Consequences of the LLO beamtube leak and strategies to deal with them

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Introduction: In May 2012 we realized that an airleak of 2×10^{-4} torr liters/sec had open in the LLO y beamtube near the middle of the tube in October 2008. There was no pressure gauge at the middle of the tube and the leak went unnoticed within the noise of the pressure measurements at the tube ends. The leak became evident once the pumping arrangements were changed to accommodate advanced LIGO installation. Averaging over the water vapor pressure as a function of temperature over the time the leak has been opened and assuming 90% relative humidity in the beamtube enclosure, the average leak rate for water is 8×10^{-6} torr liters/sec. The total water load in the tube is then 1000 torr liters or equivalently an additional 1/5 of a monolayer of water adsorbed on the tube walls. The initial water loading of the beamtube before evacuation and bakeout was an equivalent 150 monolayers.

The amount of water introduced is not catastrophic requiring a full fledged bakeout, however, it does contribute forward scattering phase noise at the sensitivity level of some of the advanced LIGO detector concepts and needs to be addressed if LIGO is ever to be used at its goal sensitivity of the quantum noise of a one ton test mass – $h(f) = 1.5 \times 10^{-25}$. The advanced LIGO h(f) sensitivity limited by other noise sources than forward scattering is : 1.3×10^{-24} for narrow band tuning configurations, 2.5×10^{-24} for broad band high power optimization for NS/NS coalescences, 4.2×10^{-24} low power minimal amplitude recycling, most likely the first configuration to run in advanced LIGO.

Without any modifications to the current vacuum system, the forward scattering from water injected by the leak will after three years of pumping give a strain noise $3.0 \times 10^{-25} <h(f)< 5.0 \times 10^{-25} >$. The band is determined by uncertainty in the model and in the amount of injected water. The hydrogen outgassing with the present pumping strategy provides a strain noise limit $h(f) = 3 \times 10^{-25}$.

In September 2012 we will install a sensitive RGA in the y arm mid building at LLO similar to the one used at LHO to measure the hydrocarbon residual gas. The intent is to measure the water pressure and validate the model and estimates. If there are no surprises, the suggested strategy is to install 2000 liter/sec ion pumps at the mid point of both arms in the mid buildings at LLO. The median values of h(f) due to forward scattering become $h(f) = 1.9 \times 10^{-25}$ for the water and 1.8×10^{-25} for the hydrogen. The pump will also lower the hydrogen pressure from beamtube outgassing at the test masses by about a factor of 2. This will help to reduce the thermal noise due to gas in the narrow gap between the electrostatic drive plates and the test mass.

To reach the goal pressure for forward scattering phase noise will require more pumping capacity along the arms to further reduce the hydrogen and it may be necessary to contemplate both more pumps as well as a low temperature bake to bring the water to the goal pressure.

This note provides estimates of the water pressure in the beamtube after the leak has been fixed for a group of strategies involving additional pumps and low temperature bakeouts. The pressure distribution is used in conjunction with the advanced LIGO Gaussian beam profile to estimate the forward scattering phase noise from both water and hydrogen.

Mechanics: In the model the beamtube is broken into 100 sections. The temperature of the tube can be changed at designated times to simulate a bakeout. Pumps can be placed at any of the ports 250 meter apart along the tube. A single leak can be opened at any section at a designated time. The diffusion of the gas between sections and to the pumps is estimated numerically with a Runge – Kutta method in double precision arithmetic. The surface adsorption dynamics is calculated for each section separately with the end result of an outgassing rate provided to the diffusion dynamics. The surface adsorption is treated by the same method as the prior program that estimated the results of the initial beamtube bakeout . The program assumes the Dubinin-Raduskevich adsorption site binding energy distribution with the Langmuir model to estimate adsorption and reemission times for the sites. The surface potential is attractive directly at the surface with a smaller repulsive term at some distance from the surface following the discovery of such potentials by Roald Hoffman. The repulsive term is needed to avoid unrealistically short readsorption times. The model parameters were determined by fitting the initial beamtube bakeout to the model. The FORTRAN program used for the calculations is included in the collection of associated files in the LIGO Document Center.

Results: The following figures and tables present the estimates for a range of pumping strategies and low temperature bakeouts to gain insight into their effects on the pressure distribution and on the phase noise. The phase noise estimate assumes the advanced LIGO beam geometry: ITMY radius of curvature 1934 meters, the ETMY radius of curvature 2245 meters and the total arm length of 3994.5 meters. The TE_{00} Gaussian beam radii are then 53mm at the ITMY 12mm at the waist on the LVEA side of the midpoint and 63mm at the ETMY. The phase noise is calculated by using the equivalent displacement noise spectral density per arm

$$x^2(f) = 8\pi^2\alpha^2 \sum_{n=1}^{\text{nsections}} \frac{\rho_{\#} l_n}{v_{th} w_n}$$

here: α is the molecular polarizability, 7.3×10^{-25} for hydrogen and 1.32×10^{-24} for water, $\rho_{\#}$ the particle density in molecules /cc, v_{th} the average molecular speed, l_n the length of the section n and w_n the Gaussian beam radius at section n. The total displacement noise power is summed over molecular species and the two arms. The strain noise is then $h(f) = \frac{\sqrt{x^2(f)}}{L}$.

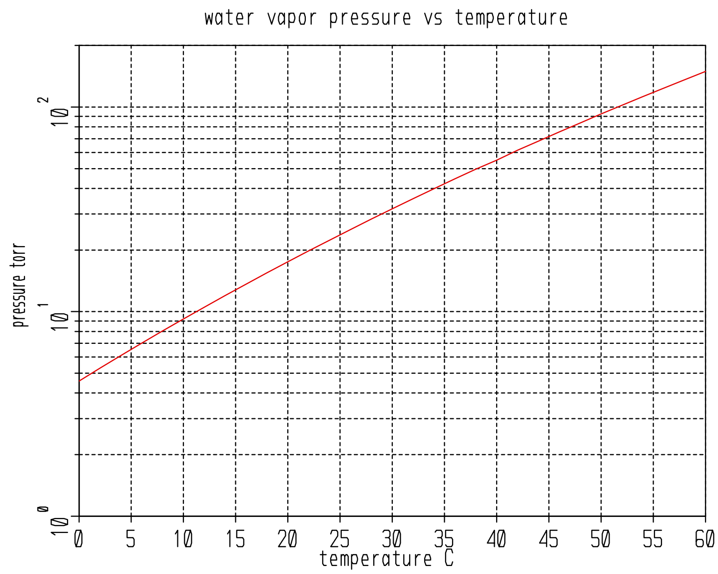

Figure 1 Vapor pressure of water vs temperature

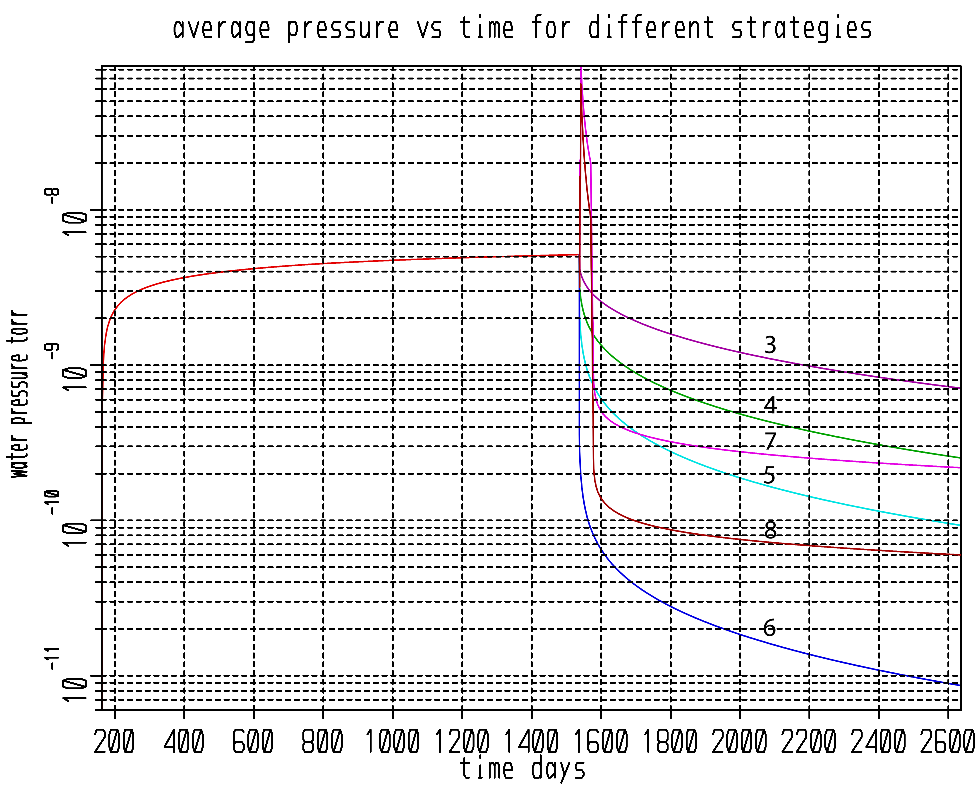

Figure 2 Average water pressure vs time for a variety of strategies described in **Table 1**. A humid air leak at 2000m from the LVEA opens at 163days and is closed at 1536 days. The relative humidity in the enclosure is assumed to be 90% with 35 torr as the average water vapor pressure over the year. The average injected water is 8×10^{-6} torr liters/sec. The curves were drawn for a 62% smaller leak by mistake. The numbers identify the pump down and bakeout cases.

Table 1 The parameters associated with the various cases for a 8 x 10^{-6} torr liter/sec water leak.

Case	pumps l/sec		Bake		p@ ends torr 3 years		<p> torr 3 years		h(f) $(\sqrt{Hz})^{-1}$ 3 years	
	H_2O	H_2	temp K	days	H_2O	H_2	H_2O	H_2	H_2O	H_2
3	10^5 ends	2500 ends	None		3.5e-12	1.6e-9	1.1e-9	4.9e-9	3.3e-25	2.9e-25
4	10^5 ends 2000 mid	2500 ends 2000 mid	None		1.8e-12	9.4e-10	4.2e-10	2.1e-9	1.9e-25	1.8e-25
5	10^5 ends 400 all	2500 ends 400 all	None		1.6e-12	4.2e-10	1.4e-10	9.7e-10	1.2e-25	1.3e-25
6	10^5 ends 6000 all	6000 ends 6000 all	None		4.6e-13	5.2e-11	1.4e-11	9.4e-11	3.8e-26	3.8e-26
7	10^5 ends	2500 ends	340	30	1.2e-12	1.6e-9	3.2e-10	4.9e-9	1.9e-25	2.9e-25
8	10^5 ends 2000 mid	2500 ends 2000 mid	340	30	4.6e-13	9.4e-10	9.4e-11	2.1e-9	9.0e-26	1.8e-25
Before leak	10^5 ends	2500 ends	433	30	2.0e-16	1.6e-9	4.3e-14	4.9e-9	2.2e-27	2.9e-25
At end of leak	10^5 ends	2500 ends	none		2.5e-11	1.6e-9	8.0e-9	4.9e-9	8.9e-25	2.9e-25

Discussion of Table 1: The current pumping system at LLO consists of 2500 liter/sec ion pumps and cryo traps at 77K at the LVEA and at the end stations. There is no pumping at the mid building. The beamtube has nine10 inch ports spaced at 250 meters along each 2km module. Although there is power along the tube, currently the only place where it is easily accessible is in the mid building. As a consequence placing pumps at the mid building is both reasonably simple and the most effective place to increase the pumping given the Gaussian beam profile and the high probability that the leak (not yet found or localized at this writing) is near the middle of the tube.

The h(f) noise estimates for the forward scattering are for both arms when considering hydrogen and one arm when estimating the contribution by water. It does not include the possible contributions from hydrogen generated by the vacuum system other than the beamtubes. The cryo traps block the water generated by outgassing of the interferometer components from entering the beamtube and causing additional forward scattering phase noise.

Another consideration in evaluating pumping strategies is to note the change in the pressure at the ends. There the thermal noise induced by collisions of the gas with the test mass in the narrow channel between the test mass and the electrostatic driver and recoil plate becomes a consideration. Water outgassed by the instrumentation is pumped with high pumping speed by the cryo trap and there is little change in the chamber with any of the strategies. The only way to reduce the water for this effect is to reduce the outgassing of the interferometer components. Pressure of the hydrogen in the chamber is changed by the various pumping strategies along the beamtube but this must be analysed by including the hydrogen generated by the ordinary stainless steel in the chamber and the other components in the LVEA torr The hydrogen outgassing rate at 300K for the beamtube steel is 5×10^{-14} torr liters/sec cm^2 while the outgassing rate for the ordinary 304 SS in the rest of the vacuum system is about a factor 200 to 500 times larger. An optimized solution for the pumping strategy to reduce the phase noise and thermal noise from the hydrogen still needs to be made. It is worth noting the expected hydrogen outgassing from the test mass chamber alone is approximately 3 to 5×10^{-6} torr liters/sec giving a pressure of 1 to 2×10^{-9} torr. The initial LIGO pumping strategy for hydrogen does not give any margin when attempting to get to the goal pressure.

Bake out at low temperatures is an effective way to reduce the water and would be needed if the total water adsorbed on the walls were larger than estimated from this leak. The concept is to heat the entire tube by passing heated gas through the enclosure after the additional pumps have been installed. The insulation would be left on the tube. The model used 340K bake temperature and a heating time of a month. The time is less critical than the temperature which reduces the final outgassing rate by about a factor of 2 for each 6K increase in bakeout temperature.

Details

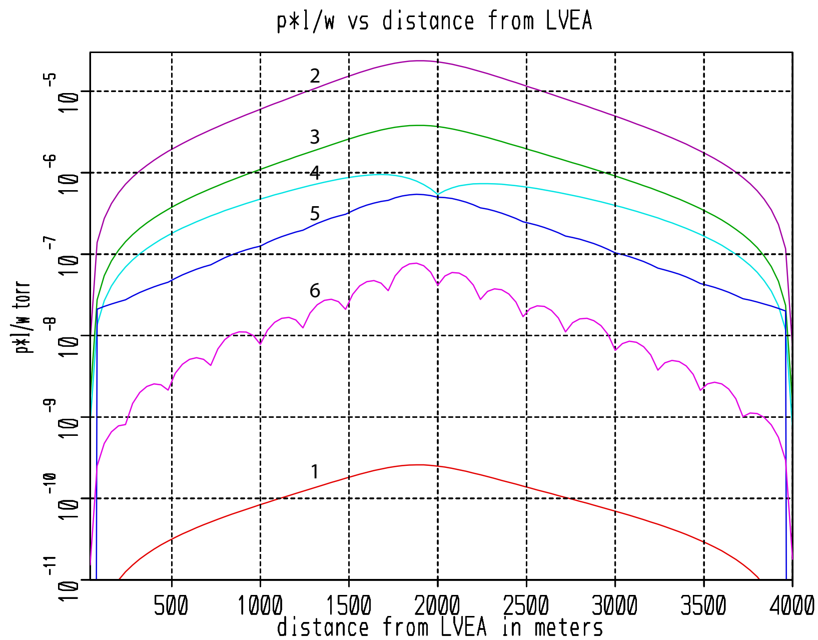

Figure 3a

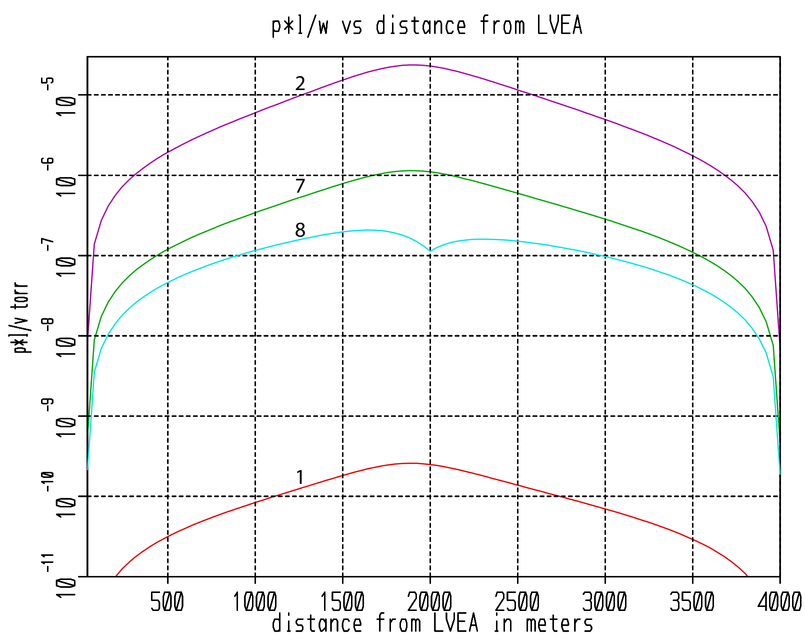

Figure 3b

Figure 3 plots the water pressure times the section length divided by the Gaussian beam radius along the beamtube length, the integrand in the forward scattered noise power. Curve 1 is the distribution after the initial LIGO 433K bake while 2 is the distribution after the leak at 2000 meters is fixed. Note the distribution skew is due to the Gaussian beam waist occurring at a location closer to the LVEA than the middle of the tube. **Figure3a** shows the various cases with different pumping strategies but no bake while **Figure3b** shows the two cases with a bakeout. Case 6 has 6000 liters/sec at each pump port along the tubes as well as the cryotrap at the ends. The pumps are the largest one would contemplate given the tube diffusion transport limit.

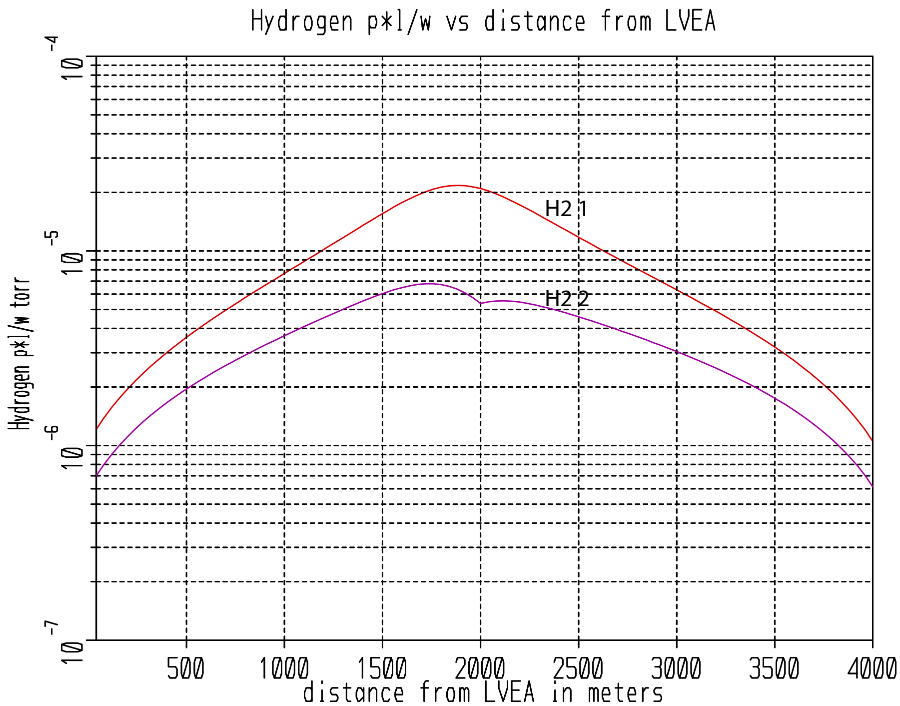

Figure 4 same as **Figure 3** but for hydrogen with a fixed outgassing rate of 5×10^{-14} torr liters/sec cm^2. H2 1 corresponds to the pumping strategy for case3 and H2 2 to case 4. The reduction in the central pressure also helps in reducing the pressure at the ends. The hydrogen estimates assume no change in the outgassing rate after a bake to remove water and no readsorption.