure leaks due to argon bubbles from the tank:
    - Unpredictable and numerous pressure leaks triggering the pressure interlock of the front-end.
    - Possible damage of electric components due to power cuts.
- Temperature hidden effects due to close proximity of the TC to the HE:
    - Real temperatures of the LBE flowing were seen when some HE stopped working.
    - TC readouts highly influenced by the HE temperature rather than the LBE inside.
- Pressure sensor unreliable:
    - The pressure sensor stopped working after 4 days of operation; the prior sensor, same model, was never operational.
- Level sensors signal:
    - Unreasonable signals detected by the level sensors during the tests. No value given during operation.
- Other minor problems:
    - The EM pump sometimes stops due to errors in the current controls.
    - Electrovalve1 is not working.
    - Data acquisition from pump speed does not take into account if the pump is actually rotating or not, just the speed input.
    - The data acquisition system does not save the power input data.

On the bright side:

- Pump and accelerometer worked fine throughout all tests, no contact and good vibration levels even with cavitation.
- LIEBE worked fine after melting the LBE for the first time. Solidification and re-melting makes the operation more complicated. However, it cannot be expected to have continuous operation of the prototype.
- Stable beam was made.
    - Big LBE contamination up to 2µA due to the LBE flowing inside the source

Future recommendations:

- Update the heating elements of the loop to achieve a homogenous 200^{o}C to start operation or re-melt the LBE.
- Develop a transfer line impeding the LBE leak and allowing the isotope effusion.
- Fill the tank from the bottom to pump the remaining gas at the beginning of the tests. Special care has to be taken to avoid oxides in the tank.
- Update the control system to be safe from possible heating element short-circuits.
- Consider the use of a bypass in the loop or a free from heating elements zone to detect a more realistic LBE temperature.
- The same bypass could be considered to install a flow meter.

Previous design assessments:

In order to detect possible omissions on the design phase, a small review of the design considerations compared with the results provided throughout the last year tests is given.

- Safety analysis pointed out the need of designing a transfer line preventing the LBE to leak through the ion source “Safety Internship for LIEBE target, Hachem Znaidi 2014”. Also presented in “LIEBE Project review, Safety work-package, 25.06.2014”.
- A committee of experts accepted the heating element plus thermocouple distribution. The hidden effects of colder LBE were not foreseen.
- Operation with just molten LBE was proposed throughout all the design phase. Possible solidification of the LBE due to unpredicted problems was not considered. Consequently, no re-melting process was designed.
- Thermal dilatation problems from the radiation coming from the hot ion-source were not predicted. The resulting vacuum leak delayed the offline tests for 7 months.
- Possible modification of the different elements of the target was not included in the design. Rigidness of the design complicates any change to be done in the prototype.
- The electromagnetic-pump power supply cables induce parasitic currents on nearby cables for signal transmission. Re-installation of the LIEBE cables in the target area was necessary to avoid this problem.