Internship at the Center for Ultracold Atoms(CUA), RLE, MIT

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Achieving Ultra-High Vacuum for Lithium 7 experiments.

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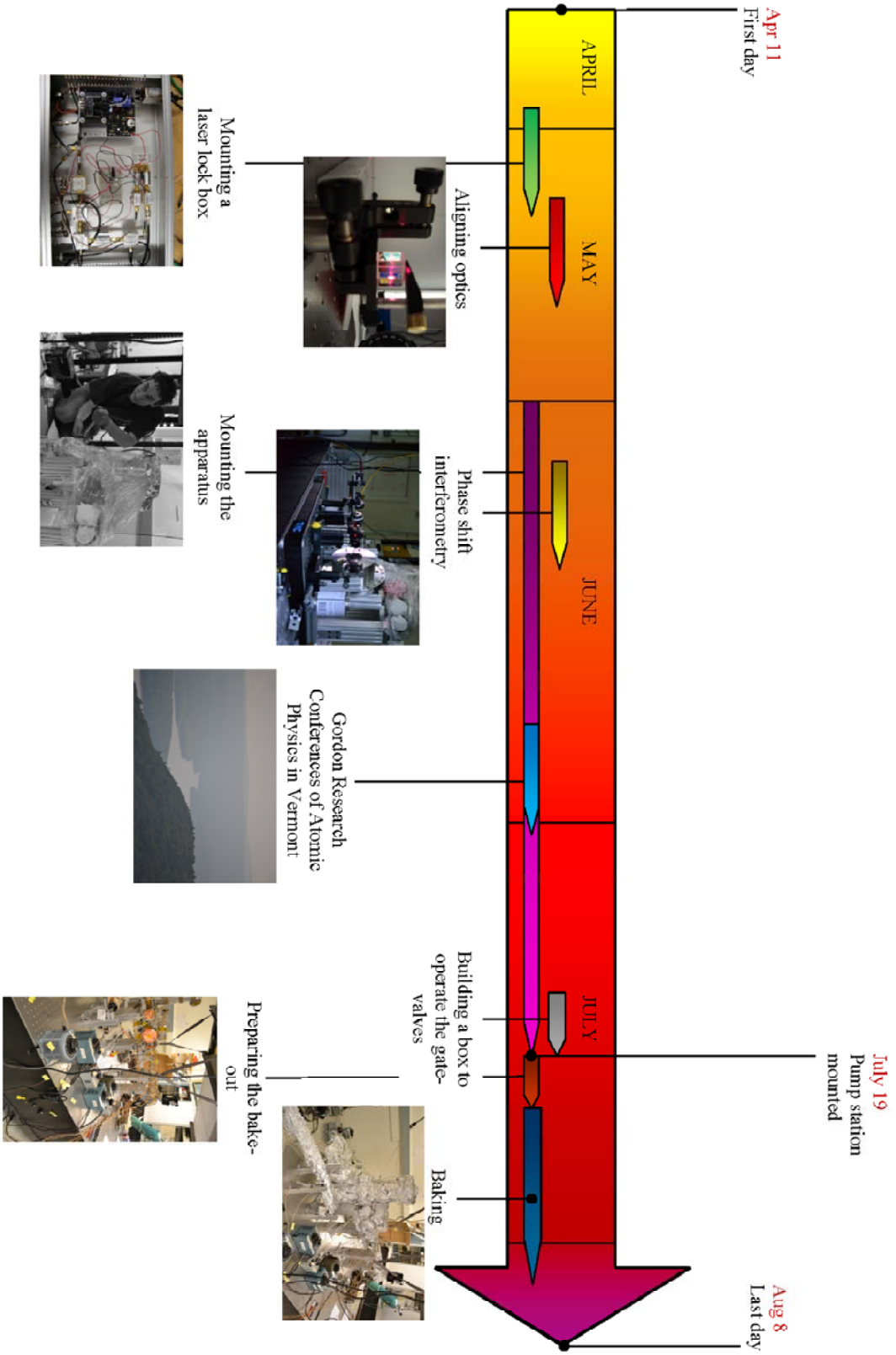
April through August 2011

The project was namely to achieve UHV in our whole machine. The machine was composed of two main parts. First, the oven part where Lithium 7 atoms are emitted through a Zeeman Slower into the second part, the main chamber. The main chamber is where the experiments involving optical lattices and magneto optical trapping (MOT) will take place.

CALENDAR


Apr 11
First day
APRIL
MAY
JUNE
JULY
July 19
Pump station
mounted
Aug 8
Last day
Aligning optics
Mounting a
laser lock box
Phase shift
interferometry
Mounting the
apparatus
Gordon Research
Conferences of Atomic
Physics in Vermont
Building a box to
operate the gate-
valves
Baking
Preparing the bake-
out

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1. Notes: Before baking-out

The baking-out process is required to achieve ultra-high-vacuum, UHV; basically it consists of baking the walls, windows, gauges, pumps in order to allow them to outgas. Once done, the experiment environment is cleaner than ever before and therefore UHV experiments are made possible.

1.1. Mounting order

The first step is to mount all the different parts of the apparatus shown below.

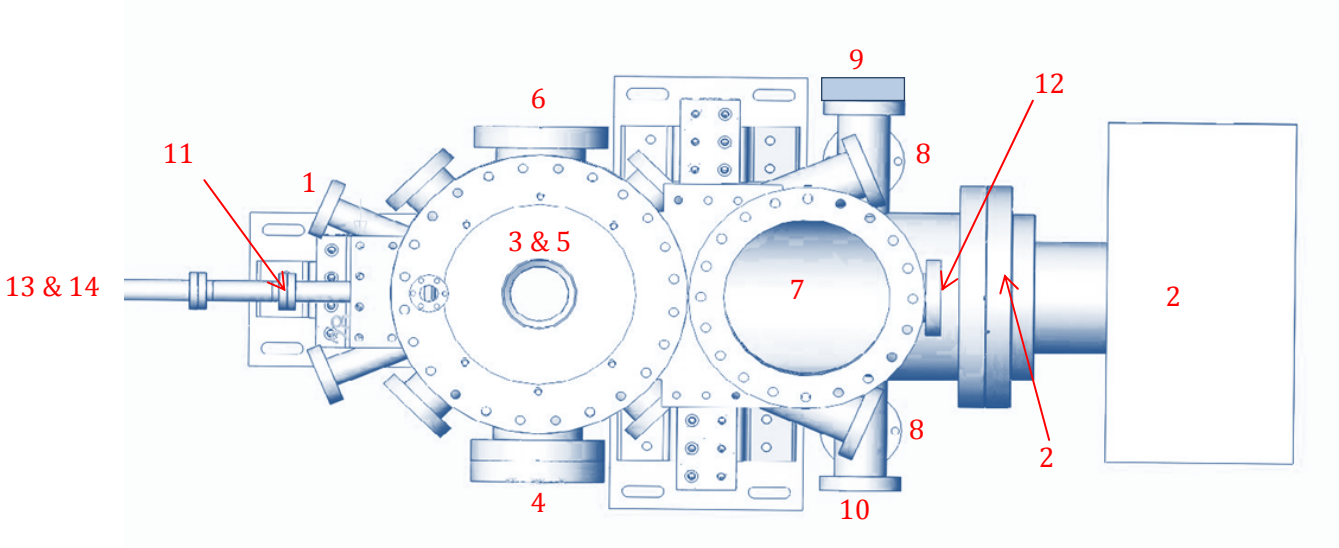


Figure 1. Mounting-order of the main-chamber

1. The four windows on each side of the Zeeman slower, see appendix 9 for a description of the slower
2. Reducer & Ion pump, see appendix 8 for the Ion pump
3. Bottom 10" flange
4. Side bucket window + RF antenna
5. Upper 10" flange & 1,33" RF flange
6. Other windows of the main-chamber
7. Reducer for Titanium Sublimation Pump (TSP) & TSP, see appendix 10 for the TSP
8. Ion gauge & symmetric blank flange, see appendix 6 for the Ion gauge
9. Angle-valve
10. Residual Gas Analyzer, see appendix 7 for the RGA
11. Zeeman slower & bellows
12. $2-3/4$" window
13. Gate-valves
14. Pump station (connected to the angle-valve)
15. (blank after gate valve)

While mounting, we have to make sure that the elements of the assembly are clean by cleaning them with at least propanol. If some parts look dirty, we clean them with an ultrasound cleaner. Then we must make sure that all flanges are tightened with the right torque.

Table 1. Flange torque values

Flange OD (in.)	1-1/3	2-1/8	2-3/4	4-1/2	6	8	10
Bolt torque (in.-lbs.)	84	140	144	180	180	180	180

Once the whole machine is mounted, we can start pumping. This is not a step of the bake because we didn't put the heaters on yet; we just want to see how our system behaves, for example, how long it takes it to get to a given pressure. We also want to see if there is already a leak due to the mounting itself.

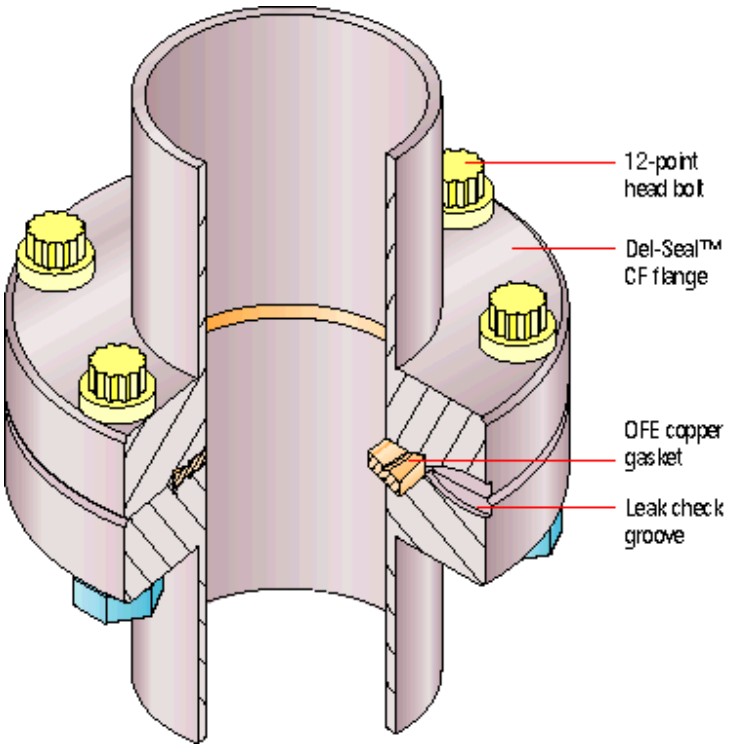


Figure 2. Description of a flange, a copper ring is used as a gasket to seal the two flanges. Each flange has two snuffing ports for leak checking.

1.2. Looking for leaks

We turn on the roughing pump. After a few hours, the pressure should drop to the $mTorr$ level. In our case, the roughing pump is supposed to achieve 8 $mTorr$ as written on the pump. Turn on the turbo pump - Starcell 75 in our case. After a few hours, the pressure should be below $10^{-6}\ Torr$.

If a leak occurs, locate it precisely using the He leak detector (or Residual Gas Analyzer + Helium blowing from a nozzle). You have located the leak only if you get a response with very low flow of He (2 bubbles per sec). Big leaks can be hard to locate cause they are likely to respond to He sprayed at different parts of the chamber. Always remove the heater of the flange you are testing and go directly to the sniffing ports (on both sides); nevertheless if you want to make a quick test, you can blow Helium at high pressure (about 10 Psi). The thing is, the room will now contain a lot of Helium, preventing a further more sensitive leak test before another few hours.

If the pressure is below 10^{-5} Torr, you can use the RGA to do a sensitive He leak testing.

In order to get rid of leaks, before un-mounting anything, first try to tighten bolts, it may work.

1.3. Putting-on heaters

- Put all heaters in place. Make sure they have good thermal contact.
- Use aluminum foils to fill gaps between heater and chamber, watch for non-insulated wires.
- Don't leave any ends dangling (the heater tapes should be disposed in order to have a constant tape-to-chamber ratio, tapes are applied to objects proportional to their surface)
- When tightening heating tape with a hose clamp, apply C100 on the thread of screws
- Label wires.
- Test the heaters by turning them on individually and touching them by hand.
- Don't use heating tape around elbows.

1.4. Putting on the thermocouples

Once all the heaters are in place, we have to put thermocouples to control the heating up. At the very least use one sensor for one heater. We will systematically check the temperature during the bake-out (see appendix 3 to see how the T-check was done).

1.5. Wrapping the chamber

- Make sure the windows are clean before wrapping.
- Use at least two layers of standard aluminum foils everywhere. Make sure the windows are well wrapped.
- Bottom flanges wraps tend to be loose during bake-out, don't let that happen.
- Wrap Ion gages, RGA port and TSP, Ion pump connector completely. (You can remove some foils at later stages of the bake-out if any of them is needed)
- Make sure that water, air- lines and plastic wires are far removed from anything that might get hot.
- Also wrap the slower and gate valves towards the oven. Make sure that the heating tapes are on good contact with the slower magnet, the gate valve itself and the oven side of the gate valve.
- Fill the magnetic flanges and recessed viewport with loose aluminum foil to keep convection at a minimum.

2. Notes: During baking-out

2.1. During warm up

- The maximum temperature of our bake-out is below $250°C$.
- The ion pump should be off during the warm-up (the ion pump is more fragile than the turbo pump for collecting bulks)
- Gauges are disconnected during the first phase of the bake-out since the pressure might temporarily rise to $10^{-3}\ Torr$ which could make the filaments burn out.
- Heat the whole apparatus by $1-2$ hours steps of $50°C$ and let the temperature values reach a steady value. Be aware that thermocouples are not really reliable, double checking each temperature is probably a good idea.
- We will tolerate a 10 degrees deviation from target temperature.
- Sometimes heaters burn out during the bake (make sure of that by measuring their resistance), use Kapton tape in such a case.
- If a spot appears to be at the wrong temperature, correct it slightly, then wait for at least half an hour before checking it again.
- Also look for leaks that could occur. At this stage, it's better to interrupt the bake-out, fix the leak then start all over again.

Table 1. Theoretical bake-out temperatures (non-realistic)

Slower	160°C
Slower gate valve	100°C if closed, 200°C open
Turbo pump	120°C at inlet valve
Field of view of the turbo	200°C
Body of the turbo	Not baked
Ion pump	200°C to 250°C
RGA without ECU	300°C
RGA operating	80°C
Windows, TSP	200°C to 250°C
Ion gauge nude	450°C
Ion gauge operating	250°C
Metal valve	100°C
Kapton wire	<250°C

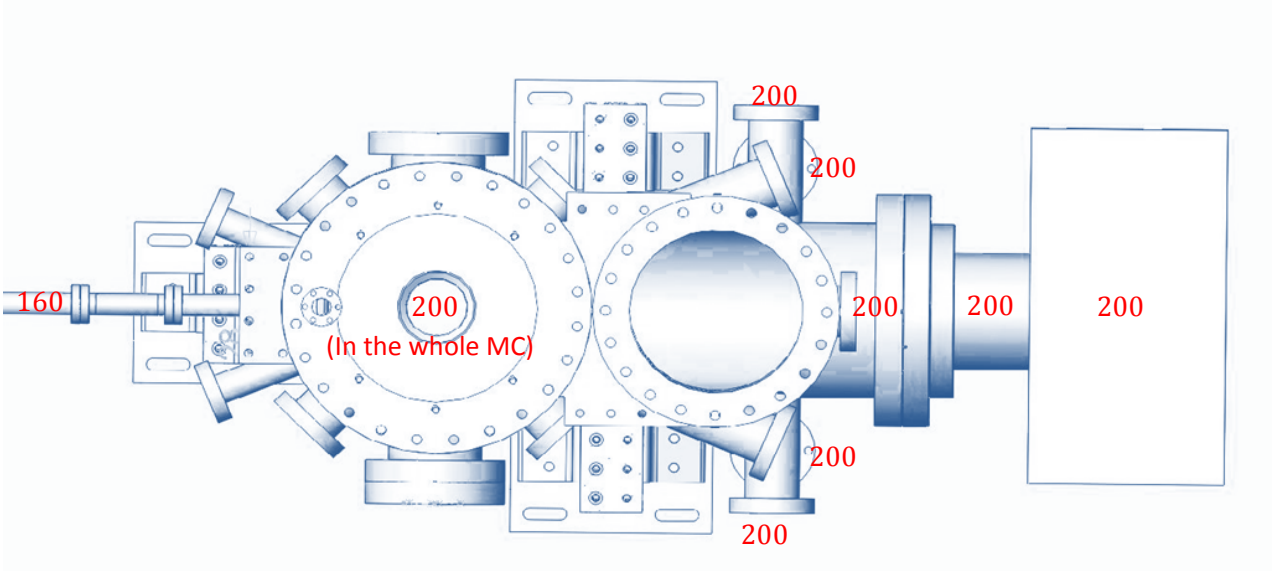


Figure 3. More realistic pattern of bake-out temperatures (strong gradients smoothed)

After discussing it during a previous meeting, achieving 160C in the slower should be OK because of the low heat-flows predicted between the tube and the MC due to the design. We can't heat more than that because the Kapton used for insulation would burn.
With our selected temperatures, the warm up phase should last from 4 to 6 hrs.

2.2. Actual bake-out phase

About out-gassing: while out-gassing, the pressure while rise significantly (typically by 3 orders of magnitude); if the pressure doesn't rise while out-gassing, that means there is nothing to out-gas: drop it for this time.

- Run the turbo pump for 24 hours (at the very least 12); degas the getter filaments for 30 sec at 5 Amp after 12 then after 24 hrs.
- After those 24 hours, the pressure should be less than 10^{-6} Torr, you can use the RGA as soon as the pressure is below 10^{-4}; turn on the ion pump(the pressure has to be below 10^{-6} when you do that and might increase as the internal components are heated). When the ion pump is stabilized, valve off the turbo pump, when the valve is above room temperature, close it finger tight. Therefore, don't allow the turbo pump to spin down until the system is back to room temperature. Good to know: you may want to apply a high voltage (> kV) on the ion pump to get it quickly started; decrease the voltage afterwards (an Ion pump controller does that automatically).
- About turning on the Ion Pump: when turned on for the first time, the ion pump controller will read a current above 15 mA and a low voltage. The trick is to turn on the turbo for a few sec (10 to 30) then to turn it back off for another minute and to repeat this cycle until you reach the appropriate values of current/voltage (it takes typically 30 cycles).
- After the second day of baking-out, first turn off the ion gauges, the RGA and the ion pump during all the process (the pressure might get temporary high). Degas the Ti filaments. The voltage drop should be about $3V$ ($\pm 10\%$) across every filament. Degas every filament two times, because dirt coming for a given filament might contaminate the previous one. Turn back on the devices you previously switched off.

- Degas the ion gauge filaments: turn off the TSP, RGA, the ion pump, switch each filaments (each gauge has 2) to degassing mode for about 2 hours. The controller will probably turn it off after 30 minutes, put the filaments back on degassing mode in such a case. (manual: *If using degas, a 15 minute e-beam degas duration, using Vacuum Technologies Multi-Gauge and sen Torr controllers, is all that is needed. Extending the degas interval only serves to heat up the surrounding chamber walls and increases the out-gassing rate from those surfaces. Bake-out is a better way to degas chamber walls.*)
- Degas the RGA: first turn off the TSP, the ion gauges, ion pump. Hook up the RGA head and air-cool it with a fan (from quite far away) so it does not get too hot. Make sure that the rest of the bake-out is not affected by this cooling. Switch the RGA to degassing mode *for about 2 hours* (2 hours looks impossible by reading the manual, chapter 8-7) (sometimes the filament trips when you turn it on the first time, since it senses its own dirt; just turn it on/off a couple of times until it stops tripping)
- Repeat these degassing operations on the fourth and sixth days of bake-out

3. Notes: After baking-out

- On the last-day of bake-out: about 5 to 10 hours before starting cooling down, turn on the ion pump (make sure the pressure is below 10^{-6} before you do that). The pressure should drop from up to five units during the next half hour; if not turn off the ion pump and retry later.
- Right before cooling-down: valve-off the turbo pump and shut it down.
- Now start cooling down: just repeat the reverse steps of the warming process, 50°C steps, the cooling down itself should last about 7hours. Take your time because leaks are likely to occur if you cool too quickly. (thermal stress inc)
- After cooling down, the pressure should be less or equal than 10^{-9} Torr. Spray Ti for about 20 min at a current of 48 Amp (no more!). After a couple of hours the final pressure is achieved.

4. Our bake-out, results

4.1. Rough pumping

First, the roughing pump is switched on until it reaches its lowest achievable pressure. The pump is supposed to go to 8 $mTorr$.

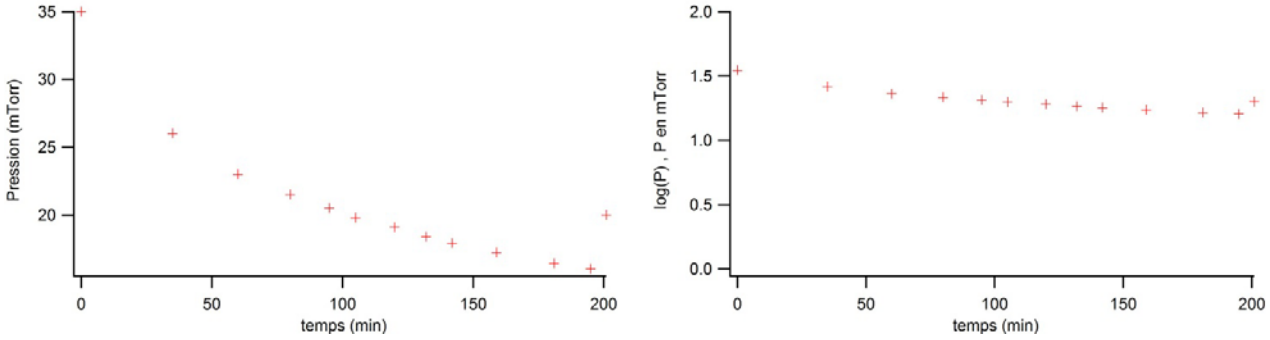


Figure 4. Pressure versus time during rough pumping.

After three hours and a half, a pressure of 16 $m\,Torr$ is achieved. It would take too long to wait till the max nominal value and it is also safe to switch on the turbo pump. (Usually, the turbo is switched on right after the roughing pump)

When the turbo pump is turned on at $t = 201\ min$, the pressure starts to rise, that's because the device heats up and therefore outgases.

Time (min)	Pressure (mTorr)	logP
0	35	1.54
35	26	1.41
60	23	1.36
80	21.5	1.33
95	20.5	1.31
105	19.8	1.30
120	19.1	1.28
132	18.4	1.26
142	17.9	1.25
159	17.2	1.24
181	16.4	1.21
195	16	1.20
201	20	1.30

Figure 5. Table of pressure, time

4.2. Turbo pumping

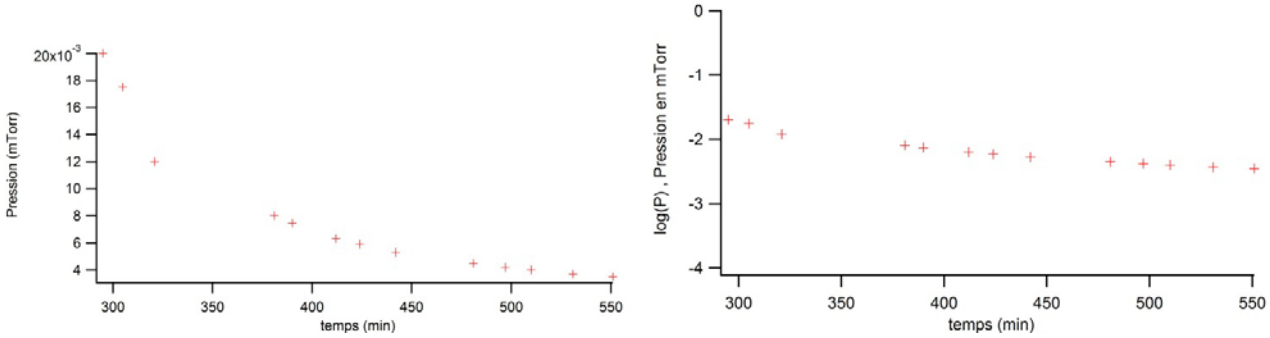


Figure 6. Pressure versus time during the beginning of turbo pumping.

It takes about 5 hours to get beyond the $mTorr$ level.

Another day was necessary to get to the lowest pressure we could before the bake-out which is $8.10^{-7}Torr$.

This value shows that it's likely there is no leak at the moment. However, most of them show up during heating up and cooling down.

Time (min)	Pressure ($mTorr$)	logP
295	0.02	-1.70
305	0.0175	-1.76
321	0.012	-1.92
381	0.008	-2.10
390	0.00744	-2.13
412	0.0063	-2.20
424	0.0059	-2.23
442	0.0053	-2.28
481	0.0045	-2.35
497	0.0042	-2.38
510	0.004	-2.40
531	0.0037	-2.43
551	0.0035	-2.46

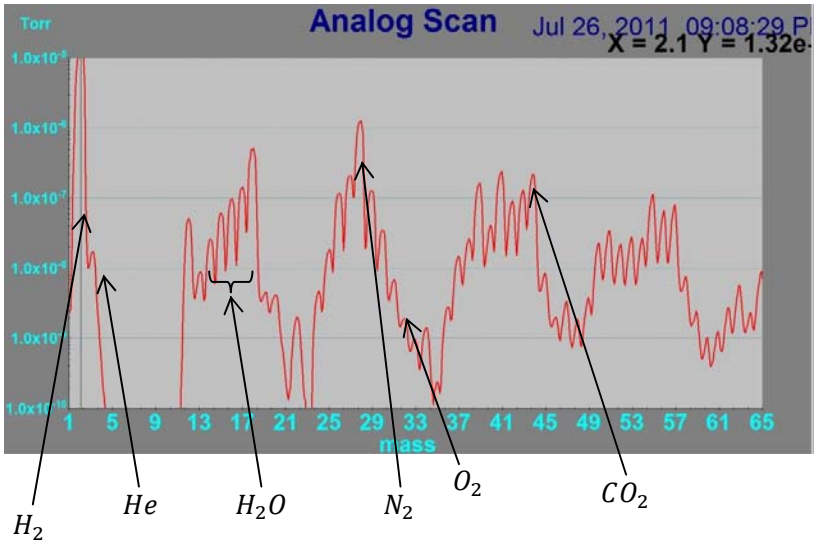
Figure 7. Values of time and pressure during turbo pumping.

4.3. RGA scans during the bake phase

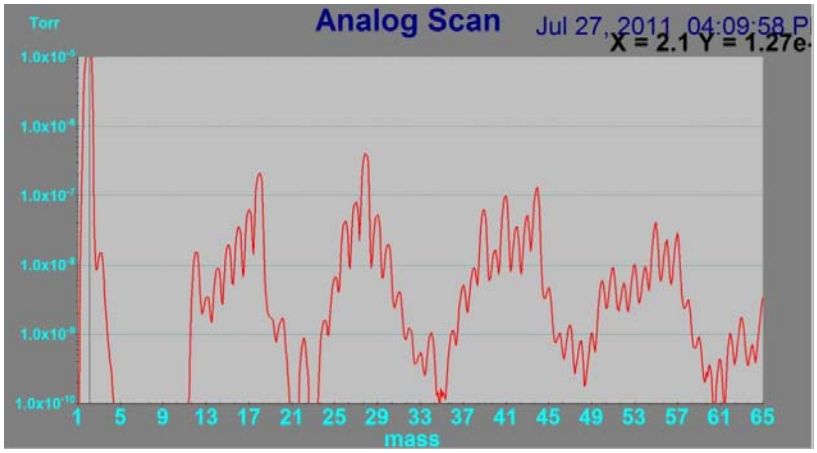
The Residual Scan Analyzer (RGA) allows us not only to get to know the pressure inside the apparatus, it also provides information about the composition of the inside gas. It is also a valuable tool for leak-checking: first if you want to do a Helium leak-check, the RGA can monitor the partial pressure of Helium only while you blow the gas around the apparatus and inside the sniffing ports of the flanges; second, all the pumps do not pump all the gases the same way, Hydrogen would be pumped by the Ion and Titanium sublimation pump mainly, and Oxygen is usually easily pumped by the roughing and turbo pumps. Therefore, by looking at a scan you should see a ratio of Oxygen-Nitrogen very different from $0.2 - 0.8$, which is the ambient air main composition. If such a ratio is to be seen, there is probably a leak.

The following plots show the evolution of the partial pressures of the different gases inside the chamber:

Figure 8. July 26, Turbo pump on and description of the important peaks



gaz	pourcentage
H_2	83%
CO	5%
H_20	4%
MP_{oil}	4%
N_2	2%
CO_2	2%
O_2	0%

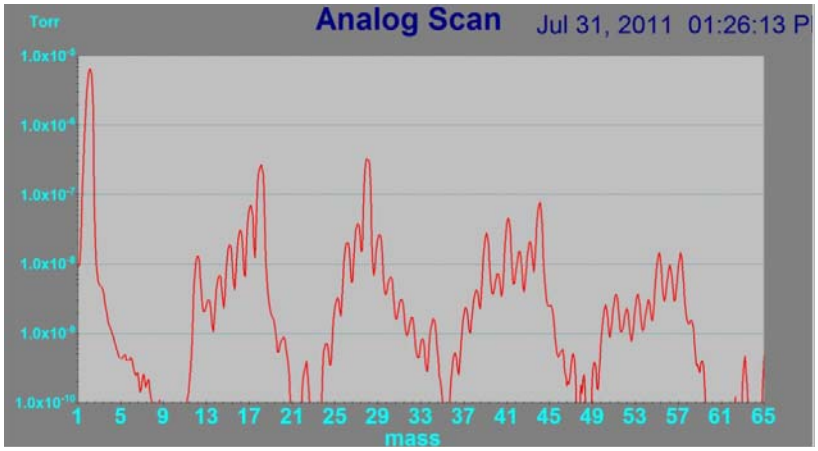


gaz	pourcentage
H_2	93%
CO	2%
H_20	2%
MP_{oil}	2%
N_2	1%
CO_2	1%
O_2	0%

Figure 9. July 27, 2nd day of turbo pumping

The scan up above shows that the turbo pump pumps all gases quite evenly except from Hydrogen. The total pressure based on Nitrogen pressure is below 10^{-6} $Torr$ according to the RGA and at the 10^{-5} level according to the ion gauge which is also based on the N_2 partial pressure. Those two different readings can be explained by the fact that the Ion gauge is closer to the turbo pump and also because of the value of the RGA's gain, indeed, it needs to be calibrated and was by the factory.

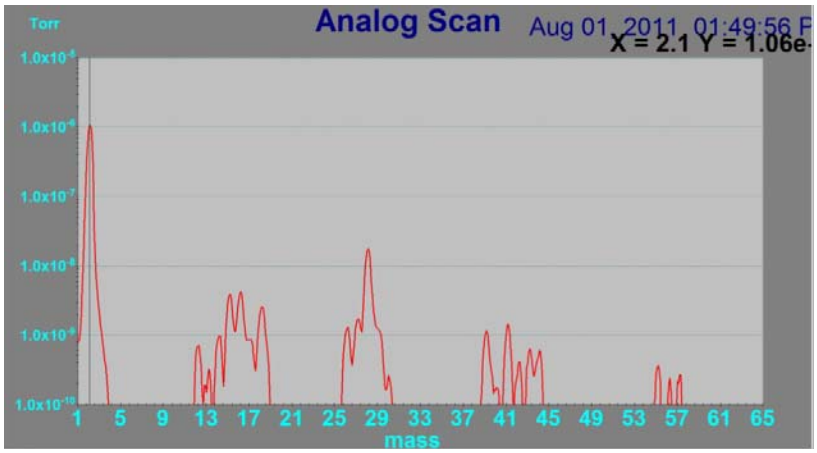
After five other days of baking, the scans still look very similar



gaz	pourcentage
H_2	88%
CO	3%
H_20	5%
MP_{oil}	2%
N_2	2%
CO_2	1%
O_2	0%

Figure 10. July 31, right before activating the Ion pump.

Turning on the Ion pump brings a drastic change



gaz	pourcentage
H_2	97%
CO	$< 1\%$
H_20	$< 1\%$
MP_{oil}	$< 1\%$
N_2	$< 1\%$
CO_2	1%
O_2	0%

Figure 11. August 1st after turning on the Ion pump.

Now that the pressure is low enough, the pumping station can be disconnected. This reduces the volume of the apparatus and disconnects the coldest spot of the baking, thereby improving it.

Only 2 hours later, the vacuum improved a lot, reaching the $10^{-8}\ Torr$ level. The inside gas is now composed by Hydrogen and Nitrogen mainly.

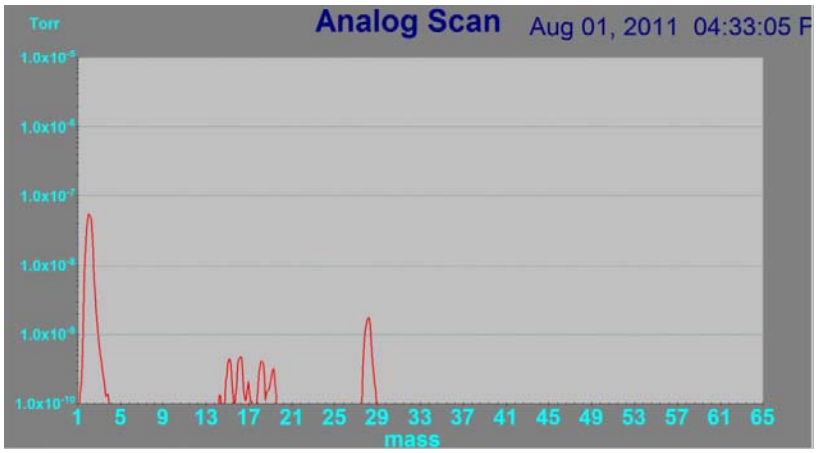


Figure 12. August 1st, after disconnecting the pumping station.

Finally, we decrease the temperature, there remains almost only Hydrogen

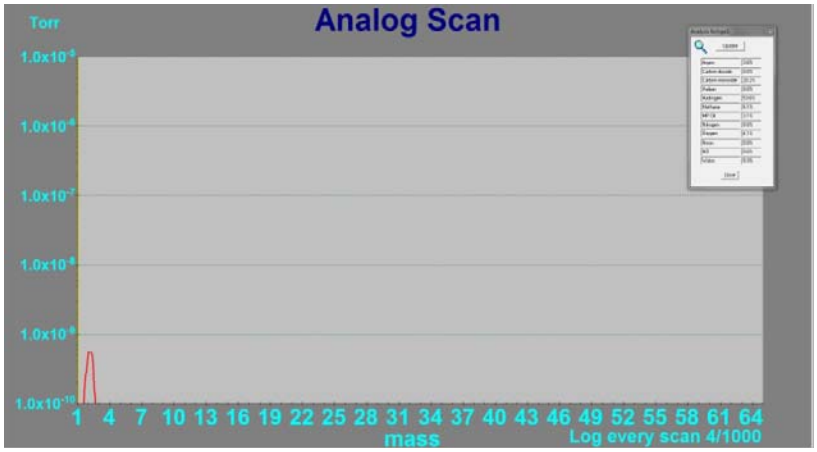


Figure 13. Decreasing the temperature.

The final step is to switch on the TSP.

4.4. Final pressure, conclusion.

When the system was cold and the TSP had run for two days, the pressure was below $8.10^{-11}\ Torr$. After another week, the pressure is below $2.10^{-11}\ Torr$ and keeps dropping. This bake is a success and the vacuum achieved should allow the people working in the lab to condensate Lithium7 atoms and trap them in a magneto optical trap once the oven part is mounted.

5. Bibliography

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- manuals: 75 L/sec Starcell Ion Pump from Varian, UHV-24p Ionization gauge from Agilent, RGA 100 from Stanford Research Systems, ESDP12 Scroll pump from Edwards, Titanium Sublimation Cartridge 916-0050 from Agilent

APPENDIX 1 – How to …

1. Put-on flanges

- Wear gloves
- If the flange is smaller than 2-¾", max torque 16 ft. pounds. If the flange is bigger than 4.5", max torque 26 ft. pounds. (But MDC says mdc says 12 to 15 ft. pounds (15 for the 10" flange))
- Try to use 12 pt. bolts and plate nuts in parts that are exposed to a high temperature during the bake-out. Those bolts are stronger than the conventional hex bolts. You also don't slip as easily when tightening them.
- Use C100 to keep bolts from ceasing: put a few mm^3 on the nut before screwing will do.
- About screwing itself: tighten evenly. The tightening process must be done gradually in ¼ to ½ turn increments by repeating the pattern of figure 4.
  After tightening, the two flange parts should kiss each other evenly. If some of the bolts are hard to screw or if any unevenness is noticed, you have to start all over again with a new gasket. (Beware: the bolts of steps 5 & 6 are more likely to touch the MC's walls and thereby losing their threading, think about using washers or shorter bolts in order to prevent that)

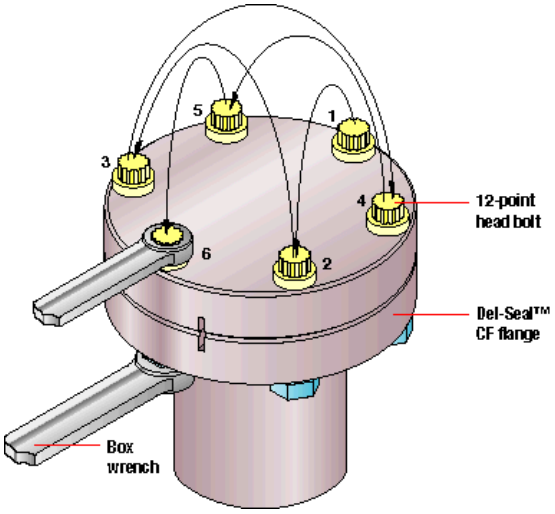


Figure 14. Tightening pattern

2. Clean flanges,…

- Place the parts in an ultrasonic cleaner (with strong soap) for up to an hour (if you're cleaning valves, don't forget to re-grease them afterwards)
- Rinse the parts with de-ionized water, then acetone and finally methanol
- Bake the parts for 4 hrs. at 400C
- After cooling down, wrap the parts in aluminum foil

APPENDIX 2 - Phase shift interferometry using polarized light

1. Principle

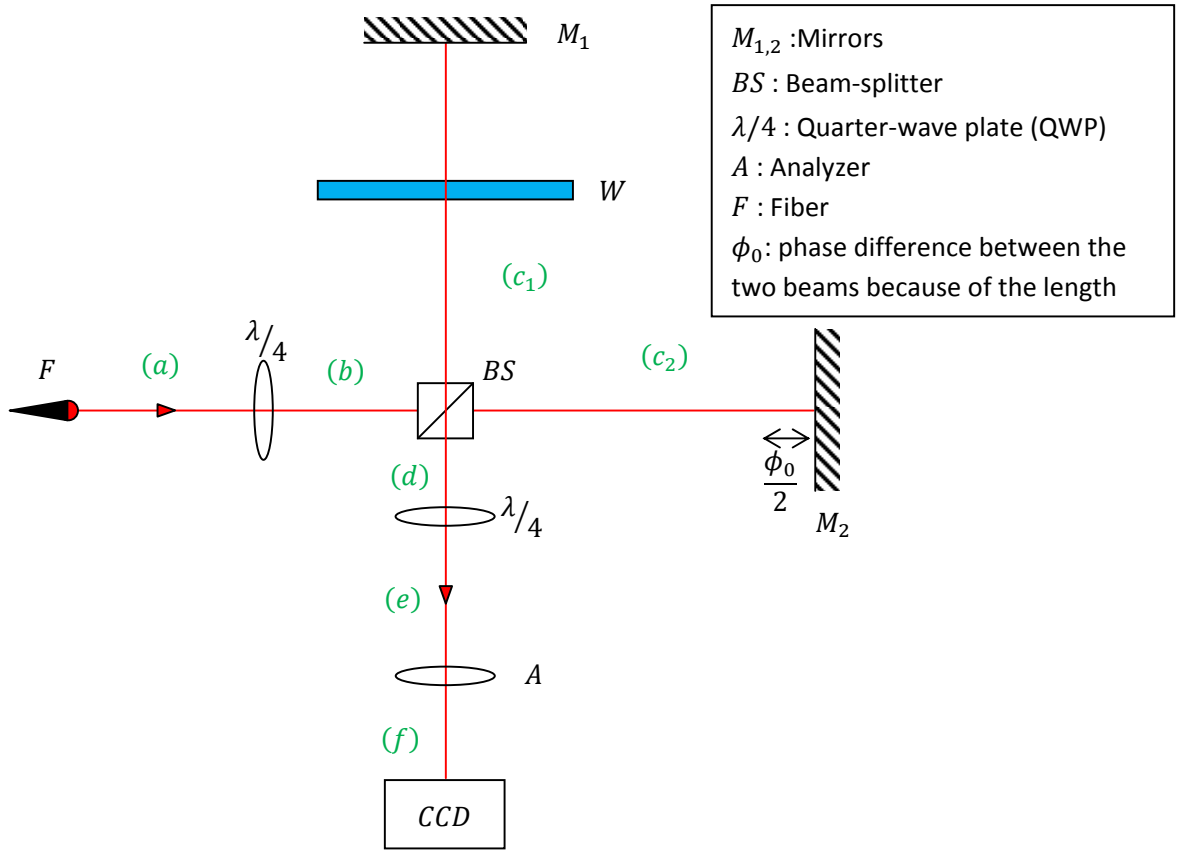


Figure 15. Interferometer set-up design

Polarization state of light :

- (a) : light emerging from the fiber, linear
- (b) : becomes circular after the QWP
- (c_1) & (c_2) : linear orthogonal to each other due to the BS
- (d) : superposition of the two orthogonal polarizations
- (e) : superposition of two circular polarizations in opposite directions
- (f) : linear

This method is meant to describe the flatness of the main-chamber's optical windows. The experimental set-up is the same as a Michelson interferometer where the mirrors are perpendicularly oriented. The difference with a classical interferometer is that the light is polarized by the beam-splitter. Each beam emerging from it is polarized in two orthogonal directions. The beams are then made circularly polarized by using a $45°$ oriented quarter-wave-plate, thereby allowing the two beams to interfere.

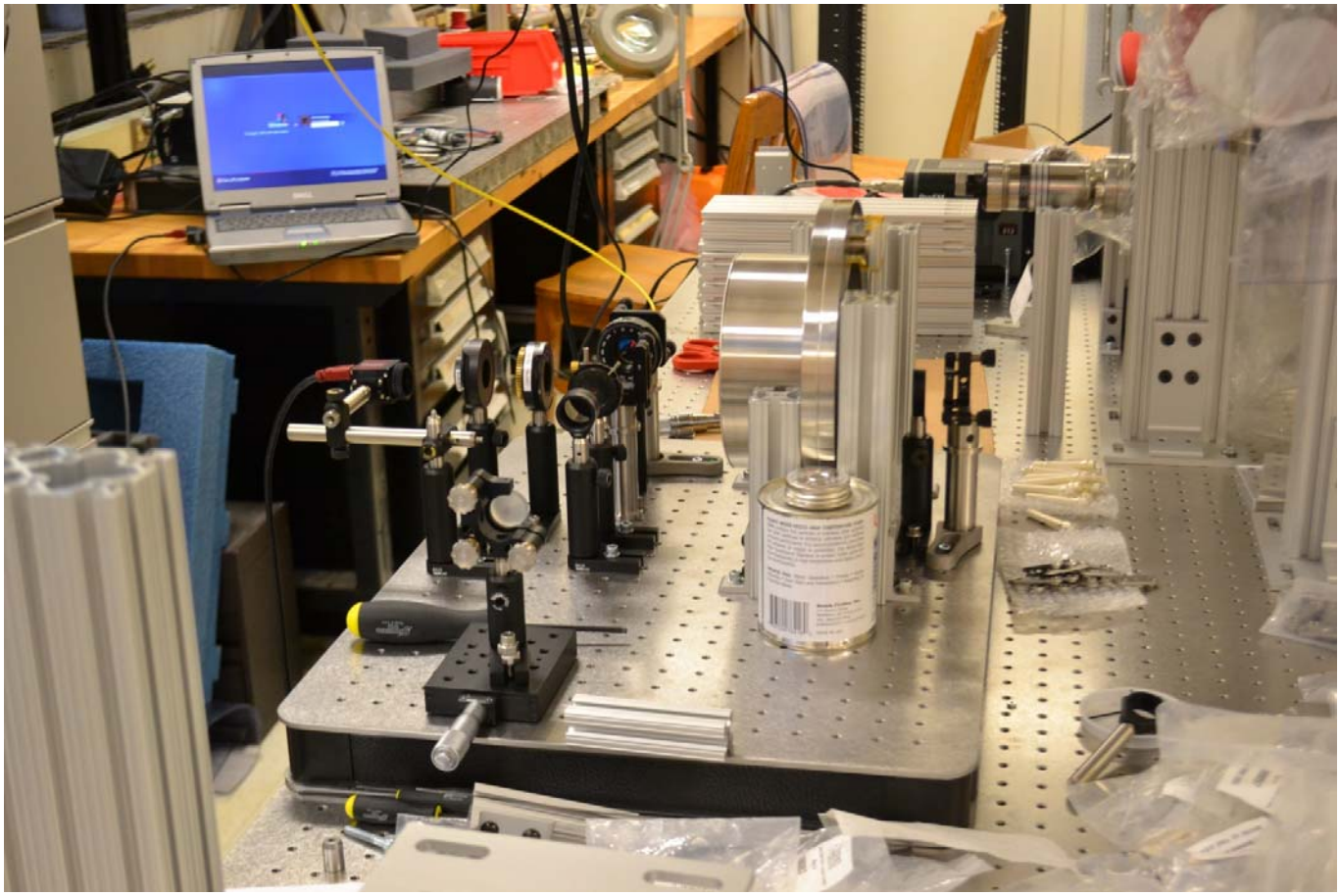


Figure 16. Actual interferometer

Four interference patterns are then recorded after an analyzer with a CCD camera by 45° steps of the analyzer.

X and Y are the neutral axis of the wave-plate

2. Phase map expression

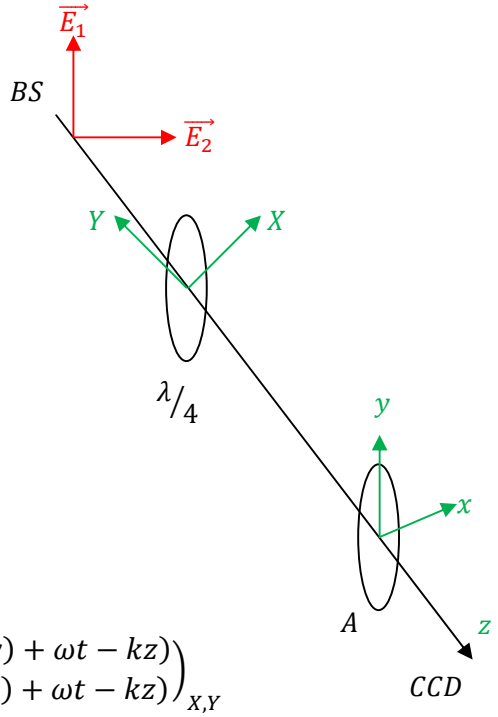
$$\begin{cases} \overrightarrow{E_1}(x,y,z,t) = E_0 \cos(\phi(x,y) + \omega t - kz)\,\overrightarrow{e_x} \\ \overrightarrow{E_2}(x,y,z,t) = E_0 \cos(\phi_0 + \omega t - kz)\,\overrightarrow{e_y} \end{cases}$$

The QWP is oriented such that:

$$\overrightarrow{e_x} = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 \\ -1 \end{pmatrix}_{X,Y} ; \overrightarrow{e_y} = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 \\ 1 \end{pmatrix}_{X,Y}$$

Thus,

$$\begin{cases} \overrightarrow{E_1}(x,y,z,t) = \frac{E_0}{\sqrt{2}}\cos(\phi(x,y) + \omega t - kz)\begin{pmatrix} 1 \\ -1 \end{pmatrix}_{X,Y} \\ \overrightarrow{E_2}(x,y,z,t) = \frac{E_0}{\sqrt{2}}\cos(\phi_0 + \omega t - kz)\begin{pmatrix} 1 \\ 1 \end{pmatrix}_{X,Y} \end{cases}$$



Let's choose the QWP located in $z = 0$, then, for $z > 0$:

$$\overrightarrow{E_1}(x,y,z,t) = -\frac{E_0}{\sqrt{2}}\begin{pmatrix} \cos(\phi(x,y) + \omega t - kz) \\ \sin(\phi(x,y) + \omega t - kz) \end{pmatrix}_{X,Y}$$

$$\overrightarrow{E_2}(x,y,z,t) = \frac{E_0}{\sqrt{2}}\begin{pmatrix}\cos(\phi_0+\omega t-kz)\\ -\sin(\phi_0+\omega t-kz)\end{pmatrix}_{X,Y}$$

(by readjusting the time origin)
By redefining the time origin again, we obtain:

$$\begin{cases}\overrightarrow{E_1}(x,y,z,t) = -\frac{E_0}{\sqrt{2}}\begin{pmatrix}\cos(\phi'(x,y)+\omega t-kz)\\ \sin(\phi'(x,y)+\omega t-kz)\end{pmatrix}_{X,Y}\\ \overrightarrow{E_2}(x,y,z,t) = \frac{E_0}{\sqrt{2}}\begin{pmatrix}\cos(\omega t-kz)\\ -\sin(\omega t-kz)\end{pmatrix}_{X,Y}\end{cases}$$

Where

$$\phi'(x,y) = \phi(x,y) - \phi_0$$

Let's write

$$\vec{E}(x,y,z,t) = \overrightarrow{E_1} + \overrightarrow{E_2}$$

And using the complex formalism:

$$\underline{\vec{E}} = \underline{\vec{E}_1} + \underline{\vec{E}_2} = -\frac{E_0}{\sqrt{2}}e^{i\left(\phi'(x,y)+\psi(z,t)\right)} + \frac{E_0}{\sqrt{2}}e^{-i\psi(z,t)} \quad ; \quad \psi(z,t) = \omega t - kz$$

Hence,

$$\underline{\vec{E}} = -\frac{E_0}{\sqrt{2}}e^{-i\phi'(x,y)}\left(e^{i\left(\frac{\phi'(x,y)}{2}+\psi(z,t)\right)} + e^{-i\left(\frac{\phi'(x,y)}{2}+\psi(z,t)\right)}\right) = -\sqrt{2}E_0\cos\left(\frac{\phi'(x,y)}{2}+\psi(z,t)\right)e^{-i\phi'(x,y)}$$

$$\underline{\vec{E}} = E_0' e^{-i\phi'(x,y)}$$

The first picture is made for $\theta = 0$, meaning $\underline{\vec{E}}$ has to be projected along the real axis, then:

$$I_{\theta=0}(x,y) = I_I(x,y) = {E_0'}^2\cos^2\phi'(x,y)$$

For $\theta = 45°$, we project along $\frac{1}{\sqrt{2}}\begin{pmatrix}1\\-1\end{pmatrix}$

$$I_{theta=45°}(x,y) = I_{II}(x,y) = \frac{{E_0'}^2}{2}(\cos\phi'(x,y) + \sin\phi'(x,y))^2$$

Thus,

$$I_{II}(x,y) = \frac{{E_0'}^2}{2}(1 + 2\sin\phi'(x,y)\cos\phi'(x,y))$$

Following the same calculus, we obtain:

$$\begin{cases} I_I(x,y) = {E_0'}^2\cos^2\phi'(x,y)\\ I_{II}(x,y) = \frac{{E_0'}^2}{2}(1 + 2\sin\phi'(x,y)\cos\phi'(x,y))\\ I_{III}(x,y) = \frac{{E_0'}^2}{2}\sin^2\phi'(x,y)\\ I_{IV}(x,y) = \frac{{E_0'}^2}{2}(1 - 2\sin\phi'(x,y)\cos\phi'(x,y))\end{cases}$$

We finally obtain:

$$\frac{I_{IV}-I_{II}}{I_I-I_{III}}=\frac{-\sin\phi'(x,y)\cos\phi'(x,y)}{\cos^2\phi'(x,y)-\sin^2\phi'(x,y)}=-\frac{1}{\frac{1}{\tan\phi'}-\tan\phi'}$$

$$\Leftrightarrow \frac{I_{IV}-I_{II}}{I_I-I_{III}}\tan^2\phi'-\tan\phi'-\frac{I_{IV}-I_{II}}{I_I-I_{III}}=0 \quad \Rightarrow \phi'(x,y)=\tan^{-1}\left(\frac{1\pm\sqrt{1+4\left(\frac{I_{IV}-I_{II}}{I_I-I_{III}}\right)^2}}{2\frac{I_{IV}-I_{II}}{I_I-I_{III}}}\right)$$

Finally, writing $\frac{I_{IV}-I_{II}}{I_I-I_{III}}=f(x,y)$

$$\phi(x,y)=\phi_0+\tan^{-1}\left(\frac{1\pm\sqrt{1+4f(x,y)^2}}{2f(x,y)}\right)$$

It is now clear that recording those four interference patterns allows us to know $\phi(x,y)$, thereby the flatness of the window.

3. Comparison with the classical phase shift interferometer

The classical one uses a real Michelson interferometer and instead of spinning the orientation of an analyzer, people actually shift one of the arm by $\lambda/8$ steps. Thus,

$$I(x,y)=I_0\left(1+\cos\left(\phi(x,y)-\phi_0+\frac{2\pi 2l}{\lambda}\right)\right)$$

where l is the length shift and $2l$ the path difference between the two beams.

We obtain,

$$I_I=I_0(1+\cos(\phi(x,y)-\phi_0)) \quad I_{II}=I_0(1-\sin(\phi(x,y)-\phi_0))$$
$$I_I=I_0(1-\cos(\phi(x,y)-\phi_0)) \quad I_{II}=I_0(1+\sin(\phi(x,y)-\phi_0))$$

Thus,

$$\phi(x,y)=\phi_0+\tan^{-1}\left(\frac{I_{IV}-I_{II}}{I_I-I_{III}}\right)$$

We see that we have:

$\phi(x,y)=\phi_0+\tan^{-1}\left(\frac{1\pm\sqrt{1+4f(x,y)^2}}{2f(x,y)}\right)$ for our interferometer and $\phi(x,y)=\phi_0+\tan^{-1}f(x)$ for the classical Michelson interferometer.

The other noticeable difference is that in our case we don't have to use a piezoelectric transducer (PZT) to shift the mirror by $\lambda/8$, instead of what we only have to turn the polarizer. This makes the experiment easier to install, cheaper but not more precise. Indeed in our case, the imprecision due to the manipulation of the analyzer is on the order of $\frac{1^\circ}{45^\circ}\simeq 2\%$. A so called "ultra-high precision" PZT positionner would induce a relative error on the order of $\frac{1\,nm}{671\,nm}\simeq 0{,}1\%$. However, we decided we didn't need such a good precision.

4. Images obtained

We've seen how we can obtain the expression of $\phi(x,y)$. Before plotting the phase map, we also calculate the phase map without the window and subtract it from $\phi(x,y)$ in order to get rid of the imperfections of the wave-plates, mirrors…

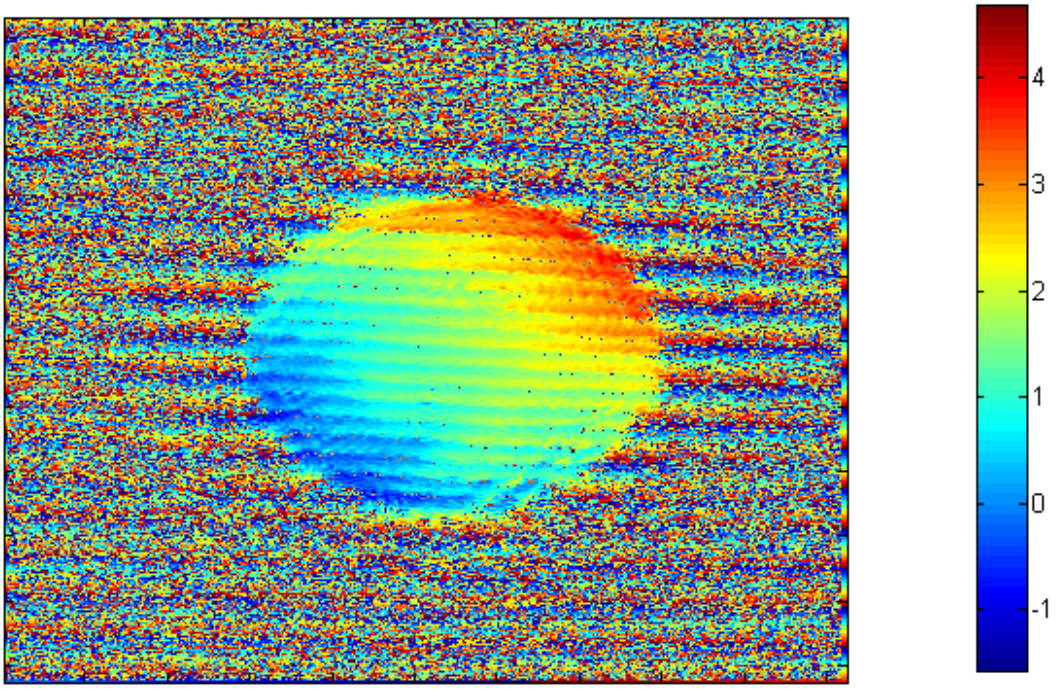
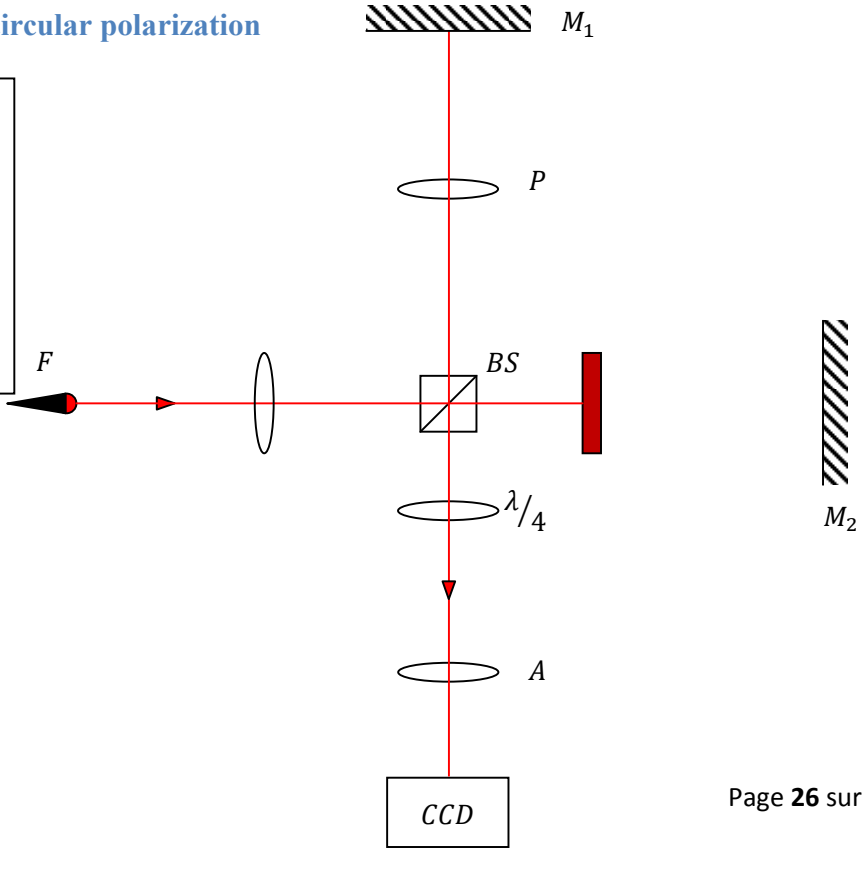


Figure 17. Typical phase map obtained

This technique convinced us that our windows can be properly used in our experiment.

5. Calibrating the QWP to get a circular polarization

$M_{1,2}$:Mirrors
P : Polarizer
$\lambda/4$: Quarter-wave plate (QWP)
A : Analyzer
F : Fiber
ϕ_0: phase difference between the two beams because of the length difference without W.



1. Without the QWP, using a power-meter instead of the CCD camera, get the lowest power: polarizer and analyzer are now crossed
2. Install the QWP, get the maximum value of power

Values:

QWP orientation (°)	Lowest power value (μW)	Highest value (μW)	Delta (μW)
251	13.7	18.7	5
252	14.0	18.4	4.4
253	14.1	18.2	4.1
254	13.9	18.4	4.5
256	13.5	19.1	5.6

We conclude that $253°$ is one of the orientation that gives the closest to a circular polarization.

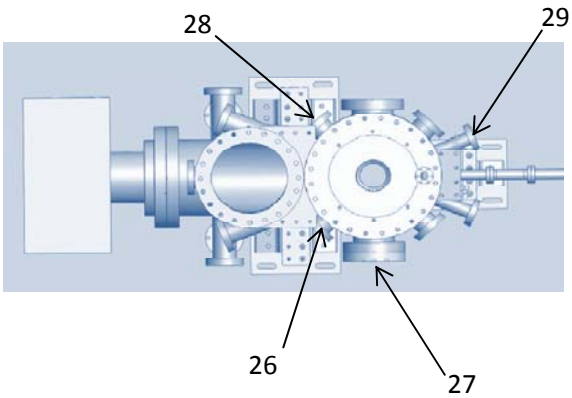
A $n\frac{\pi}{2}$ rotation of the QWP gives the other possible orientation. By measuring the power values around the $163°, 73°$ & $343°$ areas, we find out that $74°$ is the best orientation for the QWP ($Delta = 3.9\ \mu W$)

APPENDIX 3 - Example of Temperature-check

12/17, July 23rd, ~ $13h40$

#	Temp	#	Temp
1	156	16	193
2	135	17	145
3	146	18	68
4	89	19	212
5	155	20	205
6	115	21	218
7	117	22	146
8	191	23	209
9	220	24	222
10	198	25	219
11	240	26	213
12	203	27	202
13	218	28	200
14	178	29	207
15	239		

1. Main Zeeman 1
2. MZ 2
3. MZ 3
4. Bellows flange
5. Zeeman 2nd
6. GV1
7. GV2
8. Back of ion pump
9. Head of ion pump
10. Bottom back chimney
11. Side bottom chimney
23. Clamp window (left)
24. Clamp window (right)
25. Inside bottom bucket window
26. Window (left back)
12. Top chimney
13. Back MC window 1 (right)
14. Back MC window 2 (left)
15. Ion gauge
16. RGA
17. Bellows close to MC
18. Bellows close to RP
19. Inside and top of the bucket window
20. Loop MC top
21. Loop MC bottom 1 (left)
22. Loop MC bottom 2 (right)
27. Window (left middle)
28. Window right back
29. Window (right front)



APPENDIX 4 - -List of variable transformers (variacs)

1. Gate-valves 1 & 2, beginning of the Zeeman slower
2. Middle of the first part of the Z. slower
3. End of the first part of the Z. slower & bellows flange
4. Bellows and other part of the Z. slower
5. Inside bottom of bucket window & loop around chimney
6. Four windows on one side of the Main Chamber
7. Four windows on the other side of the MC
8. 2 symmetric windows heating clamps
9. Loop MC bottom
10. Inside & top of top bucket window
11. Loop MC top flange
12. Chimney bottom
13. Three windows on the back of the MC
14. RGA
15. 8" to 6" flange adapter & head of ion pump
16. Chimney top (TSP)
17. Ion pump body
18. Ion gauge & angle valve
19. Bellows between pump station and MC, closest to MC
20. Bellows between pump station (PS) and MC, closest to PS
21. Ion gauge on PS
22. Tee on PS
23. Angle valve on PS

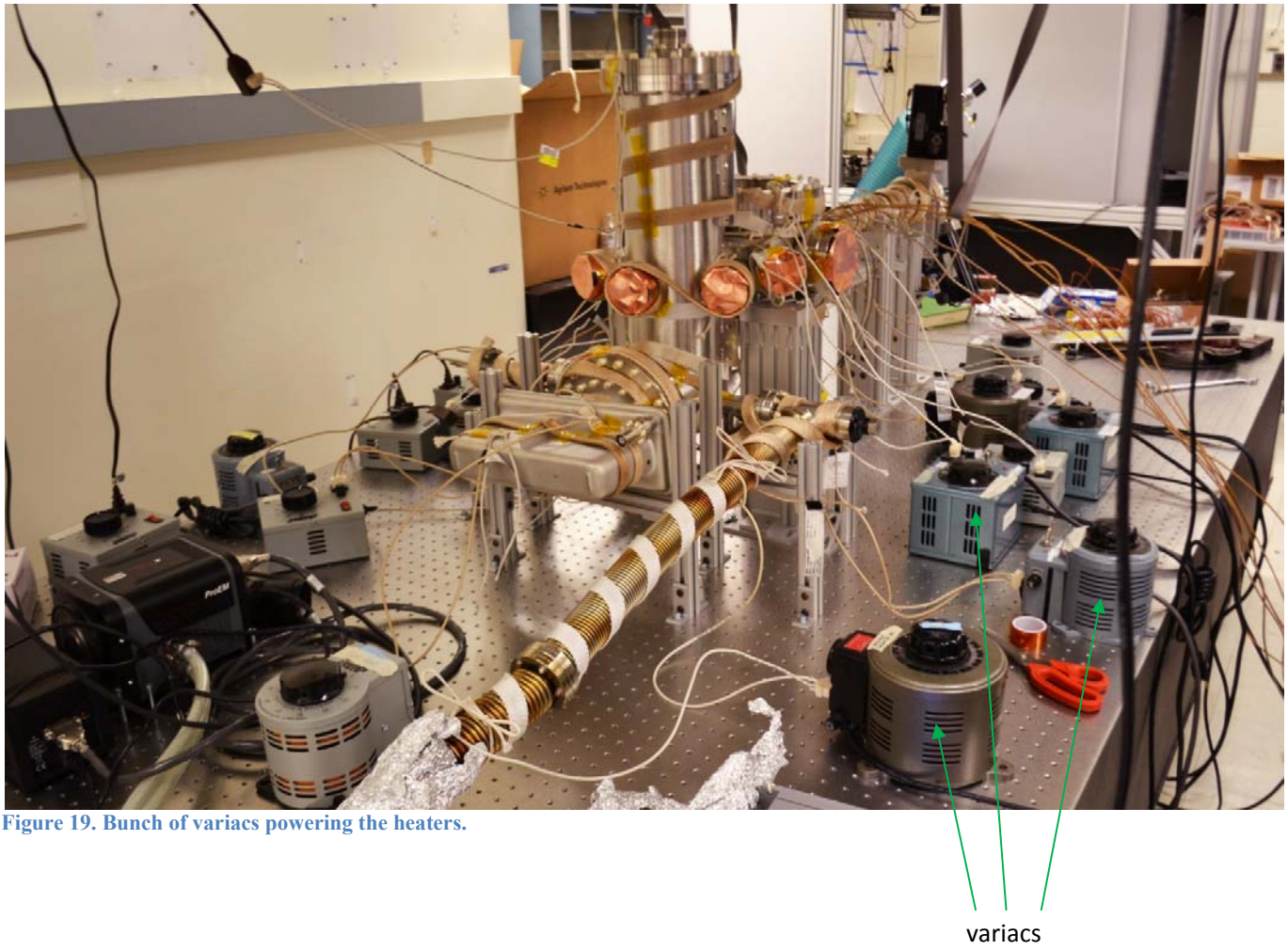


Figure 19. Bunch of variacs powering the heaters.

APPENDIX 5 - List of stuff ordered for the bake in April

Blank flanges (@ **MDC**)

- 1-1/3", 1 piece, #130000

Ion gauge (@ **MDC**)

- #432006

Nipples (for ion gauges) (@ **MDC**)

- #402002 (x2)

Feedthrough (@ **MDC**)

- For bucketwindows (1-1/3") (x2), probably will be #9412001

Gaskets (Copper) (@ **MDC**)

- 2-3/4", 6 holes, 24 spots, 18/60 pieces, #191004
- 1-1/3", 6 holes, 4 spots, 9/12 pieces, #19000
- 10", 24 holes, 3 spots, 9/9 pieces, #191019
- 6", 16 holes, 2 spots, 0/6 pieces, #191013
- 4-1/2", 8 holes, 12 spots, 0/30 pieces, #191009
- 2-1/8", 4 holes, 3 spots, 9/9 pieces, #191002
- 8", 2 spots, 10/10 pieces,
- 3", 1 spot, 0/2 pieces, David may have ordered them (nickel).

Tapped bolts (@ **MDC**)

MDC address: http://www.mdcvacuum.com/displayproductcontent.aspx?d=MDC&p=m.1.a.1.9

- 2-3/4", 66 needed, #190057
- 10", 48 needed, #190059
- 6", 32 needed, #190058
- 2-1/8", 8 needed, #190057

Adaptor (@ **Duniway**)

- 2-3/4 to 8" for TSP cartridge. Part # A800X275T

2 holes Plate-nuts (@ **Duniway**)
(@ http://www.duniway.com/images/pdf/pg/p-21-to-23-hard-bolts-studs-nuts.pdf)

- 2-3/4", ½*11*6=33 needed, PN-275-25
- 1-1/3", ½*6=3 needed, PN-133-25
- 10", ½*2*24=24 needed, PN-1000-25
- 6", ½*2*16=16 needed, PN-600-25
- 4-1/2", ½*2*8=8 needed, PN-450-25
- 2-1/8", ½*2*4=4 needed, PN-218-25

Heating tape (@ **OMEGA** *cf* desktop pdf)

Size	Model number	#
1" x 4'	**STH101-040**	6
1" x 2'	**STH101-020**	2
1/2" x 4'	**STH051-040**	2
1⁄2" x 2'	**STH051-020**	1

Handheld thermometer @ **OMEGA** (http://www.omega.com/ppt/pptsc.asp?ref=HH81A_82A)

Band heaters (@ **Omega**)

MC

- (1.75"x1.5") x 6, terminal style B, MBH-1715300B, (α), power 300W
- (3"x1.5") x 2, ts B, MBH-3015400, (β), 400W
- (1"x 1.5") x 2, ts B, MBH-1015130B, (γ), 130W

Tees

- (2.5"x1.5")x4, ts A, MBH-2515300A, (δ), 300W

Ion gauge nipples

- (1.5"x1.5")x4, ts A, MBH-1515275A, (ϵ), 275W

Power supply (for band heaters) (@**McMaster** Carr) (http://www.mcmaster.com/#variacs/=c18p7k)

- $(\alpha, \delta, \epsilon)$, 6994K32, (x14)
- (β), 6994K34, (x2)
- (γ), 6994K31, (x2)

Insulation tape (@ **McMaster** Carr http://www.mcmaster.com/#thermal-insulation-tape/=bzoaly)

1" width, 2 needed

(Temperature range: -100degF to +500degF)

Kapton tape

Anti-seize grease (@ **TsMoly**)

(http://www.tsmoly.com/catalog/product_info.php?cPath=1_7&products_id=115)

TS-84 synergel, 2.5 lb, temperature range $[-20{,}350]$ $(degF)$

Vacuum sealer (@**2spi** http://www.2spi.com/catalog/vac/vacleak.shtml)

- SPI# 05052-AB

APPENDIX 6 - UHV-24p Ionization Gauge

Manufacturer: Agilent Technologies
Cette jauge a un filament “à nu”, ce qui permet d’accroitre sa sensibilité jusque $5.10^{-11}\ Torr$ en conférant à l’imstrument une exposition maximale au vide.

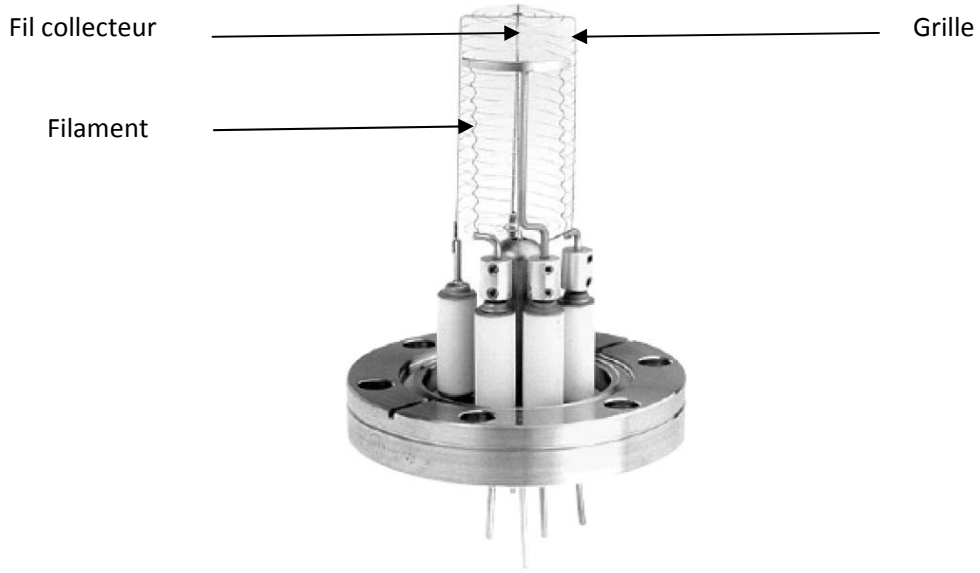


Figure 20. UHV 24 Ionization Gauge.

1. Eléments de la jauge

- Une source d’électrons: le filament.
- Une grille en forme de cylindre en acier inoxydable de Tungstene: sert de cathode (typiquement $+150V$ par rapport au filament) et collecte les electrons.
- Un fil “collecteur” en Tungstene au centre de la grille: collecte les ions (fonctionne à $+28V$ par rapport au filament).

2. Principe de fonctionnement:

1. Les électrons émis par le filament traversent la grille plusieurs fois en moyenne avant d’être “capturés” par celle-ci. C’est précisément lorsqu’ils sont “libres” que les électrons ionisent les molécules de gaz avec un taux qui est proportionnel à la densité de gaz.
2. Les ions ainsi formés sont accélérés vers le fil collecteur où ils sont neutralisés. Le courant d’ions positifs est proportionnel à la densité du gaz; ces ions, lorsqu’ils atteignent le collecteur créent à leur tour un courant d’électrons qui est ainsi un indicateur de la pression. Pour une valeur constante du potentiel d’ionisation, le nombre d’ions positifs créés est proportionnel avec la pression et le courant d’électrons:

$$I_c = S.P.I_e$$

- I_c est le courant en *Ampère* au niveau du collecteur.
- I_e le courant d’electrons au niveau de la grille.
- P la pression en $Torr$.

- S la sensibilité de la jauge, qui pour la notre est estimée à $20\ Torr^{-1}$ et est basée sur l'azote; le courant d'électrons vaut typiquement $4mA$; ainsi, pour une pression de $10^{-9}\ Torr$, le courant dans la jauge est estimé à $8.10^{-11}A$.

3. Dégazage de la jauge

Le principe consiste à faire circuler un courant élevé a travers la grille. La grille est alors portée a $+600V$, le courant d'electrons à $67mA$ et le filament à $7V$.

Source: *Instruction manual, UHV-24/UHV-24p Ionization Gauge,* *http://www.chem.agilent.com/Library/usermanuals/Public/6999-05-505E%20UHV-24%20UHV-24p%20Ionization%20Gauge%20Instruction%20Manual.pdf*

APPENDIX 7 - Residual Gas Analyzer (RGA)

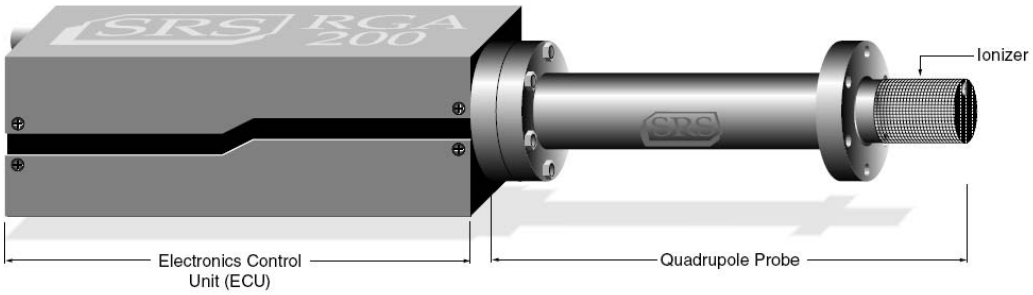


Figure 21. RGA elements

The RGA is a mass spectrometer of small physical dimensions. It is directly connected to the vacuum.

A small fraction of the gas molecules are ionized (positive ions), and the resulting ions are separated, detected and measured according to their molecular masses.

The RGA can be used to determine the

concentrations or absolute partial pressures of the components of a gas mixture.

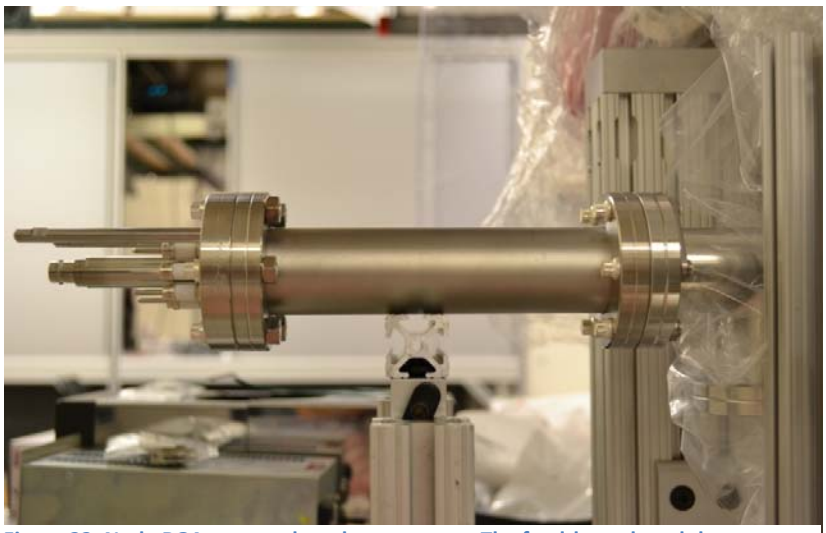


Figure 22. Nude RGA mounted on the apparatus. The feedthrough and the Quadrupole probe can be seen.

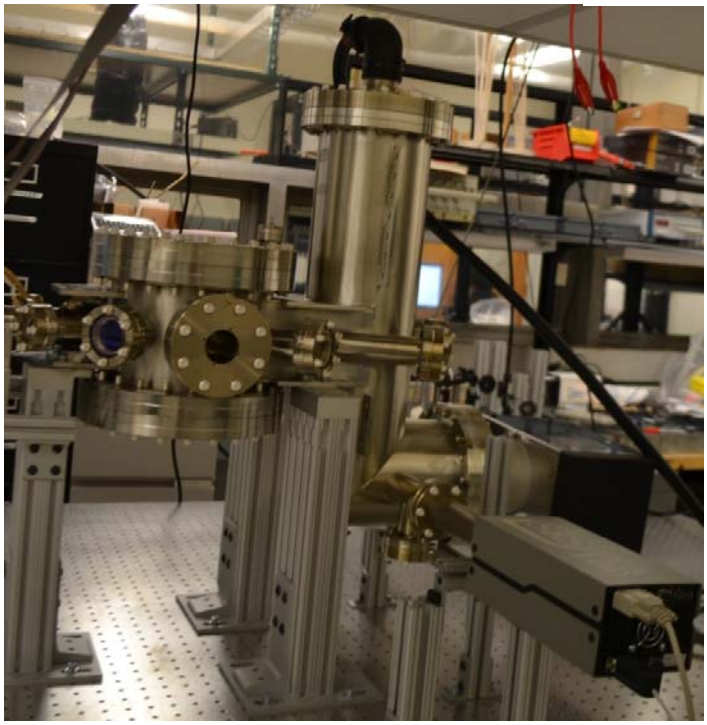


Figure 23. Operating RGA with the ECU on.

The probe consists of three parts: the ionizer, the quadrupole filter and the ion detector. Those parts are exposed to vacuum side.

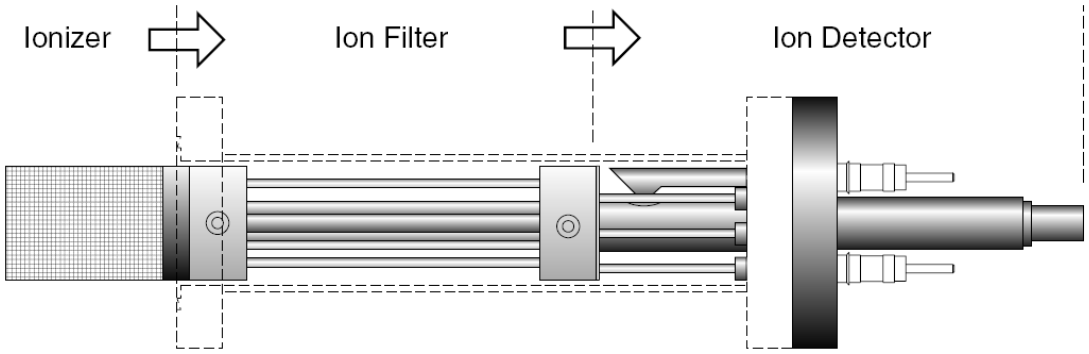


Figure 24. Probe components

Positive ions are produced in the ionizer by bombarding residual gas molecules with electrons derived from a heated filament. The ions are then transferred from the ionizer into the quadrupole where they are filtered according to their mass-to-charge ratios. Ions that successfully pass through the quadrupole are focused towards the detector by an exit aperture held at ground potential. The detector measures the ion currents using an optional electron multiplier detector, measures an electron current proportional to the ion current.

APPENDIX 8 - VacIon Plus 75 Starcell pump

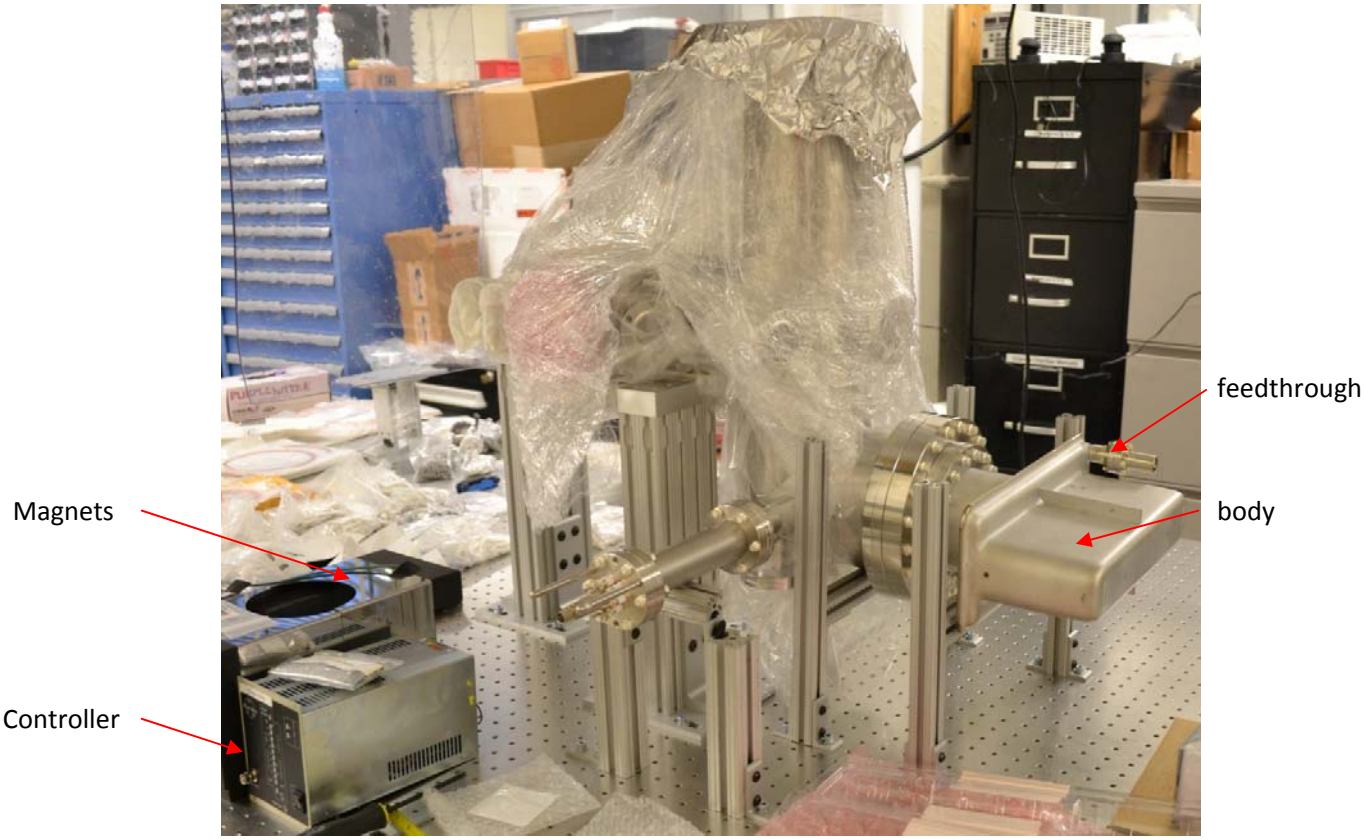


Figure 25. Ion pump mounted.

An ion pump captures the gas molecules which stick to its walls. As a result, at some point the pump must be out-gassed again after some ten years of use. The gas molecules are ionized through a high electric field, then they bound chemically with Titanium provided by the electrode of the pump. The formed molecules are deposited on the internal walls of the pump afterwards. These electrical potentials are usually in the range of a few kilovolts DC.

The ionization of the gas molecules themselves happens as the following: they are bombarded with high energy electrons. Collisions occur; thereby the molecules lose some of their own electrons. Those new positively charged ions are accelerated by the outer electrical field towards the Titanium electrode on which they collide again. This collision at high velocity makes the formed molecules smash the walls and stick into them.

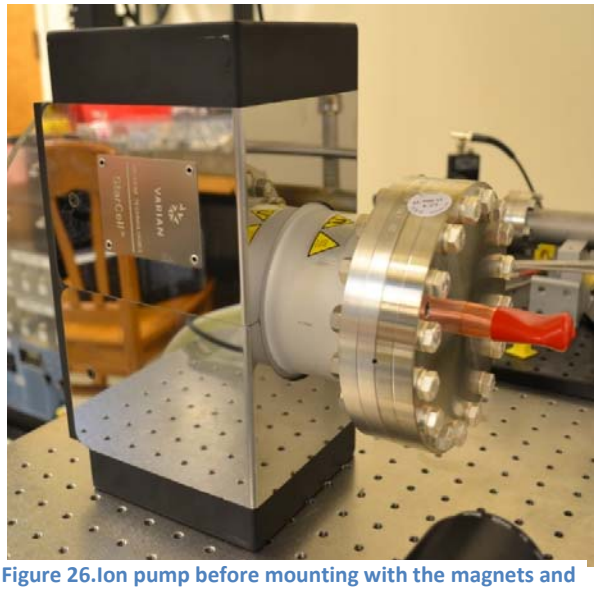


Figure 26.Ion pump before mounting with the magnets and the inlet flange on.

APPENDIX 9 - Zeeman slower (ZS)

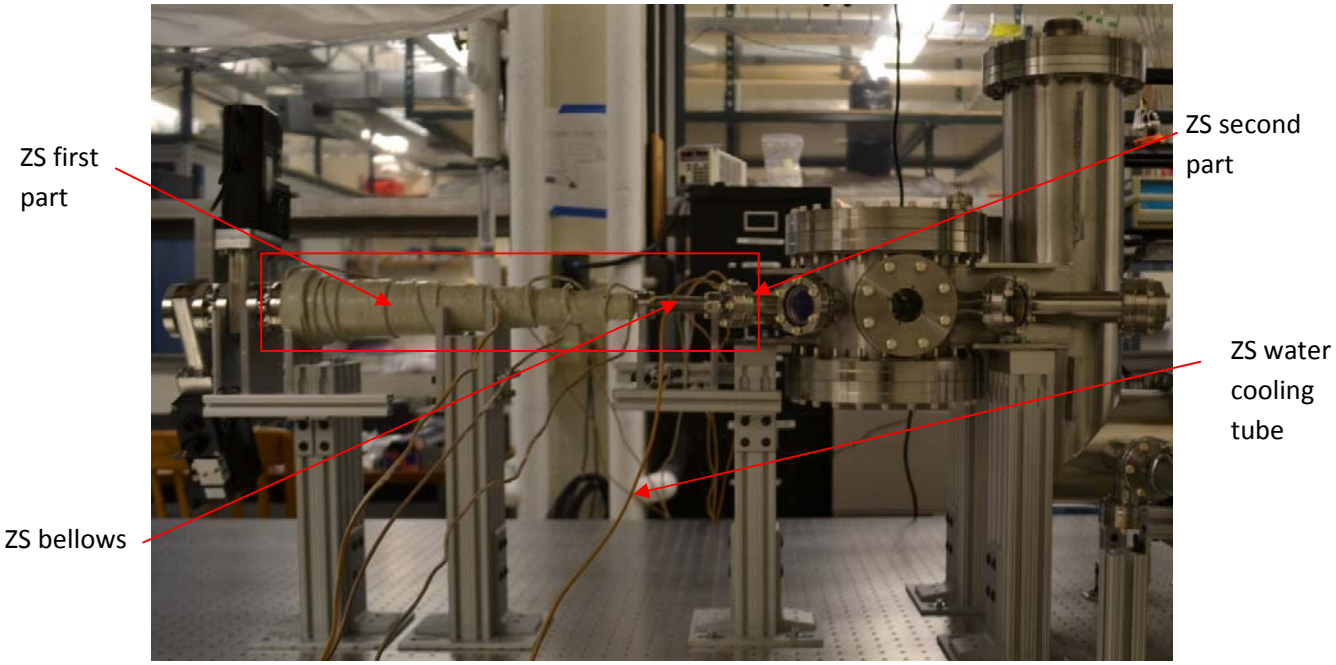


Figure 27. Zeeman Slower mounted.

The Zeeman slower (ZS) slows atoms, in our case Lithium 7, from $1km/sec$ to a speed of a ew m/sec, thereby cooling them and making them easier to trap.

The cooling itself is a Doppler cooling technique; a contra-propagating laser beam slows the atoms and a magnetic field created by the coils wrapped around the tube keeps the atoms near-resonant as their speed decreases.

After the atoms went through the ZS, they go into the main-chamber where the last step will take place: the magneto optical trap.

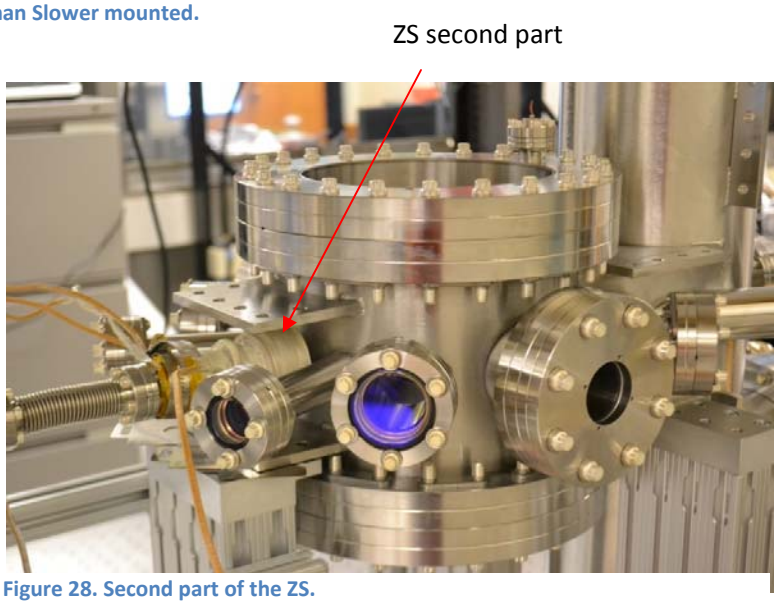


Figure 28. Second part of the ZS.

The ZS used on our apparatus is actually a spin-flip ZS made of three sections: the first one creates a decreasing magnetic field from $600\ to\ 0G$ as they atoms reach the bellows. The bellows is the second part where the field is 0, called spin-flip section. And finally, the last section creates an increasing field along its axis (up to $400G$).

Currents up to a 100 $Amps$will run through the coils.

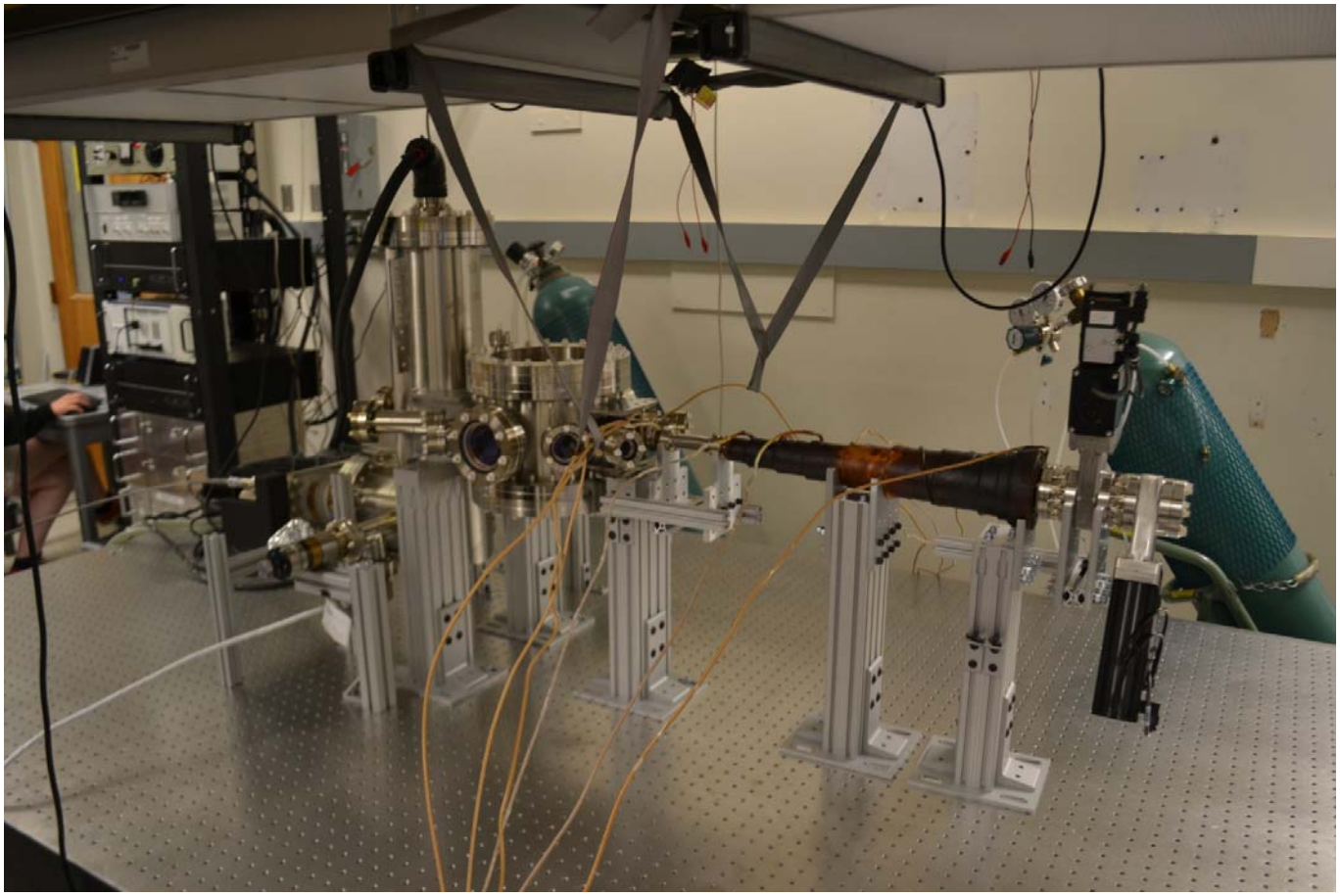


Figure 29. Zeeman slower after the bake.

APPENDIX 10 - Titanium Sublimation Pump (TSP)

Figure 30. TSP Cartridge.

The TSP is basically a Titanium filament. High current is sent through it, typically 48 Amps and sublimates some Titanium. This gas forms a layer on the walls of the chamber. This layer acts as a getter since Ti is very reactive, thereby lowering the pressure.

The TSP can't be running all the time, because it increases the temperature and hence the pressure inside the apparatus and also because Ti is quite expensive. Usually Ti is sprayed about once every one or two weeks and allows us to reduce the pressure by about one order of magnitude.

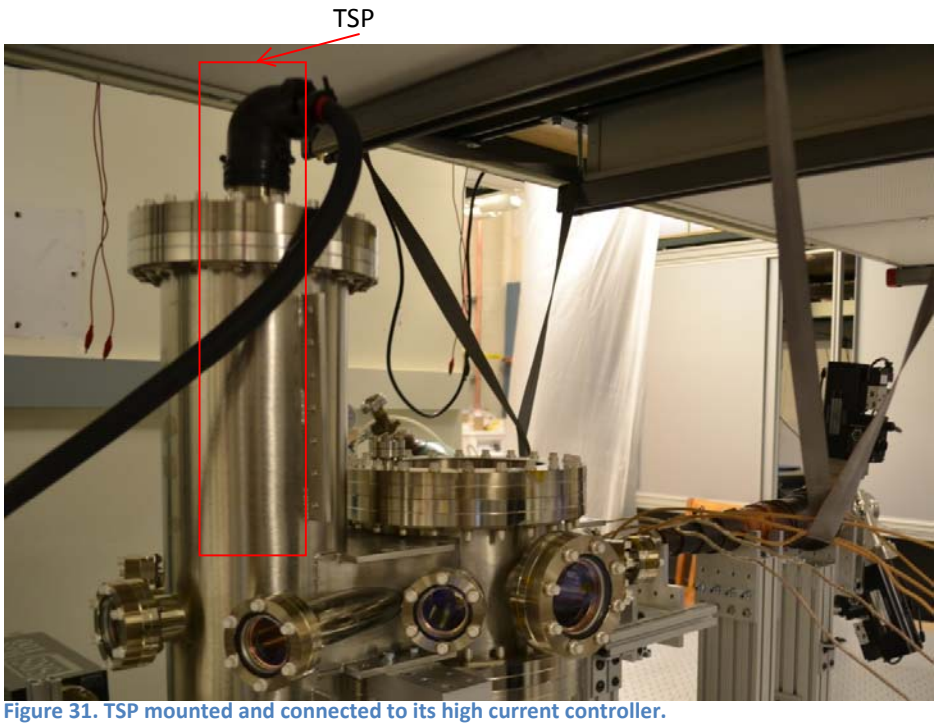


Figure 31. TSP mounted and connected to its high current controller.