LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
CALIFORNIA INSTITUTE OF TECHNOLOGY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Technical Note **LIGO-T000126- 00- R** 11/20/2000

Vacuum pressure at the 40 Meter and the new Output Optic Chamber

D. Ugolini, S. Vass, A. Weinstein

This is an internal working note
of the LIGO Project.

California Institute of Technology
LIGO Project - MS 18-34
Pasadena CA 91125
Phone (626) 395-2129
Fax (626) 304-9834
E-mail: info@ligo.caltech.edu

Massachusetts Institute of Technology
LIGO Project - MS NW17-161
Cambridge, MA 02139
Phone (617) 253-4824
Fax (617) 253-4824
E-mail: info@ligo.mit.edu

WWW: http://www.ligo.caltech.edu/

Vacuum pressure at the 40 Meter and the new Output Optic Chamber

Dennis Ugolini, Alan Weinstein, Steve Vass
November 20, 2000

Abstract

We describe the procedure by which we pumped down the newly-commissioned output optic chamber for the 40 Meter upgrade, and evaluated its total outgassing rate. Comparing this with the measured outgassing rate of the entire 40 Meter vacuum volume, we conclude that the chamber is sufficiently clean to be added to the 40 Meter vacuum volume with no additional cleaning or baking required.

1 Introduction

The vacuum system at the 40 Meter laboratory must maintain high vacuum in the interferometer volume, with minimal contamination from organic molecules which could stick to the surfaces of the optics and degrade the performance of the optical cavities.

The vacuum system is described in [1]. In winter 2001 we will add an output optics chamber (OOC, built many years ago), an OOC seismic stack (newly built), and 12 meter mode cleaner tube and chamber (with seismic stack) to the vacuum envelope. It is important to evaluate whether these elements are contaminated, so that they might degrade the overall vacuum pressure acheivable at the 40 meter, as well as the partial pressure of known contaminants.

The tools we have to do this evaluation are: a variety of pumps (turbopumps and ion pumps) with a range of pumping speeds, cold-cathode gauges, and a residual gas analyzer (RGA) manufactured by Dycor.

A typical RGA scan is shown in Fig. 1. Peaks associated with N_2, O_2, CO_2, H_2O, and H_2, and fragments thereof, are seen. They dominate the total pressure. The absolute value of the pressures in the RGA scan are not well calibrated (see below), either absolutely or relatively as a function of AMU.

The partial pressures of the high-AMU molecules are of concern. These are typically organic molecules formed from the breakdown of pump oil. They can stick to mirror surfaces and degrade their optical quality. Above AMU's of 100, the partial pressures are so small that the RGA is not very sensitive to them. However, the partial pressures of molecules with AMU of 41 and 43 (byproducts of pump oil) have been observed to roughly scale with the higher mass ones, and they are large enough to measure (you can see them in Fig. 1 in between the much higher peaks from Ar-40 and CO_2-44). Thus, we use these RGA measurements as a gauge of the vacuum quality at the 40 Meter, and they are carefully monitored.

2 Pumping speeds, partial pressures, outgassing rate

Pump-down of the 40 Meter from the vented state proceeds in stages:

- Roughing pumps clear out the small volumes between the pumps and the main volume.
- Roughing pumps reduce the pressure in the main volume from 760 torr to 0.5 torr, over about 3 hours. Pressure is monitored using Pirani gauges from 760 torr to 10^{-4} torr, then using cold cathode gauges on down.

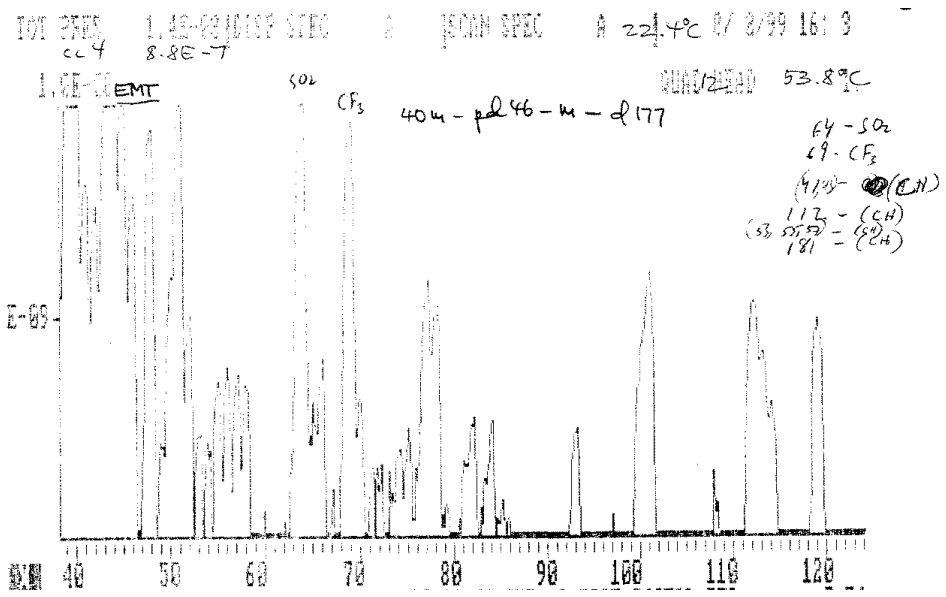

Figure 1: A typical RGA scan at the 40 Meter (partial pressure in torr vs AMU), taken after 177 days of pumping, with the maglev turbopump ON and electron multiplier ON.

- Turbopumps take over at around 0.5 torr, reducing the pressure to some equilibrium value over many days. We rely mainly on one maglev turbopump for the main 40m volume.
- For vibration-free pumping, ion pumps are used (for pressures below 10^{-6} torr). There are 4 ion pumps distributed around the 40m volume (a fifth pumps on the annulus regions of the optics chambers). They have not been used for many years, because they get saturated during vents. We will install gate valves, and regenerate these ion pumps, in winter 2001.

3 Time dependence of pressure, outgassing, etc

The ideal time-dependence of the pressure is described as follows:

- The number of molecules at a particular AMU, in volume V, is $N = pV/kT = nV$, where n = molecular number density.
- The pump pulls molecules out at a rate

$$\frac{dN}{dt} = -\frac{N}{V}\frac{dV}{dt} = -nS_p$$

  where S_p is the pump speed in ltr/s. the pump speed depends on the type of molecule (or AMU) and also on the pressure; it is approximately constant only over some range of pressures.
- Molecules enter the volume through leaks, diffusion through O-rings, or outgassing from the walls, at a rate $\dot{N}_{out}$, which is slowly-varying. Thus,

$$\frac{dN}{dt} = \dot{N}_{out} - nS_p \quad \Rightarrow \quad \frac{dp}{dt} = \frac{\dot{N}_{out}kT}{V} - \frac{S_p}{V}p.$$

  Light molecules like H_2 diffuse through the viton O-rings, while heavier organic molecules stick to, and outgas from, the walls.

- the solution to this differential equation (assuming constant S_p) is

$$p(t) = (p_0 - p_u)e^{-S_p/Vt} + p_u, \qquad p_u = \dot{N}_{out}kT/S_p$$

where p_0 is the initial pressure (760 torr), and p_u is the ultimate pressure (limited by outgassing).

- The time to pump down from p_0 to p_u, assuming $p_0 \gg p_u$, and assuming constant S_p, is

$$t_{down} = \frac{V}{S_p} \ln\left(\frac{p_0}{p_u}\right).$$

By measuring the exponential decay time constant V/S_p between a range of pressures for which S_p is roughly constant, and estimating V, we can determine S_p, and compare with what the pump manufacturer claims. Typically, the measured number is smaller than the manufacturer's spec, because the pumps are typically mounted to the volume in a conductance-limited manner.

- The outgassing rate can be written as $\dot{N}_{out} = (N_W/A)Ar_{out}$, where N_W/A is the number of molecules per unit area stuck to the walls, A is the area of the vacuum volume walls, and r_{out} is the rate for one molecule to desorb from the walls. Both N_W/A and r_{out} depend strongly on the molecule in question, the material and preparation of the walls, etc, and both can be slowly varying in time. For the sticky organic molecules, r_{out} is very small; $1/r_{out}$ is weeks or months.

- The number of molecules per unit area stuck to the walls, N_W/A, slowly falls as we get down below one layer:

$$\frac{dN_W}{dt} = -r_{out}N_W + r_{rea}n,$$

where r_{rea} is the re-adsorption rate (which is presumably small for small n, we will neglect it). So:

$$N_W = N_W^0 e^{-r_{out}t} + \text{readsorption}.$$

- In the end, the figure of merit for the cleanliness of a vacuum volume is given by the outgassing rate

$$\rho_{out} \equiv \frac{N_W kT}{A} r_{out}$$

in torr-ltr/s/cm^2. Typical outgassing rates are 10^{-7} for metals, 10^{-5} for silicone, or larger for really sticky gunk. The ultimate pressure (for constant ρ_{out}) is

$$p_u = \rho_{out}A/S_p.$$

- So, we can estimate A, measure S_p from pump-down or from a calibration, and then determine ρ_{out} from the observed p_u.

- Note that diffusion through o-rings at ports can also contribute to the "outgassing" rate.

4 Estimate of 40 Meter vacuum volume and surface area

Precise values for the dimensions of all components of the 40m vacuum envelope presumably exist; but we're not sure where to find them. Below, we make a reasonable estimate of the volume and surface area of the vacuum envelope. This does not include the contributions from the contents of the vacuum envelope (seismic stacks, optical tables, IFO equipment). This, of course, makes a significant uncertainty in the surface area; and, most likely, the outgassing rate per unit area is most likely dominated by these contents. Thus, all numerical conclusions drawn from these estimates should be taken with a generous margin of error.

The full 40 meter volume consistes of:

- Two beam tubes, 4000 cm each, 24" diameter (61 cm). Volume = 11,690 ltr, area = 766,549 cm^2 (each).
- Five BSC's, each 124 cm diameter, 155 cm high. Volume = 1872 ltr, area = 60,381 cm^2 (each).
- One side chamber, 2'x2.5'x4.5' (61x76x137 cm). Volume = 637 ltr, area = 46,916 cm^2 (each). We will add a second (output optic) chamber, soon.
- Total volume = 33,347 ltrs.
- Total area = 1.9×10^6 cm^2
- Since we are ignoring the surface area of the contents of the 40 Meter vacuum, this is surely a (gross?) underestimate.

5 OOC Pumpdown

The OOC is an empty volume with steel walls. It has five large doors (not shown), each with single baked viton o-ring seals (no annulus region), and ten 8" or smaller flanges with copper gaskets. It was pumped down on 7/31/00, and the pressure was monitored for 77 days, followed by a vent on 10/16/00. The configuration is shown in Fig. 2. A Welsh rotary pump rated at 650 l/s was used to rough out the volume to around 0.5 torr (it took about 14 minutes), a Balzer turbopump rated at 60 l/s brought the total pressure down to 10^{-5} torr in 75 minutes.

During this time, the total pressure was monitored regularly using Pirani and then cold cathode gauges, and a Dycor RGA was used to monitor the partial pressure of various molecules, especially those with AMU of 41, 43, 53, 55, and 57, all of which are hydrocarbon fragments associated with pump oil breakdown and which are thought to be particularly dangerous to optical surfaces.

The turbopump brought the total pressure down to 4×10^{-6} torr after two weeks of pumping. At that point, a new ion pump rated at 400 l/s took over, quickly bringing the pressure to 1.4×10^{-7} torr. Over the next two months, the total pressure hovered around 9×10^{-8} torr.

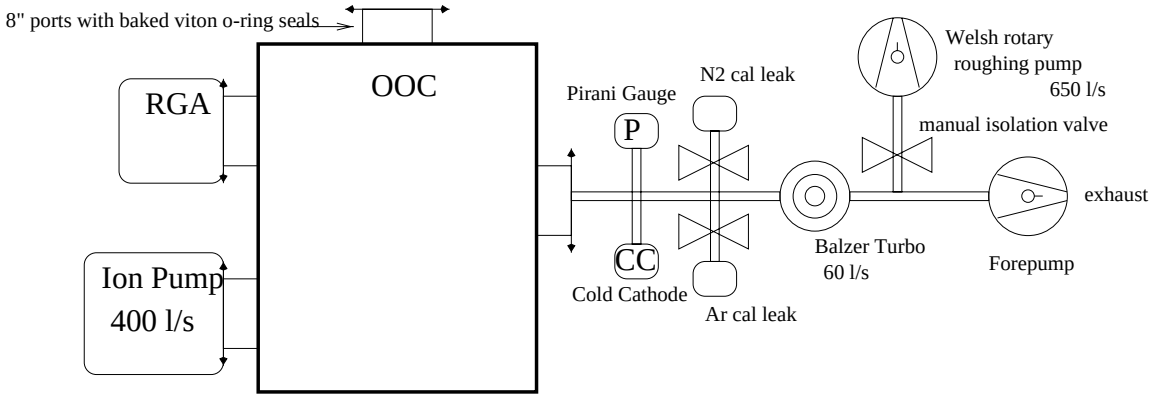

Figure 2: Configuration for pump-down of the output optic chamber (OOC) from 7/31/00 through 10/16/00.

6 Calibration

In order to establish the outgassing rate of the OOC (due to outgassing from the walls, diffusion through o-rings, or leaks), we need to know the pump speed and the partial pressures for the AMU's of concern (41, 43, 53, 55, 57) from the RGA. Both of these quantities require calibration.

The Balzer turbopump was rated at 60 ltr/s, but it was connected to the chamber via a tube of diameter $d = 3.4$ cm and length ℓ =10" = 25.4 cm, with an elbow. Thus, at low pressures (molecular flow), the effective pumping speed is limited by conductance. The conductance limited pumping speed is given by the formula [2] $S_{pc} = 12.1$ ltr/s $\times d^3/\ell$, with d and ℓ measured in cm. Further, the elbow reduces this by a factor 0.3. So, effective pumping speed is roughly 12 ltr/s. The effective pumping speed was checked with a calibrated leak, as discussed below.

6.1 Nitrogen leak

We have a calibrated leak source on the OOC, produced by Vacuum Technology Inc (VTI, Oak Ridge TN), part number C8-8-N2-2CFF-FV. It is N_2 at 7.4 psia. The leak rate is 1.0×10^{-8} torr-ltr/s at 24°C. It degrades by -0.6% per year, and it is around 10 years old (built 10/91). Thus, the current leak rate is around $LR = 0.94 \times 10^{-8}$ torr-ltr/s.

We vented the leak into the chamber, then closed it. We left it for 26 hours, then vented it into the 625 ltr OOC. We expect a rapid rise in the partial pressure for N_2 of

$$\Delta P_{14} = LR \times t_{leak}/V = 0.94 \times 10^{-8} \times (26 \times 3600)/625 = 1.4 \times 10^{-6}\,\text{torr}.$$

On the RGA, we saw a sharp rise of $\Delta P_{14} = 1.3 \times 10^{-7}$ torr, followed by an exponential decay back to the baseline (Fig. 6.1).

From the N_2 calibrated leak, it appears that the RGA appears to be off in absolute pressure calibration, by a factor of 10. The RGA had been calibrated while attached to the 40m main volume some time ago, and a factor of 10 mis-calibration seemed unlikely. As we will see below, an independent calibration of the RGA gives results in much better agreement with previous calibrations. We thus strongly suspect that the N_2 leak rate is wrong.

Despite this, the pump speed can be reliably determined. After the initial sharp rise, the ΔP_{14} dropped back to its previous value with a time constant of $\tau_{1/e^2} = 2V/S_{pc} = 84$ s, so $S_{pc} = 14.9$ ltr/s, compared to the expected 12 ltr/s. This is independent of the calibration of the calibrated leak and of the RGA.

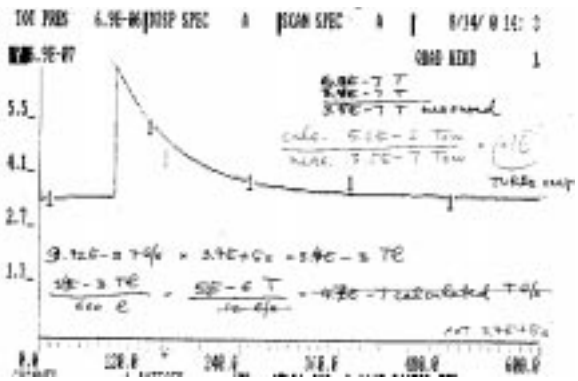

Figure 3: Response of RGA channel 14 (N_2) to the release of 26 hours of calibrated leak accumulation.

6.2 Argon leak

We have a calibrated Argon leak source, produced by Vacuum Technology Inc (VTI, Oak Ridge TN), part number CL-8-AR-2CFF-FV. It is Ar at 15. psia. The leak rate is 5.3×10^{-8} torr-ltr/s at 24.3°C. It degrades by -0.7% per year, and it is around 8 years old (built 10/1/92). Thus, the current leak rate is around $LR = 5.00 \times 10^{-8}$ torr-ltr/s.

For various reasons, the Ar calibrated leak was not installed on the OOC. We were able to use it once we vented the OOC (on 10/15/00), and re-plumbed the small turbo pump, calibrated leaks, and RGA head together (without the OOC).

With the 14.9 ltr/s turbopump going, we turned the leak on for a while, then turned it off for a while, and repeated. We found that the RGA-reported pressure for AMU 28 (Argon) changed from $p_{28} = 3.5 \times 10^{-11}$ torr when closed to $p_{28} = 1.3 \times 10^{-9}$ torr when open. We would predict an "open" pressure of $p_{28}^{pred} = LR/S_p = 5.00 \times 10^{-8}$ (torr-ltr/s) / 14.9 ltr/s $= 3.3 \times 10^{-9}$ torr. Thus, we conclude that the RGA readings for AMU 28 need to be multiplied by $3.3/1.3 = 2.5$ in order to be interpreted at true partial pressure in torr.

There is much better agreement than was seen with the N_2 leak. For various reasons, we believe the Ar leak calibration and not the N_2 leak calibration. However, the determination of the pump speed $S_{pc} = 14.9$ ltr/s using the N_2 leak should be reliable, as it does not depend on the accuracy of the N_2 leak calibration.

7 Conclusions

We use the nitrogen leak calibration to determine the pumping speed of the turbo-pump used to pump on the OOC. We use the argon leak calibration to determine the absolute scale of the RGA partial pressure readout, for argon.

The absolute scale of the RGA partial pressure readout for AMU 41 will be different than for AMU 28, due to the mass dependence of the RGA response, which is (naively) expected to scale like $\sqrt{\text{AMU}}$. Thus, an additional calibration factor of $\sqrt{41/28}$ must be applied.

The partial pressure of AMU 41 acheived after 77 days of pumping on the OOC, was 2.7×10^{-11} torr at the turbo-pump speed of 14.9 ltr/s. Applying the two calibration corrections mentioned above gives $p_u(41) = 8.2 \times 10^{-11}$ torr, or an outgassing rate of $\dot{N}_{41} = 1.2 \times 10^{-9}$ torr-ltr/s. The outgassing rate per unit area is

$$\rho_{41} = 1.2 \times 10^{-9}\,\text{torr-ltr/s}/47,000\,\text{cm}^2 = 2.6 \times 10^{-14}\,\text{torr-ltr/s/cm}^2.$$

This should be compared with the total outgassing rate at the 40 Meter. The maglev turbopump (TP1) at the 40 Meter has a rated speed of 300 ltr/s. On 3/6/00, after 26 days of pumping, the corrected partial pressure of AMU 41 was $p_{41} = 7.6 \times 10^{-11}$ torr, corresponding to an outgassing rate of $\dot{N}_{41} = 2.2 \times 10^{-8}$ torr-ltr/s. The outgassing rate per unit area at the 40m is $\rho_{41} = 1.1 \times 10^{-14}$ torr-ltr/s/cm^2, somewhat lower than the OOC.

This calculation was repeated using the sum of the partial pressures of AMU's 41, 43, 53, 55, and 57, instead of just AMU 41. The results were quite consistent.

From these calculations, we see that the addition of the OOC will increase the total outgassing rate at the 40m by 5%. This is acceptable. We conclude that no additional cleaning or baking of the OOC is required before installation into the 40m vacuum.

References

[1] Upgrade of the 40m Vacuum System. LIGO note T000054-00-R.

[2] Leybold catalog.