LECTURE 17
The LIGO Vacuum System
Lecture by Jordan Camp

Assigned Reading:
WW. J. H. Moore, C. C. Davis, M. A. Coplan, Building Scientific Apparatus (Addison-Wesley, 1983), Chapter 3. "Vacuum Technology." A good overview of the basic issues involved in vacuum system design, including gas kinetics, pressure measurement, and pumping.

Suggested Supplementary Reading:

A Few Suggested Problems
1. Residual gas damping of test mass: In Lecture 13, the following expression for the losses due to residual gas damping was given:

   \[ \phi(\omega) \sim \frac{2AP}{M} \sqrt{\frac{\mu}{kT}} \frac{\omega}{\omega_0^2} \]

   where \( A, M \) are the test mass area and mass, \( P \) is the residual gas pressure, \( \mu \) is the mass of a gas molecule, and the gas molecules are thermalized at temperature \( T \). (Recall that \( \phi = \gamma\omega/\omega_0^2 \), where \( \gamma \) is the acceleration due to gas damping and \( \omega \) is the test mass velocity.) Derive this expression. For simplicity, assume that the gas molecules are of uniform velocity and normally incident on the test mass.

2. Pressure in LIGO beam tubes: The final pressure achieved in the LIGO beam tubes will depend on the outgassing rates, conductances and pumping speeds, and available budget.
a. Conductance of an orifice: the ion pumps, which will provide quiet, high vacuum pumping for the beam tubes, will be connected to the tubes through 25 cm diameter orifices. The conductance of an orifice of area $A$ for molecular nitrogen (atomic weight=28) is given by $C$ (in Liter/sec) = $11.6A$ (in cm$^2$). How does this value scale with the molecular mass, and what is the conductance for hydrogen (atomic weight=2)? (Hint: the conductance is linearly related to the flux of molecules across the aperture). Assuming that the ion pumps have pumping speeds of 10000 L/sec, what is the combined pumping speed of the orifice and pump?

b. Conductance of a beam tube: in paper 4 of the suggested reading K. Welch derives the following expression for the average pressure of a long outgassing tube of diameter $D$ and tube length $l$:

$$P_{av} = P_p + \frac{\pi q l^2}{3kD^2}$$

Here $q$ is the outgassing rate (torr l/(sec-cm$^2$)) and $k$ is a function of temperature and molecular weight ($k=45$ for hydrogen at room temp). The first term, $P_p$, is the pressure at the ion pump, while the second term accounts for the finite conductance of the 1.2 m diameter beam tube.

1) for the special LIGO low-outgassing steel, $q \sim 1.0 \times 10^{-13}$ torr l/(sec-cm$^2$). Assume an initial pumping configuration of 2 end pumps per each 2 km long beam tube module. What is the total outgassing flux (torr l/sec) seen by each of the pumps? Using the earlier calculation of pumping speed, find $P_p$. What is $P_{av}$? This number should be close to the goal of $1.0 \times 10^{-9}$ torr for the advanced interferometer.

2) assume that unprocessed steel with a higher outgassing rate is used, where $q \sim 1.0 \times 10^{-12}$ torr l / (sec cm$^2$). What is $P_{av}$ for this beam module? How many additional equally spaced pumps would be necessary to recover the desired value of $P_{av}$? (The 2 pieces of $P_{av}$ scale differently with the # of pumps.) With a cost of $35$ K per additional pump station and a total of 8 beam tube modules for the two sites, how much additional cost would be incurred if this steel were used?
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LIGO Vacuum System
by Jordan Camp, 25 May 1994

Camp lectured from the following transparencies, which Kip has annotated a bit.
Thermal equilibrium:

\[ N(v) d^3v = n \left( \frac{m}{2 \pi k T} \right)^{3/2} e^{-mv^2/2kT} d^3v \]

\[ F_z = \int d^3v \, mv_z \quad \text{N}(v) \, V_z \quad n \, dA \]

momentum transfer

Flux

\[ \bar{p} = \frac{F_z}{dA} = n m \bar{v}_z^2 \]

\[ = \frac{1}{3} n m \bar{v}^2 \]

\[ = n k T \]
Interferometer Noise From Gas Pressure: Displacement Noise

1) Acoustic Noise

\[ \tau_0 = \pi d^2 \]

\[ l \approx \text{mean free path} \Rightarrow n \tau_0 l = 1 \]

\[ n = \frac{P}{kT} \]

\[ l = 3 \times 10^{-5} \text{ cm} \quad 770 \text{ torr (STP)} \]

\[ \sim 3 \text{ m} \quad 10^{-4} \text{ torr} \]

2) Residual Gas Damping

\[ \phi(\omega) \sim \sqrt{\frac{2AP}{M}} \sqrt{\frac{M}{kT}} \frac{\omega}{\omega_0^2} \]

\[ \Rightarrow \tilde{x}(100 \text{ Hz}) \sim 10^{-20} \text{ m/} \sqrt{\text{Hz}} \quad @ 10^{-4} \text{ torr} \]
Sensing Noise:

Phase Noise

EFFECT OF GAS MOLECULES ON OPTICAL PHASE

\[ dL_i = C_i e^{-\frac{2r^2}{w^2}} \]

\[ = \frac{2(n-1)}{n_0 \pi w^2} e^{-\frac{2r^2 + (t-t_i)^2}{w^2} V_i^2} \]

(Number density of molecules of species \( i \))

\[ G(F) = \int N(\rho, v) d\rho \int dL(\rho, v) e^{+i\pi Ft} \int dt \int d\rho dv dz \]

\[ \Delta L \sim \sqrt{6} \sim n_{i/2} \alpha L_{i/2} e^{-\pi r f w / v_0} \]

\[ \frac{V_{i/2}^2}{w} \]

\[ \sim \frac{r_{i/2}^2 \alpha L_{i/2}^2}{v_0\alpha^2} \]

\[ \text{Note:} \quad \frac{V_0}{2\pi w} \sim 10 \text{kHz} \]
Beam tube partial pressure requirements:

<table>
<thead>
<tr>
<th>GAS</th>
<th>INITIAL REQUIREMENT (TORR)</th>
<th>GOAL (TORR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H2</td>
<td>$1 \times 10^{-6}$</td>
<td>$1 \times 10^{-9}$</td>
</tr>
<tr>
<td>H2O</td>
<td>$1 \times 10^{-7}$</td>
<td>$1 \times 10^{-10}$</td>
</tr>
<tr>
<td>N2</td>
<td>$6 \times 10^{-8}$</td>
<td>$6 \times 10^{-11}$</td>
</tr>
<tr>
<td>CO</td>
<td>$5 \times 10^{-8}$</td>
<td>$5 \times 10^{-11}$</td>
</tr>
<tr>
<td>CO2</td>
<td>$2 \times 10^{-8}$</td>
<td>$2 \times 10^{-11}$</td>
</tr>
<tr>
<td>CH4</td>
<td>$3 \times 10^{-8}$</td>
<td>$3 \times 10^{-11}$</td>
</tr>
<tr>
<td>Ar</td>
<td>$5 \times 10^{-8}$</td>
<td>$5 \times 10^{-11}$</td>
</tr>
<tr>
<td>He</td>
<td>$1 \times 10^{-5}$</td>
<td>$1 \times 10^{-8}$</td>
</tr>
</tbody>
</table>

H$_2$ outgases more easily than other molecules, and thus is a special problem.

Also, hydrogen is infused into steel in large quantities in the production process.

4) Optical Contamination of mirrors

$$\sum_{i} P_{HC_i} < 10^{-11} \text{ torr} \Rightarrow$$ mirrors won't degrade faster than a few ppm/few months (rough rule of thumb from current studies)

Hydrocarbons

(working limit)
Sources of Gas

Volume: \( N_2, O_2, Ar, H_2O, CO_2 \)

Surface: \( H_2O, (CH)_N \) \(-\) In-Situ bake

Diffusion: Elastomers: \( N_2, H_2O, (CH)_N \)

Metal: \( H_2 \) \(-\) Pre-bake

Fig. 4.6 Rate limiting steps during the pumping of a vacuum chamber.

\( \text{This figure is for a typical unbaked vacuum wall; the numbers thus are not relevant to L160, but the qualitative behavior is relevant.} \)
Residual Gas Analysis

Goal: Keep hydrogen, helium, argon, krypton, xenon, nitrogen, and carbon dioxide away from 2 x 10^-11 torr.

Pumping: 30 l/s

30 Viton springs (baked)

RGA: (Residual Gas Analyzer)

Collector

Hydrocarbon fragmentation peak

Mass

Pressure (torr)

10^9 10^-10 10^-11 10^-12 10^-13 10^-14
Fig. 10.1 Sectional view of the Pfeiffer DUO-35, 35-m³/h double-stage, rotary vane pump: (1) intake, (2) filter, (3) rotor, (4) spring, (5) vane, (6) gas ballast valve, (7) filter, (8) discharge valve, (9) exhaust, (10) sealing surface. Reprinted with permission from A. Pfeiffer Vacuumtechnik G.m.b.H. Wetzlar West Germany.

Fig. 14.6 Schematic diagram showing sputter deposition and pumping in a Penning cell:
- chemically active gases buried as neutral particles;
- chemically active gases ionized before burial;
- inert gases buried as neutral particles;
- inert gases ionized before burial.
Pumping Speed and Conductance

Pump, in its design range, pumps a given volume of gas per unit time, independent of the pressure.

\[ Q = \text{throughput (mass rate of flow)} \]

\[ S \equiv \text{pumping speed (volume rate of flow)} \]

\[ Sp \, P_1 = Q \]

\[ C \equiv \text{conductance (Ability of tube to transmit mass flow)} \]

\[ C (P_2 - P_1) = Q \]

What is \( S = \frac{Q}{P_2} \)

\[ \frac{1}{S} = \frac{1}{Sp} + \frac{1}{C} : \text{Conductance limit} \]

\[ P_1 = 0 \Rightarrow P_2 = \frac{Q}{C} \]
Pressure Distribution in L160 vacuum tube

- Mass: 2, 300K, q=1E-13
- 10000 l/s pumps at 2000m

1.0E-07
1.0E-08
1.0E-09
1.0E-10
1.0E-11

0 200 400 600 800 1000 1200 1400 1600 1800 2000

Pressure Distribution

- Mass: 2, 300K, q=1E-13
- 10000 l/s pumps at 2000m

1.0E-07
1.0E-08
1.0E-09
1.0E-10
1.0E-11

0 200 400 600 800 1000 1200 1400 1600 1800 2000

Thus, going to higher pump speed improves pressure only a little.
Vacuum Test Facility Concept

CALIBRATED \( H_2 \) LEAK

SPIRAL WELD 2 TEST TANK

1 TEST TANK

CHAMBER WITH STEEL SWATCHES

MASS SPECTROMETER

COMPUTER

PUMP

HYDROGEN OUTGASSING TESTS

Logio \( H_2 \) outgassing in torr liters/sec/cm\(^2\) After vacuum bake

Legend:

\# = Original Process

Initial Steel

distributed pump goal -- -12

end pump goal --

air bake

36 hr, 450 °C

Steel that has been subjected to different kinds of bakes
LIGO Initial Pumping

A few feet long section of cylindrical tube @ liquid nitrogen temperature catches molecular hydrogen leaks.

LN$_2$ pump: $\sim 10^5$ l/sec
For condensible gases (to keep hydrocarbons etc out of vacuum)

Ion pump: $S = 10^4$ l/sec
For H$_2$
Cavity Losses vs. Time

RTV Rubber:
- $0.16 \pm 0.08$ ppm/wk; $\leq 0.29$ ppm/wk, 95% CL

Viton:
- $0.25 \pm 0.06$ ppm/wk; $\leq 0.35$ ppm/wk, 95% CL

Control:
- $0.13 \pm 0.07$ ppm/wk; $\leq 0.24$ ppm/wk, 95% CL

Time, hours

ppm