Report on the Leak Localization on the Y arm at LLO

M. Meyer, H. Overmeir, K. Thorne, R. Weiss, M. Zucker   October 10 – November 30, 2012

Abstract: A leak of close to the estimated size has been found at 2258 meters from the LVEA port on the yarm. The best estimate for the location of the leak was at 2067 +- 39 meters . The 10 inch ports in the mid building are at 1966 and 1972 meters with the next port toward the Yend being at 2284 meters. Based on the initial estimate, we mounted the helium leak detector for the leak hunt in the mid building. The leak behaves as though it is in a single location and is constant to 5% at 2.495+-0.03 x 10^{-4} torr liters/sec from August 15 to October 15, 2012. The report gives the results of the leak localization and its limitations. It presents the analysis methods used as well as the results of numerical modeling based on the underlying diffusion process.

Introduction RGA's and discharge gauges were used at the LVEA and yend to measure the pressure of atmospheric gas species and the total pressure change in two methods with sensitivity to the location of the leak. The simplest technique was to close valves at the ion pumps at both ends and accumulate the gas – the dynamic method. The difference of the ratio of the pressure derivative with time to the pressure at the two ends allows for a localization. The more difficult but potentially more accurate method was to modulate the pumps with valve closure with a sequence that first closed the valve at the LVEA leaving the yend valve open and then, after the system had come to equilibrium, to open the LVEA valve and close the yend valve. The DC method uses the pressure differences to solve for the leak position. A key element in the localization strategy is to calibrate the sensors by recognizing that the pressure derivative with time, when the system is not being pumped, is independent of the sensor location and leak position after a stationary flow pattern has been established in the tube.

The errors in the leak location are not Gaussian. Typical random error for any several day measurement as determined by the shot noise in the ion currents both in the discharge gauges and the RGA's would give localization errors of 5 to 10 meters. The measurements are insensitive to parameters common to both ends (ie., uniform outgassing, common temperature changes…). The measurements are dominated by uncontrolled (and currently unmeasured) sources of systematic errors such as temperature gradients along the tube and differential non-linearities in the sensors. These cause the errors to be larger and non-Gaussian. There are outliers in the data at distances as large as 90 meters from the most likely position. Taking more data without understanding and controlling or measuring the systematic error sources in the system would have been unproductive. If we had not found the leak, the model of a single leak might have been wrong and more pressure sensors would have been needed at different places along the tube to solve for the leak locations. If there are n leaks in the tube it requires n+1 sensors to uniquely solve for their positions. In addition, further efforts at localization would have hopefully gotten closer to the random statistical errors which will require an array of thermometers along the beam tube. The almost 200 meter difference between the average localization position and the actual leak is not yet explained. We will know more once the leak is covered and the new leak rate into the tube is measured.

The measurements used the RGA at amu 2, 14, 28, 32 and 40. The initial localizations were made with amu 28 and 14, the molecular nitrogen peaks, until we noticed that the discharge gauges mounted next to the RGA gave similar results and that the noise in the localization was not dominated by the shot noise but was correlated between the discharge gauges and the RGA due to a systematic we were not controlling. The other consideration for using the RGA rather than the total pressure measurements of the discharge gauges was the molecular hydrogen, amu 2, outgassing which could have skewed the results if it was inhomogeneous. With a leak as large as the current one, the Hydrogen outgassing is a few percent of the signal and the inhomogeneity a factor of 10 to 100 smaller.

We noticed non-linearity in the RGA once the Faraday mode ion current exceeded 10^{-10} amperes or the total pressure was larger than 3 x 10^{-6} torr. The amu 40 peak, due to the argon entering through the leak, has a much longer time constant than the nitrogen both because of the reduced thermal velocity (reduced diffusion constant) and the storage time of Argon in the cryo pumps. The amu 32 peak from molecular oxygen follows the nitrogen closely but is not at the atmospheric ratio to nitrogen due to gettering by the tube surface.

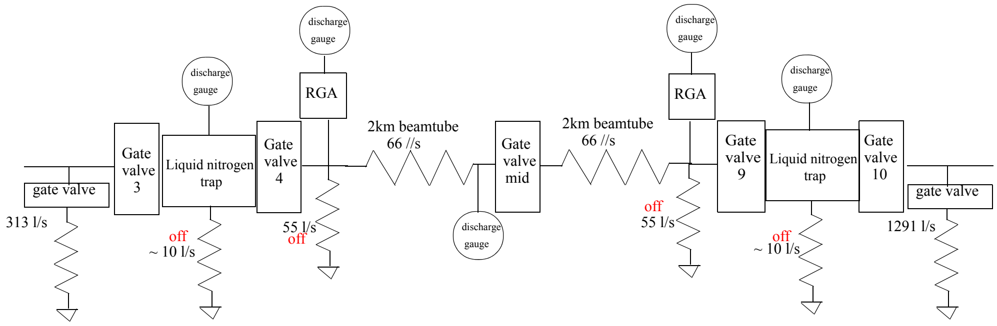


Figure 1 Schematic of the yarm. The measurements were carried out with gate valves 3,4,mid,9 and 10 open and the liquid nitrogen traps cold. The ion pump at the left (LVEA pump labeled by 313 l/s) was measured to have a pumping speed of 215 liters/sec for nitrogen and the one on the right (Yend labeled 1291 l/s) was measured to have a pumping speed of 1640 liters/sec for nitrogen. The valves modulated were the smaller gate valves associated with these two pumps. During an accumulation the smaller gate valves were both shut. The RGAs and discharge gauges used to perform the measurements are mounted on 10 inch ports on the beamtube adjacent to the gate valve 4 (the LVEA pressure sensors) and gate valve 9 (the yend pressure sensors).

Calibration

A critical part of the leak localization is to establish the relative sensitivity of the discharge gauges and the RGAs to a few parts in a thousand. The absolute calibration is not critical except to estimate the size of the leak which is determined by accumulation of the leak into the known volume of the beamtube. The localization trades on pressure ratios and their differences. The relative sensitivity of the RGA's and discharge gauges is determined during accumulation measurements. Once the diffusion transients have damped out, the time derivative of the pressure in the tube due to the leak and outgassing is independent of where in the tube the pressure is measured (shown in **Appendix 1**) . The fact that dp/dt is the same everywhere in the tube allows the pressure sensors to be normalized by simply dividing the sensor output by the derivative of the sensor output during the accumulation after the transients have died away.

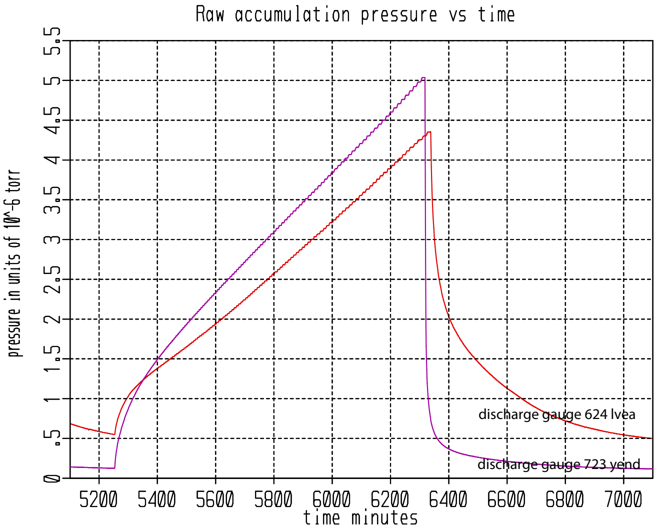


Figure 2 The accumulation begins at 5250 minutes and is ended at about 6300 minutes as the yend and lvea valves are open in sequence. The steady pressure derivative begins at 5800 minutes and shows a 10% difference in the gauge sensitivities. 10 hours is typical for the transients to die off.

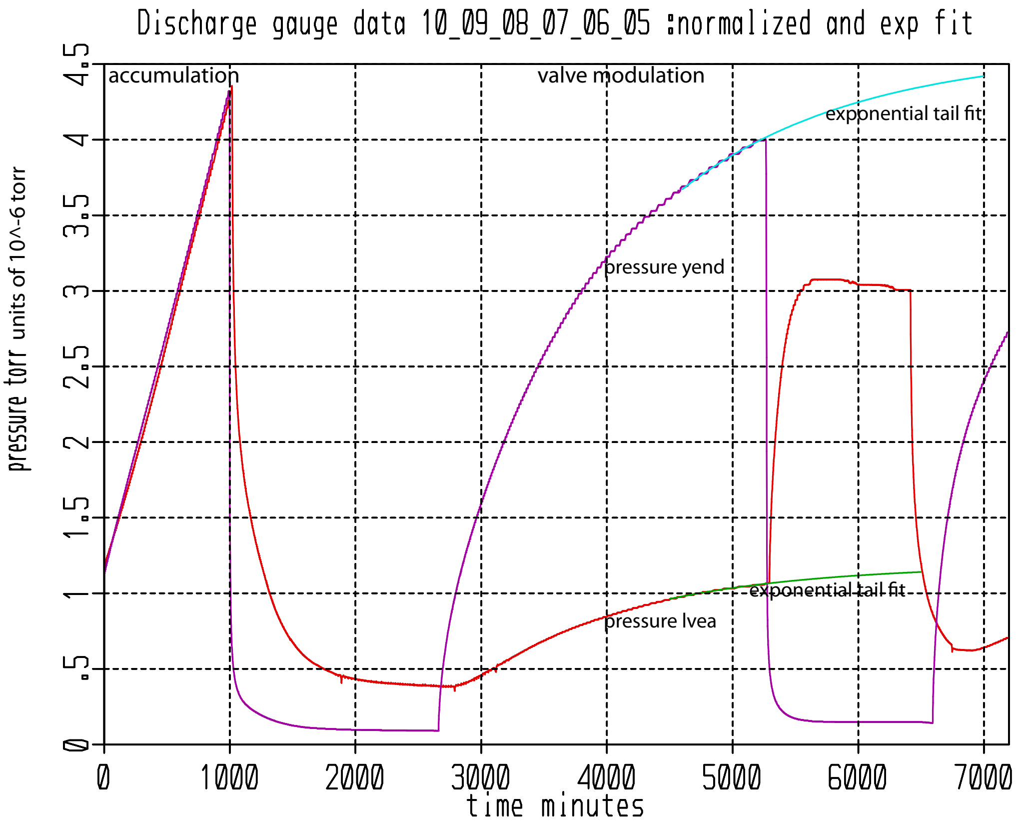


Figure 3 A complete leak localization sequence showing both the initial accumulation between 0 to 1000 minutes followed by a valve modulation. The data has been normalized to remove the differences in gauge sensitivity: the lvea discharge gauge output has been multiplied by 1.051 while the yend output has been multiplied by 0.9496. The values are determined by the transient free parts of the accumulations at the beginning and end of the sequence. In the time between 1000 to 2800 minutes, the yend and lvea valves are open. Between 2800 minutes to 5200 minutes, the yend valve is closed and the lvea valve is open. Between 5200 minutes and 6600 minutes, the yend valve is open and the lvea valve is closed. The pumping speed at the lvea is about ¼ of that at the yend which accounts for the difference in time to reach steady state for the two valve configurations. As shown in **Appendix 1**, the transient solutions to the diffusion are a sum of exponentials with different time constants with time origin at the moment when a valve is activated. The times to achieve steady state were not always attained in the data taking and we had to resort to exponential curve fitting at the ends of a valve state to determine the equilibrium pressure values in the valve modulation method. The difference in pressure between the lvea and yend during the steady state part of the accumulation carries the localization information.

Dynamic method The beamtube is isolated from the pumps and the pressure at the yend and lvea as a function time is recorded. In the steady state dp/dt is a constant independent of location in the tube and the pressure difference between the gauges after normalization provides the leak localization. As is shown in **Appendix 1**, the location of the leak is given by

$$x_{lk} = \left(\frac{2av}{3L}\right)\left[\frac{P_{yend}(t)}{\frac{dP_{yend}}{dt}} - \frac{P_{lvea}(t)}{\frac{dP_{lvea}}{dt}}\right] + \frac{L}{2} \qquad t > \frac{2L^2}{av} \qquad \text{eq 1}$$

L is the length of the beam tube between the ports at the LVEA and the yend, a is the radius of the beamtube and v the thermal velocity of the gas for which the pressure is being measured.

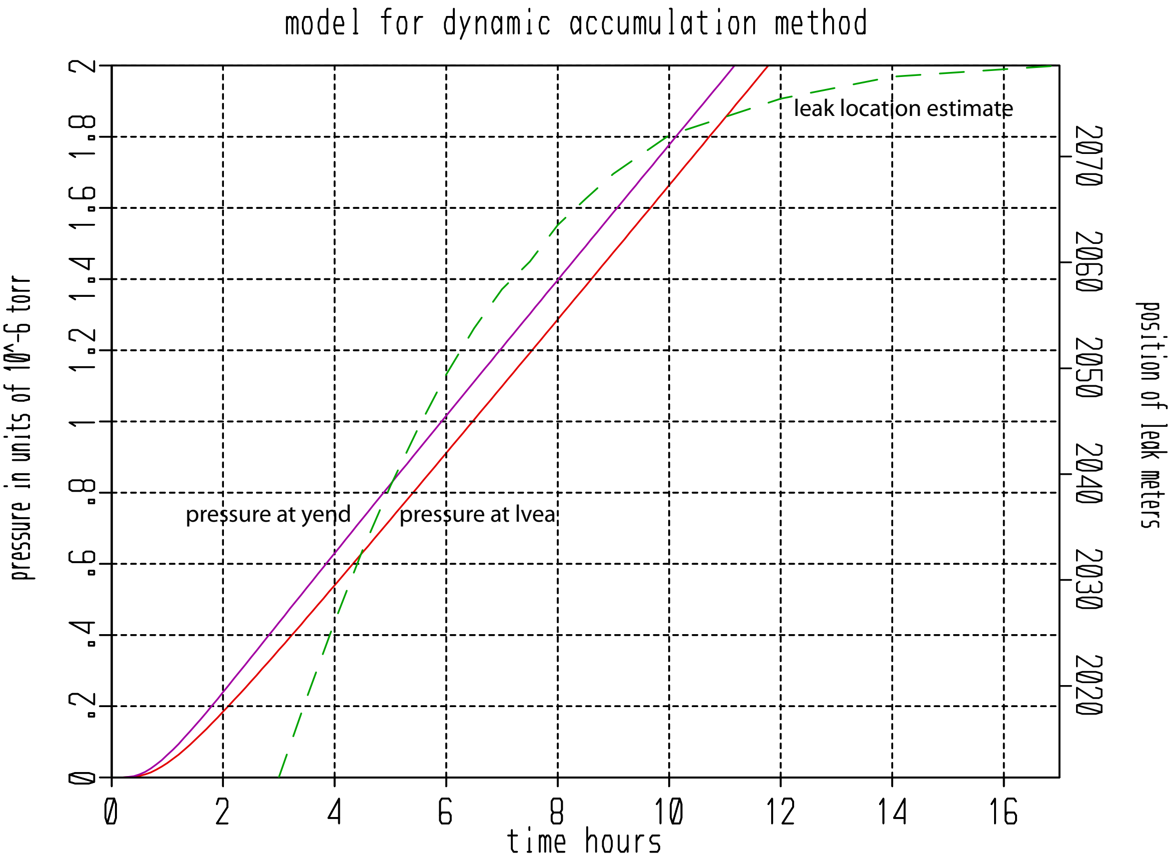


Figure 4 Model generated by the FORTRAN program btleakfind5 of the accumulation of the 2.5 x 10^{-4} torr liters/sec placed at 2089 meters from the LVEA 10 inch port on the beamtube. The pressure at the lvea and yend are plotted along with the leak location estimates of eq. 1. The transients in the accumulation are damped out well enough by 10 hours after the accumulation was started.

An accumulation is part of each localization sequence and reaches steady state more quickly than the valve modulation technique. More than 2/3 of the data we have taken used the dynamic method.

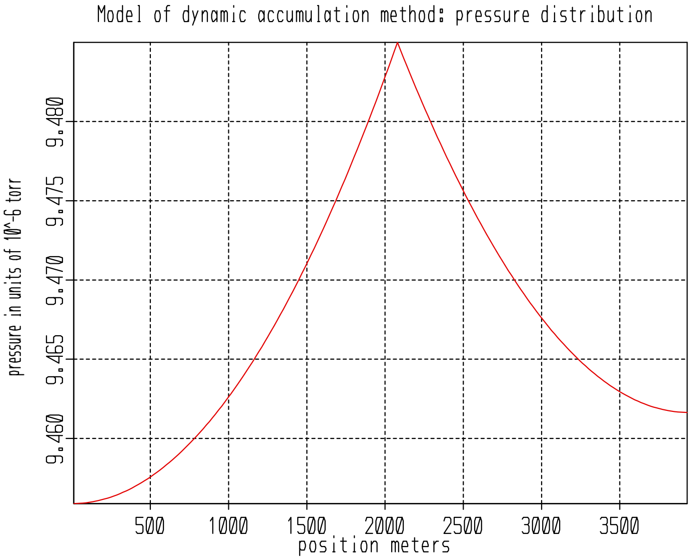


Figure 5 The model pressure distribution in the tube after the transients have decayed for the accumulation of a 2.5 x 10^{-4} torr liter/sec leak at 2089 meters from the lvea 10" flange on the tube**.**

Valve modulation method (DC method) The technique is easier to understand and was the first proposed. The concept is a straightforward application of the linear relations between the pressure in the tube and the pumping impedence of the tube which varies linearly with the length (the baffles and bellows are a perturbation and discussed later under error sources). **Figure 6** shows the method. It is first order independent of the pumping speeds of the pumps.

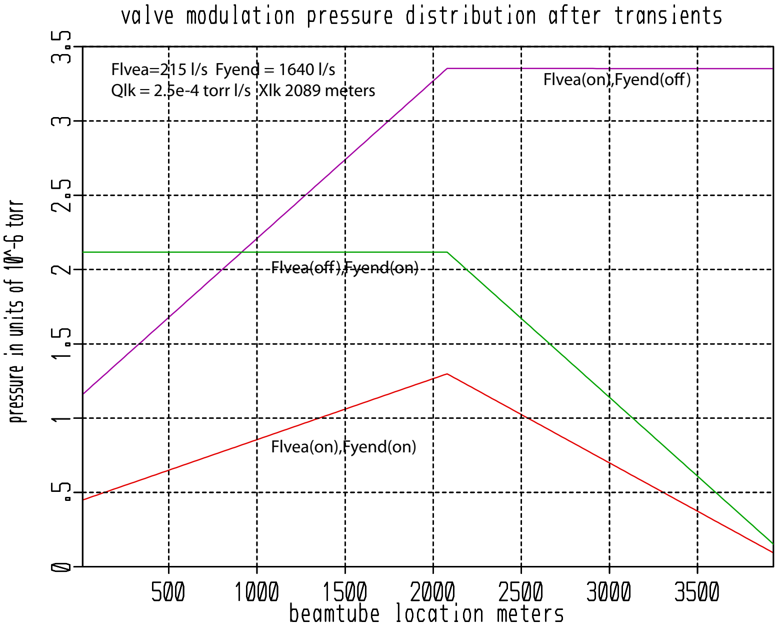


Figure 6 The static pressure distribution of nitrogen in the beamtube after the transients have died off for a leak of 2.5 x 10^{-4} torr liters/sec located 2089 meters from the LVEA beamtube 10 inch pump out port. The red curve is with both LVEA and yend gate valves open, the green curve is with the lvea valve closed and yend open while the violet curve has the lvea gate open and the yend closed.

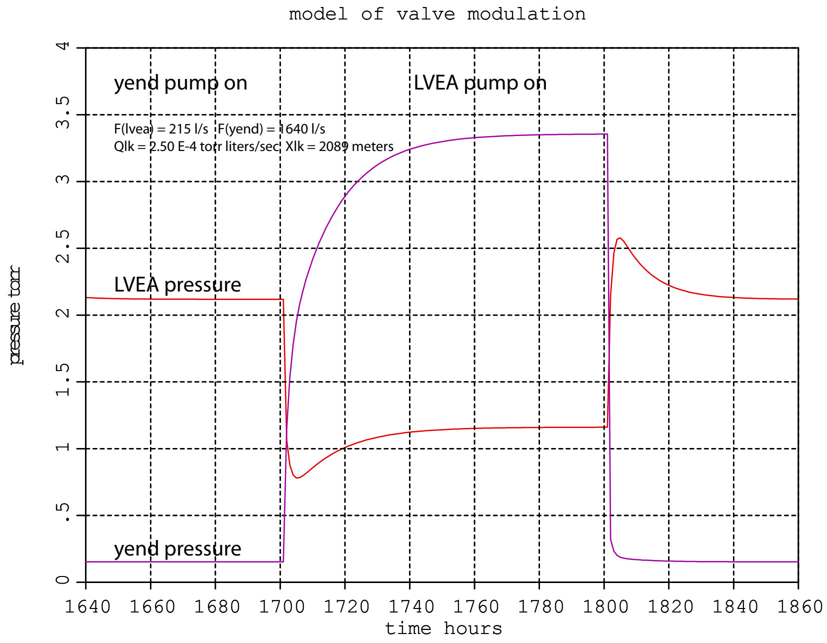


Figure 7 Model of the valve modulation after several cycles of the valve modulation. The equilibrium values are those in **Figure 6.** The cycle times are longer than those used in the actual data taking shown in **Figure 8.** A comparison of the model with the data shows that the pumping speed of the modulated pumps, data at the minimum pressures, have been assigned correctly but that the peak pressures, which involve the impedence of the beamtube, do not match the data; the tube impedence is about 25% larger than that used in the model. The model assumes a tube with radius 62cm, the discrepancy is most likely due to the baffles and bellows in the tube.

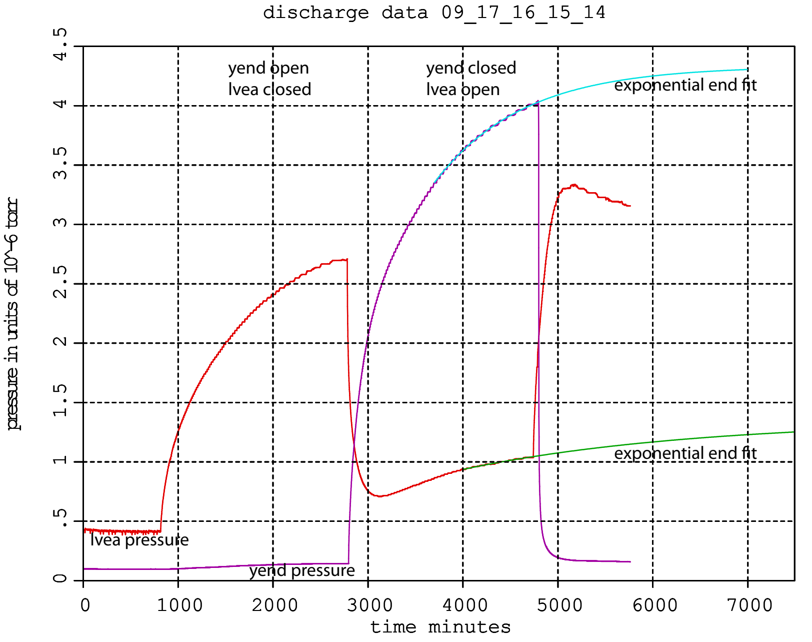


Figure 8 Data from the discharge gauges at the LVEA and yends. The LVEA valve is closed at 900 minutes while the yend valve is open. At 2900 minutes the LVEA valve is open and the yend valve is closed. The valve modulation times are too short to achieve equilibrium and an exponential end fit has been done to project to the equilibrium values. The exponential end fit to the LVEA pressure at 2900 minutes was carried out but is not shown in the figure. The pressure was normalized by dividing by the transient free values of dp/dt: the raw LVEA pressure was multiplied by 1.0516 and the yend pressure by 0.95323.

The position of the leak is determined from

$$x_{lk} = L \frac{\left(\frac{P_{yend}}{\frac{dP_{yend}}{dt}} - \frac{P_{lvea}}{\frac{dP_{lvea}}{dt}} \right)_{lvea-on}}{\left(\frac{P_{yend}}{\frac{dP_{yend}}{dt}} - \frac{P_{lvea}}{\frac{dP_{lvea}}{dt}} \right)_{lvea-on} - \left(\frac{P_{yend}}{\frac{dP_{yend}}{dt}} - \frac{P_{lvea}}{\frac{dP_{lvea}}{dt}} \right)_{yend-on}} \qquad \text{eq 2}$$

where the pressures are the equilibrium values after the valve modulation has taken place and the pressure derivatives with time are the transient free values during the accumulations. The notation *lvea-on* is the valve state with the lvea valve open and the yend closed while *yend-on* is the case for the yend valve open and the lvea valve closed. The equation is derived in **Appendix 1**.

Sensitivity and Errors **Table 1** lists the sensitivity of the localization to variations in the measured variables. The units in the table are in meters of leak position for a 1% change in the measured variable.

Table 1 Sensitivity of leak position to 1% change in measured variable

measured variable	change in leak position meters	measured variable	change in leak position meters
dp_{lvea}/dt	13.7	P_{lvea}(lvea-on)	-3.5
dp_{yend}/dt	-13.7	P_{lvea}(yend-on)	-10.1
$dp_{yend}/dt + dp_{lvea}/dt$	0.08	P_{yend}(lvea-on)	13.1
sum of all p	0.38	P_{yend}(yend-on)	0.38

Table 2 shows the average pressure values derived from the valve modulation technique, the statistical errors of the pressures are all about 5×10^{-9} torr.

Table 2 Average equilibrium pressure for the different valve states

location and state	pressure 10^{-6} torr	location and state	pressure 10^{-6} torr
lvea (yend-on)	2.991	yend (yend-on)	0.1522
lvea (lvea-on)	1.161	yend (lvea-on)	4.401

Uniform temperature changes do not effect the localization, however, temperature gradients along the tube are significant. The temperature gradients cause several different errors. The gas pressure is linear with the temperature, a 1K temperature difference between the LVEA and the yend will cause a 3 meter error in the localization if not corrected in the analysis. Another contribution comes from the change in the diffusion constant in the tube with temperature which amounts to about 1 meter for one 1K difference between the tube sections between the lvea and the leak and the yend and the leak. The pumping speed of ion pumps at the LVEA and yend change with temperature by close to 1% for 1K which corresponds approximately to a 10 meter change in the localization. The unmeasured temperature gradients in the beamtube could account for between 30 to 60 meters of noise in the localization. If there is further work needed to localize the leak or other leaks form, it would be valuable to monitor thermometers every 250 meters along the beamtube.

The baffles were not included in the modeling which assumes a tube with constant radius of 62 cm. The baffles extend 8 cm into the tube. In the middle of the arm at LLO there is close to 1 baffle per 20 meters of tube length. This reduces the pumping speed of each 20 meter section by 10% and upto 30% at the ends where there are multiple baffles per 20 meter section. The leak is close to the middle of the tube and the reduction in pumping speed is symmetric about the leak causing little error (less than 1 meter) in the leak localization. If the leak had been near one end of the tube at LLO or should there be a leak at either end of the tube modules at LHO, the corrections would be significant and the model would need to be modified. The reduction in the pumping speed due to the baffles can be seen in the discrepancy between the modeled and measured pressure in the valve modulation method where the measured pressures are higher than the modeled ones in those cases when the pump is separated from the leak by a long section of tube.

Appendix 1 : One dimensional diffusion in a tube

The molecular flow in a tube when the pressure is low enough so that the transverse dimensions of the tube are smaller than the mean free path is described by the diffusion equation for the molecular density $\rho(x,t)$

$$D\frac{\delta^2\rho(x,t)}{\delta x^2}=\frac{\delta\rho(x,t)}{\delta t}$$

where $D=\frac{2}{3}av_{th}$ is the diffusion constant, a the radius of the tube, $v_{th}=\sqrt{\frac{8kT}{\pi m}}$ the most probable thermal speed. k is Boltzmann's constant, T the absolute temperature and m the mass of the molecule. The transient equation is solved by separation of variables $\rho(x,t)=X(x)T(t)$ which yields the ordinary differential equations

$$\frac{d^2X(x)}{dx^2}+\frac{\lambda^2}{D}X(x)=0\rightarrow X(x)=A\sin(\frac{n\pi x}{L})+B\cos(\frac{n\pi x}{L})$$

$$\frac{dT(t)}{dt}+\lambda^2T(t)=0\rightarrow T(t)=\sum_{n=1}^{\infty}\alpha_n e^{-\frac{(n\pi)^2Dt}{4L^2}}$$

The transients die off exponentially with the longest time constants, n =1, associated with the largest spatial dimensions , $\tau = \frac{6\,L^2}{\pi^2 a v_{th}}$ about 8 hours for nitrogen at 296K.

The special solutions associated with the transient free accumulations and steady state pressure distributions, are determined from the boundary conditions imposed by the leak and the pumping. A useful quantity is the diffusive particle flux determined by the equations above coupled to the continuity equation for conservation of the molecules

$$J = D\frac{d\rho}{dx}$$

In the valve modulation method the only flow is from the leak at x_{lk} through the beamtube to the pump at x =0 or x = L depending on which valve is open. J is constant in the beamtube (as long as the radius a of the tube is fixed) and therefore the density or pressure gradient is constant. The flow between the leak to the open valve is the same for both valve modulations while the pressure difference between the two ends of the tube is proportional to the tube length – the distance between the leak and the pump. The assumption made is that the quantity of gas leaking into the tube is independent of the pressure in the tube, valid as long as the pumping speed of the leak is tiny compared to that of the beamtube or pumps. The flow in the tube is then proportional to

$$\text{Flow} \propto \frac{(P_2 - P_1)_{1\text{open}}}{x_{lk}} = \frac{(P_1 - P_2)_{2\text{open}}}{L - x_{lk}}$$

which gives equation 1 when the individual pressure readings are normalized for the gauge constants using the transient free accumulation rates.

The transient free accumulation is most easily treated by noting that J decreases linearly with distance from the leak to the ends where it becomes equal to zero. J is not the same at the leak into the two regions x_{lk} to x =0 and x_{lk} to L if the leak is not exactly in the middle. At the leak, J into the direction with the longer tube is larger than J into the direction with the smaller tube length in proportion to the length (the volume that needs to be filled). When the transients have died off, the second derivative of the pressure with distance in the tube becomes constant and the first derivative of the pressure with time in the tube (as indicated by the diffusion equation) at any location becomes the same. Combining these relations with the need to have the total J into the two sections of tube be given by the leak size Q_{lk} gives

$$J_1 + J_2 = \frac{Q_{lk}}{\pi a^2} \quad \text{at the leak and everywhere} \quad \frac{dP}{dt} = \frac{Q_{lk}}{\pi a^2 L}$$

The relations discussed in the paragraph above and the two equations lead to equation 2.

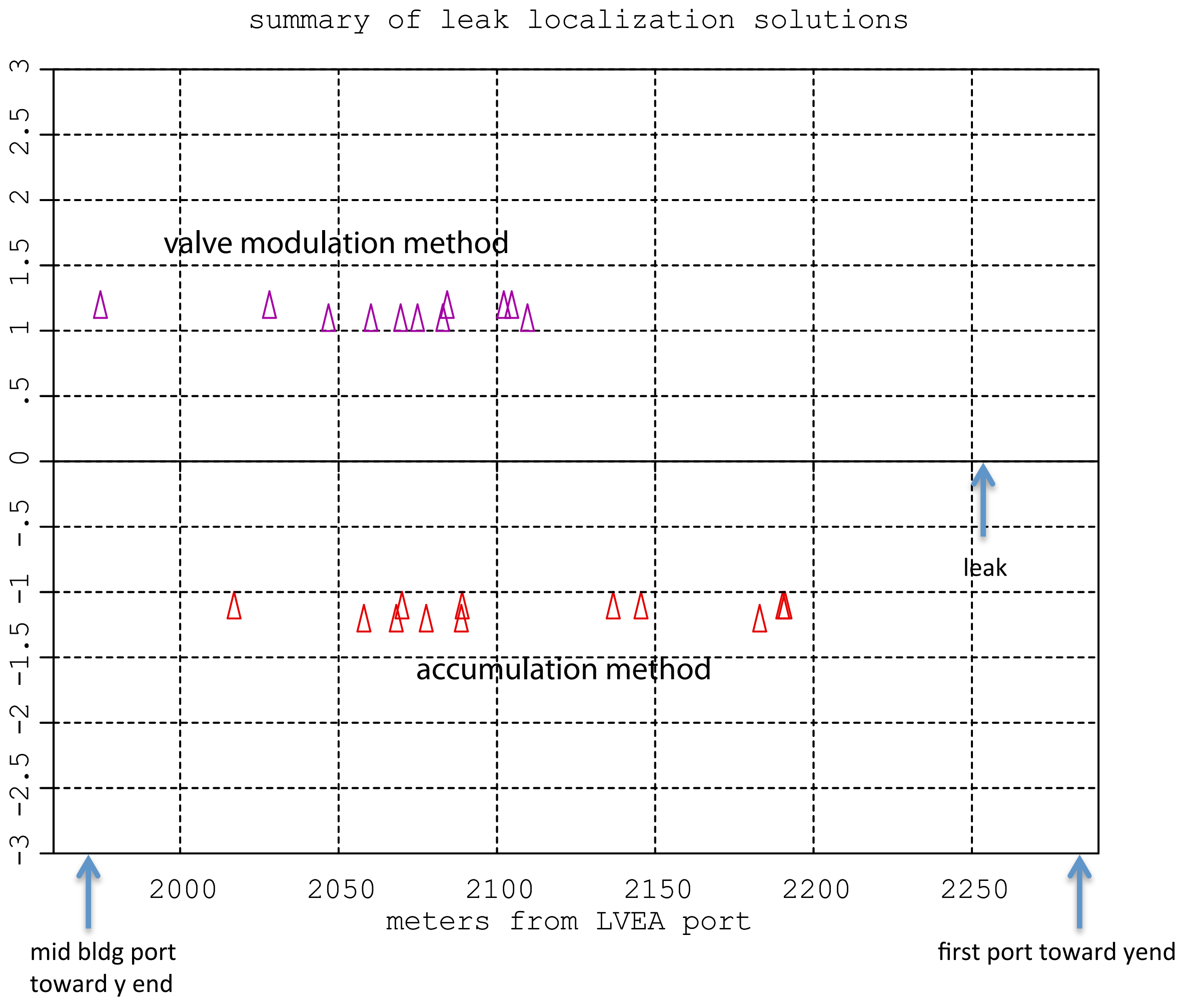
Both equations 1 and 2 were checked in detail by using a finite element diffusion model for the tube incorporated into the FORTRAN program btleakfind4 and btleakfind5. The programs determine the pressure profiles for different pumping speeds at the ends and the leak with adjustable size and position. If it should ever become necessary to fit to the full solution for the evolution of the pressure in space and time, the FORTRAN programs are the best way to determine the solutions.

Appendix 2: The data

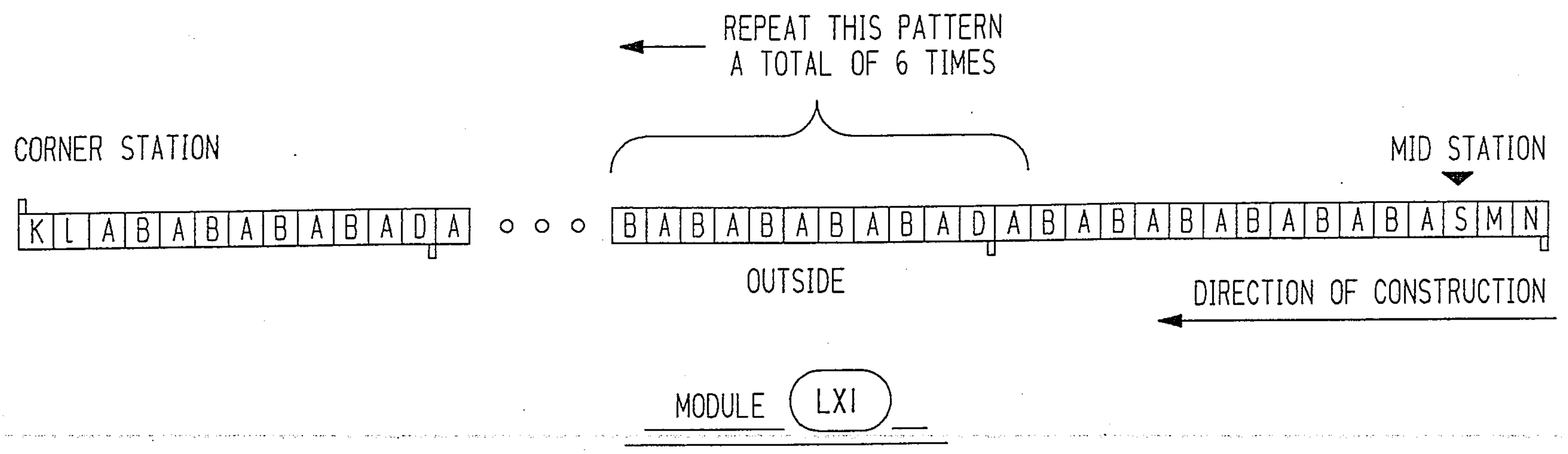
The table on the next and following page show the reduced data for both methods as well as some tests to determine the effect of constant outgassing and the solutions for other than amu 14 and 28. The third page gives a graphical display of the solutions. The data is clearly not Gaussian with a distribution of points much larger than simply due to random errors which in principle have an rms of 10 meters. Table 1 gives direct estimates of the localization errors as determined by running the FORTRAN programs with a range of parameters. The actual errors are about three times larger than one would determine from the variation of the experiment parameters, especially, estimated temperature gradients. It is very hard to believe that temperature gradients of 10K occur along the north and south sections of the tube. The discrepancy between the found leak position and the various localization solutions has not yet been explained. The tube dimensions come from the CB&I table in Appendix 3. There is some suspicion that these numbers are not the as built values and we will check them with GPS in the near future.

type	method	directory/files pressure or current	directory/files dp/dt, di/dt	calibration	lk position meters from LVEA RGA all +- 5 to 10 m	notes
accumulation	discharge	1015_17/624_10_16_15 1015_17/723_10_16_15		dp/dt(lvea) 5.98994e-11+-3.0e-13 dp/dt(yend) 6.7250e-11+-3.0e-13	2070.07	no traps
accumulation	amu28	1015_17/amu28_10_16_yend 1015_17/amu28_10_16_lvea		di/dt(lvea) 1.46493e-15+-3.0e-18 di/dt(yend) 1.10594e-15+-2.0e-18	2068.25	no traps
accumulation	amu14	1015_17/amu14_10_16_lvea 1015_17/amu14_10_16_yend		di/dt(lvea) 1.62750e-16+-2.0e-19 di/dt(yend) 1.50098e-16+-4.0e-18	2089.01	no traps
accumulation	amu32	1015_17/amu32_10_16_lvea 1015_17/amu32_10_16_yend		di/dt(lvea) 2.432995e-16+-6.0e-19 di/dt(yend) 1.84592e-16+-4.0e-19	2111.18	no traps
accumulation	amu40	1015_17/amu40_10_16_lvea 1015_17/amu40_10_16_yend		di/dt(lvea) 1.82476e-17+-2.0e-19 di/dt(yend) 1.53863e-17+-2.0e-19	2008.21	no traps
accumulation	amu2	1015_17/amu2_10_16_lvea 1015_17/amu2_10_16_yend		di/dt(lvea) 2.34403e-17+-2.0e-19 di/dt(yend) 1.66064e-17+-2.0e-19	*1620* f(temp)	test of concept no agree, no traps
valve mod	discharge	1011_14/624_10_09_08_07_06_05 1011_14/723_10_09_08_07_06_05	1011-14/624_10_14_13…… 1011_14/723_10_14_13……	dp/dt(lvea) 5.63517e-11+-1.0e-13 dp/dt(yend) 6.29781e-11+-1.0e-13	2074.91	
valve mod	amu28	1011_14/amu28_10_14_lvea 1011_14/amu28_10_14 yend	1011_14/amu28_10_14_yend 1011_14/amu28_10_14_lvea	di/dt(lvea) 1.412302e-15+-2.0e-18 di/dt(yend) 1.0460e-15+-3.0e-18	2028.21	
valve mod	amu14	1011_14/amu14_10_14_lvea 1011_14/amu14_10_14 yend	1011_14/amu14_10_14_yend 1011_14/amu14_10_14_lvea	di/dt(lvea) 1.553415e-16+-4.0e-19 di/dt(yend) 1.39821e-16+-6.0e-19	2060.25	
valve mod	amu2	1011_14/amu2_10_14_lvea 1011_14/amu2_10_14_yend	1011_14/amu2_10_14_yend 1011_14/amu2_10_14_lvea	di/dt(lvea) 4.09979e-17+-3.0e-19 di/dt(yend) 2.36028e-17+-2.0e-19	*2732* f(temp)	test of concept not to agree
accumulation	discharge	1011_14/624_10_14_13_12_11_10 1011_14/723_10_14_13_12_11_10		dp/dt(lvea) 5.63517e-11+-1.0e-13 dp/dt(yend) 6.29781e-11+-1.0e-13	2136.7	
accumulation	amu28	1011_14/amu28_10_14_yend 1011_14/amu28_10_14_lvea		di/dt(lvea) 1.393565e-15+-2.0e-18 di/dt(yend) 1.0460e-15+-3.0e-18	2088.8	
accumulation	amu14	1011_14/amu14_10_14_lvea 1011_14/amu14_10_14_yend		di/dt(lvea) 1.55341e-16+-4.0e-19 di/dt(yend) 1.39821e-16+-6.0e-18	2190.3	
accumulation	amu32	1011_14/amu32_10_14_lvea 1011_14/amu32_10_14_yend		di/dt(lvea) 2.28186e-16+-6.0e-19 di/dt(yend) 1.73542e-16+-5.0e-19	2109.7	
accumulation	amu40	1011_14/amu40_10_14_lvea 1011_14/amu40_10_14_yend		di/dt(lvea) 1.762180e-17+-4.0e-19 di/dt(yend) 1.45388e-17+-2.0e-19	2071.6	
accumulation	amu2	1011_14/amu2_10_14_lvea 1011_14/amu2_10_14_yend		di/dt(lvea) 4.09979e-17+-3.0e-19 di/dt(yend) 2.36028e-17+-2.0e-19	*2804.6* f(temp)	test of concept not to agree
valve mod	discharge	1006_09/624_10_09_08_07_06_05 1006_09/723_10_09_08_07_06_05	1003_05/624_10_05_04_03 1003_05/723_10_05_04_03	dp/dt(lvea) 4.9620e-11+-1.0e-13 dp/dt(yend) 5.7894e-11+-1.0e-13	2082.9	
valve mod	amu28	1006_09/amu28_10_9_lvea 1006_09/amu28_10_09 yend	1003_05/amu28_10_05_yend 1003_05/amu28_10_05_lvea	di/dt(lvea) 1.18803e-15+-1.0e-18 di/dt(yend) 9.50980e-16+-1.0e-18	1974.8	

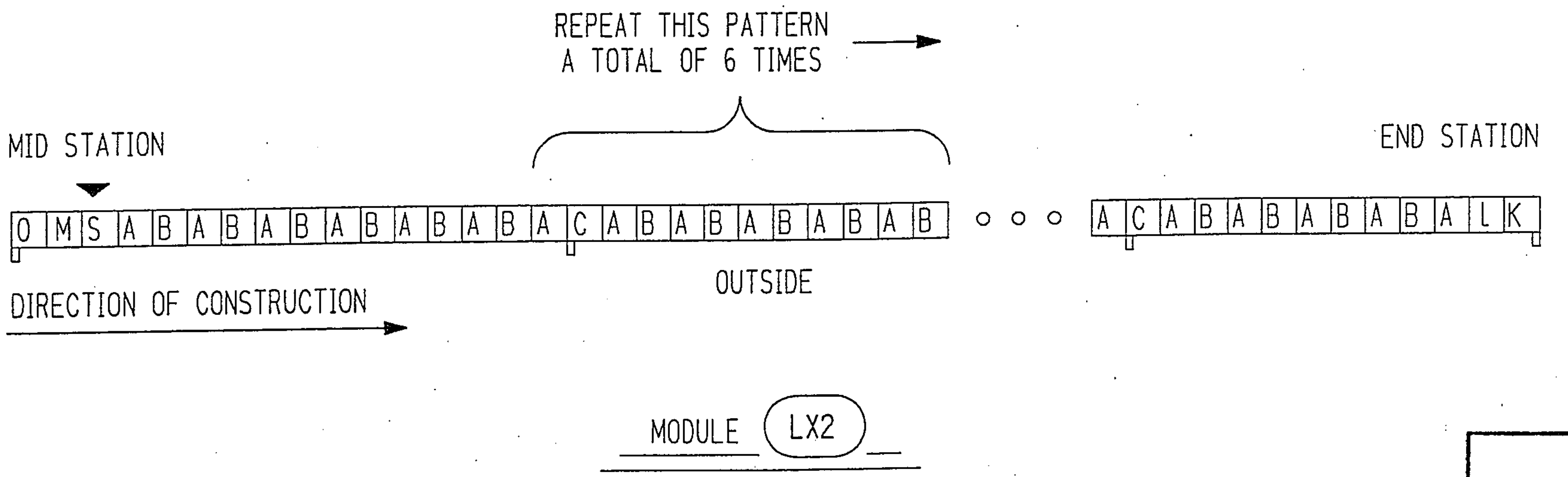
valve mod	amu14	1006_09/amu14_10_9_lvea 1006_09/amu14_10_09 yend	1003_05/amu14_10_05_yend 1003_05/amu14_10_05_lvea	di/dt(lvea) 1.3740e-16+-1.0e-18 di/dt(yend) 1.2850e-16+-1.0e-18	2069.6	
accumulation	discharge	1003_05/624_10_05_04_03 1003_05/723_10_05_04_03		dp/dt(lvea) 4.9620e-11+-1.0e-13 dp/dt(yend) 5.7894e-11+-1.0e-13	2058	
accumulation	amu28	1003_05/amu28_10_05_lvea 1003_05/amu28_10_05_yend		di/dt(lvea) 1.18803e-15+-1.0e-18 di/dt(yend) 9.50980e-16+-1.0e-18	2017	
accumulation	amu14	1003_05/amu14_10_05_yend 1003_05/amu14_10_05_lvea		di/dt(lvea) 1.3740e-16+-1.0e-18 di/dt(yend) 1.2850e-16+-1.0e-18	2183	
accumulation	discharge	1003_05/624_10_03_02_01 1003_05/723_10_03_02_01		dp/dt(lvea) 5.1380e-11+-1.0e-13 dp/dt(yend) 5.6660e-11+-1.0e-13	2191	
valve mod	amu14	0920_23/amu14_09_25_lvea 0920_03/amu14_09_25 yend	0924_25/amu14_10_05_yend 0924_25/amu14_10_05_lvea	di/dt(lvea) 1.37656e-16+-1.0e-18 di/dt(yend) 1.4939e-16+-1.0e-18	2084.3	
valve mod	discharge	0920_23/624_09_23_22_21_20 0920_23/723_09_23_22_21_20	0924_25/624_09_26_25_24 0924_25/723_09_26_25_24	dp/dt(lvea) 4.7251e-11+-1.0e-13 dp/dt(yend) 5.2127e-11+-1.0e-13	2046.8	
valve mod	discharge	0915_18/624_09_17_16_15_14 0915_18/723_09_17_16_15_14	0924_25/624_09_26_25_24 0924_25/723_09_26_25_24	dp/dt(lvea) 4.7251e-11+-1.0e-13 dp/dt(yend) 5.2127e-11+-1.0e-13	2102.2	
valve mod	discharge	0920_23/624_09_20_19_18 0920_23/723_09_20_29_18	0924_25/624_09_26_25_24 0924_25/723_09_26_25_24	dp/dt(lvea) 4.7251e-11+-1.0e-13 dp/dt(yend) 5.2127e-11+-1.0e-13	2109.7	
valve mod	discharge	0920_23/624_09_20_19_18 0920_23/723_09_20_19_18	0910_15/624_09_13_12_11 0910_15/723_09_13-12_11	dp/dt(lvea) 5.3846e-11+-2.0e-13 dp/dt(yend) 5.7868e-11+-2.0e-13	2104.7	same as above new calibration
accumulation	discharge	0924_25/624_09_26_25_24 0924_25/723_09_26_25_24		dp/dt(lvea) 4.8205e-11+-2.0e-13 dp/dt(yend) 5.2394e-11+-2.0e-13	2145.5	
accumulation	discharge	0910_15/624_09_13_12_11 0910_25/723_09_13_12_11		dp/dt(lvea) 5.3846e-11+-2.0e-13 dp/dt(yend) 5.7868e-11+-2.0e-13	2077.7	
				Do not use amu: 2,32,40		
				accumulation method	2110+-58	12pts
				valve modulation method	2067+-39	11pts
				mid pt avg accumulation	2113+-51	10 pts
				mid pt avg valve mod	2073+-24	9pts


summary of leak localization solutions
valve modulation method
accumulation method
leak
mid bldg port
toward y end
first port toward yend
meters from LVEA port
2000
2050
2100
2150
2200
2250
3
2.5
2
1.5
1
.5
0
-.5
-1
-1.5
-2
-2.5
-3

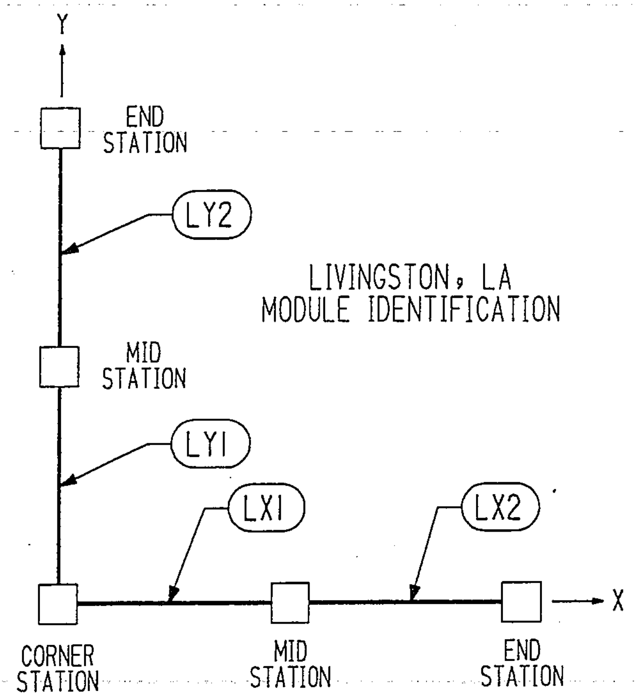
Appendix 3: The CB&I port positions



MODULE (LX1)



MODULE (LX2)



LIVINGSTON, LA
MODULE IDENTIFICATION

46710
277223
514967
752711
990455
1228199
1465943
1703687
2015722
2018778
2330813
2568557
2806301
3044045
3281789
3519533
3757277
3987790

PUMP PORT LOCATIONS

APPROVED

M. Tellalian	6-24-96
CBI	DATE
J. Jones	7/23/96
CALTECH	DATE

▶ INDICATES CHANGE FROM PREVIOUS ISSUE

REV	BY	CHKD	DATE	REMARKS
6	ARL	[illegible]	6-24-96	MODIFIED TUBE TYPES CHANGED REV. NO. TO BE IN SEQUENCE WITH CONTRACT 930212
5	ARL	MLT	3-11-96	ENTIRE DRAWING REVISED

REVISIONS

CBI

SUPPLIER'S / PURCHASER'S NO

LIGO BEAM TUBE
HANFORD, WA & LIVINGSTON, LA

LIVINGSTON BEAM TUBE MODULES
(LX1) & (LX2)

CUSTOMER'S NO
BY ARL CHKD MLT DATE 3-11-96
M. L. TELLALIAN
ENGINEERING ASSIGNED

CONTRACT NO 953571
DWG 1
SHT 3
REV 6

55710301.DGN

TUBE NO.	TYPE	LENGTH	[END-A]	[END-B]
▶ 1	N*, P**	17361	2016432	1999071
2	M	16562	1999071	1982509
▶ 3	S	19812	1982509	1962697
4	A	19812	1962697	1942885
5	B	19812	1942885	1923073
6	A	19812	1923073	1903261
7	B	19812	1903261	1883449
8	A	19812	1883449	1863637
9	B	19812	1863637	1843825
10	A	19812	1843825	1824013
11	B	19812	1824013	1804201
12	A	19812	1804201	1784389
13	B	19812	1784389	1764577
14	A	19812	1764577	1744765
15	B	19812	1744765	1724953
16	A	19812	1724953	1705141
17	D	19812	1705141	1685329
18	A	19812	1685329	1665517
19	B	19812	1665517	1645705
20	A	19812	1645705	1625893
21	B	19812	1625893	1606081
22	A	19812	1606081	1586269
23	B	19812	1586269	1566457
24	A	19812	1566457	1546645
25	B	19812	1546645	1526833
26	A	19812	1526833	1507021
27	B	19812	1507021	1487209
28	A	19812	1487209	1467397
29	D	19812	1467397	1447585
30	A	19812	1447585	1427773
31	B	19812	1427773	1407961
32	A	19812	1407961	1388149
33	B	19812	1388149	1368337
34	A	19812	1368337	1348525
35	B	19812	1348525	1328713
36	A	19812	1328713	1308901
37	B	19812	1308901	1289089
38	A	19812	1289089	1269277
39	B	19812	1269277	1249465
40	A	19812	1249465	1229653
41	D	19812	1229653	1209841
42	A	19812	1209841	1190029
43	B	19812	1190029	1170217
44	A	19812	1170217	1150405
45	B	19812	1150405	1130593
46	A	19812	1130593	1110781
47	B	19812	1110781	1090969
48	A	19812	1090969	1071157
49	B	19812	1071157	1051345
50	A	19812	1051345	1031533
51	B	19812	1031533	1011721
52	A	19812	1011721	991909
53	D	19812	991909	972097
54	A	19812	972097	952285
55	B	19812	952285	932473
56	A	19812	932473	912661
57	B	19812	912661	892849
58	A	19812	892849	873037
59	B	19812	873037	853225
60	A	19812	853225	833413
61	B	19812	833413	813601
62	A	19812	813601	793789
63	B	19812	793789	773977
64	A	19812	773977	754165
65	D	19812	754165	734353
66	A	19812	734353	714541
67	B	19812	714541	694729
68	A	19812	694729	674917
69	B	19812	674917	655105
70	A	19812	655105	635293
71	B	19812	635293	615481
72	A	19812	615481	595669
73	B	19812	595669	575857
74	A	19812	575857	556045
75	B	19812	556045	536233
76	A	19812	536233	516421
77	D	19812	516421	496609
78	A	19812	496609	476797
79	B	19812	476797	456985
80	A	19812	456985	437173
81	B	19812	437173	417361
82	A	19812	417361	397549
83	B	19812	397549	377737
84	A	19812	377737	357925
85	B	19812	357925	338113
86	A	19812	338113	318301
87	B	19812	318301	298489
88	A	19812	298489	278677
89	D	19812	278677	258865
90	A	19812	258865	239053
91	B	19812	239053	219241
92	A	19812	219241	199429
93	B	19812	199429	179617
94	A	19812	179617	159805
95	B	19812	159805	139993
96	A	19812	139993	120181
97	B	19812	120181	100369
98	A	19812	100369	80557
99	L	16561	80557	63996
▶ 100	K*, R**	17996	63996	46000

▶ * TYPE FOR MODULE LX1
▶ ** TYPE FOR MODULE LY1

APPROVED

M. Tellalian 6-29-96
CBI DATE

J. Jones 7/23/96
CALTECH DATE

▶ INDICATES CHANGE FROM PREVIOUS ISSUE

BY	CHKD	DATE	BY	CHKD	DATE	BY	CHKD	DATE	REVISIONS
ARL (3)	MLT	3-11-96				ARL (4)	DTR	6-24-96	
ENTIRE DRAWING REVISED						MODIFIED TUBE TYPES AND NOTES CHANGED REV. NO. TO BE IN SEQUENCE WITH CONTRACT 930212			REMARKS

CBI

SUPPLIER'S / PURCHASER'S NO

LIGO BEAM TUBE
HANFORD, WA & LIVINGSTON, LA

SUB-ASSEMBLY END LOCATIONS FOR
LIVINGSTON MODULES (LX1) & (LY1)

CUSTOMER'S NO
BY ARL CHKD MLT DATE 3-11-96
M. L. TELLALIAN
ENGINEERING ASSIGNED

CONTRACT NO 953571
DWG 2
SHT 3
REV 4

55710302.DGN

TUBE NO.	TYPE	LENGTH	[END-A]	[END-B]
▶ 1	O×, Q××	17996	2017433	2035429
2	M	16562	2035429	2051991
▶ 3	S	19812	2051991	2071803
4	A	19812	2071803	2091615
5	B	19812	2091615	2111427
6	A	19812	2111427	2131239
7	B	19812	2131239	2151051
8	A	19812	2151051	2170863
9	B	19812	2170863	2190675
10	A	19812	2190675	2210487
11	B	19812	2210487	2230299
12	A	19812	2230299	2250111
13	B	19812	2250111	2269923
14	A	19812	2269923	2289735
15	B	19812	2289735	2309547
16	A	19812	2309547	2329359
17	C	19812	2329359	2349171
18	A	19812	2349171	2368983
19	B	19812	2368983	2388795
20	A	19812	2388795	2408607
21	B	19812	2408607	2428419
22	A	19812	2428419	2448231
23	B	19812	2448231	2468043
24	A	19812	2468043	2487855
25	B	19812	2487855	2507667
26	A	19812	2507667	2527479
27	B	19812	2527479	2547291
28	A	19812	2547291	2567103
29	C	19812	2567103	2586915
30	A	19812	2586915	2606727
31	B	19812	2606727	2626539
32	A	19812	2626539	2646351
33	B	19812	2646351	2666163
34	A	19812	2666163	2685975
35	B	19812	2685975	2705787
36	A	19812	2705787	2725599
37	B	19812	2725599	2745411
38	A	19812	2745411	2765223
39	B	19812	2765223	2785035
40	A	19812	2785035	2804847
41	C	19812	2804847	2824659
42	A	19812	2824659	2844471
43	B	19812	2844471	2864283
44	A	19812	2864283	2884095
45	B	19812	2884095	2903907
46	A	19812	2903907	2923719
47	B	19812	2923719	2943531
48	A	19812	2943531	2963343
49	B	19812	2963343	2983155
50	A	19812	2983155	3002967
51	B	19812	3002967	3022779
52	A	19812	3022779	3042591
53	C	19812	3042591	3062403
54	A	19812	3062403	3082215
55	B	19812	3082215	3102027
56	A	19812	3102027	3121839
57	B	19812	3121839	3141651
58	A	19812	3141651	3161463
59	B	19812	3161463	3181275
60	A	19812	3181275	3201087
61	B	19812	3201087	3220899
62	A	19812	3220899	3240711
63	B	19812	3240711	3260523
64	A	19812	3260523	3280335
65	C	19812	3280335	3300147
66	A	19812	3300147	3319959
67	B	19812	3319959	3339771
68	A	19812	3339771	3359583
69	B	19812	3359583	3379395
70	A	19812	3379395	3399207

TUBE NO.	TYPE	LENGTH	[END-A]	[END-B]
71	B	19812	3399207	3419019
72	A	19812	3419019	3438831
73	B	19812	3438831	3458643
74	A	19812	3458643	3478455
75	B	19812	3478455	3498267
76	A	19812	3498267	3518079
77	C	19812	3518079	3537891
78	A	19812	3537891	3557703
79	B	19812	3557703	3577515
80	A	19812	3577515	3597327
81	B	19812	3597327	3617139
82	A	19812	3617139	3636951
83	B	19812	3636951	3656763
84	A	19812	3656763	3676575
85	B	19812	3676575	3696387
86	A	19812	3696387	3716199
87	B	19812	3716199	3736011
88	A	19812	3736011	3755823
89	C	19812	3755823	3775635
90	A	19812	3775635	3795447
91	B	19812	3795447	3815259
92	A	19812	3815259	3835071
93	B	19812	3835071	3854883
94	A	19812	3854883	3874695
95	B	19812	3874695	3894507
96	A	19812	3894507	3914319
97	B	19812	3914319	3934131
98	A	19812	3934131	3953943
99	L	16561	3953943	3970504
▶ 100	K×, R××	17996	3970504	3988500

▶ × TYPE FOR MODULE LX2
×× TYPE FOR MODULE LY2

APPROVED

M. Tellalian	6-24-96
CBI	DATE
L Jones	7/23/96
CALTECH	DATE

▶ INDICATES CHANGE FROM PREVIOUS ISSUE

REV	BY	CHKD	DATE	REMARKS
3	ARL	MLT	3-11-96	ENTIRE DRAWING REVISED
4	ARL		6-24-96	MODIFIED TUBE TYPES AND NOTES CHANGED REV. NO. TO BE IN SEQUENCE WITH CONTRACT 930212

REVISIONS

CBI

SUPPLIER'S / PURCHASER'S NO

LIGO BEAM TUBE
HANFORD, WA & LIVINGSTON, LA

SUB-ASSEMBLY END LOCATIONS FOR LIVINGSTON MODULES (LX2) & (LY2)

CUSTOMER'S NO
BY ARL CHKD MLT DATE 3-11-96
M. L. TELLALIAN
ENGINEERING ASSIGNED

CONTRACT NO 953571
DWG 2
SHT 4
REV 4

55710402.DGN

Appendix 4 The FORTRAN program to estimate the pressure in the tube vs position and time. The program requires the pumping speed at the tube ends, the size and position of the leak, the amu and temperature of the molecule being measured.

```
c *******btleakfind4.for ****** August 30, 2012
c try to fix problem with incorrect results due to number of steps
c Include writing file of the pressure across the tube at a fixed time
c iterative and computational intense variables in the Runge-Kutta
croutines are double
c precision. Runge - Kutta now has fixed step size
c Program shows the pressure at the 4km tube ends as one goes through
c the process of finding a single leak in the module at position x. The
technique is to
c close off first the pump at one and and then the pump at the other end
while observing
c the pressure at both ends.
c
c The program uses the Runge Kutta techniques from Numerical Recipes
c The calculation is made in cgs units with the pressure in torr
c
c  The outgassing is described by:
c
c      aj = fixed outgassing rate
c
c      a = tube radius
c
c      al = length of module/number of sections = section length
c
c      fp = pumping speed of the pumps
c
c      v = thermal velocity of molecule at 300K
c
c      alk = leak at position x along the tube
c Difference equation to solve
c
c Section 1:  dp/dt = ((2*v*a)/(3*al**2))*(p(2)-p(1)) + (2/a)*aj
c end pt             + (aqlk(1))-fp(1)*p(1))/(pi*al*a**2)
c
c Section n: dp/dt = ((2*v*a)/(3*al**2))*2*(p(n-1)-p(n))
c sym mid pt             + (2/a)*(aj)
c                        + (aqlk(n)))/(pi*al*a**2)
c
c Section k : dp/dt = ((2*v*a)/(3*al**2))*(p(k-1)-2*p(k) +p(k+1))
c                    + (2/a)*(aj)
c                    + (aqlk(k))/(pi*al*a**2)
c
c section m : dp/dt = ((2*v*a)/(3*al**2))*(p(m-1)-p(m)) +b(2/a)*aj
c                    +(aqlk(m)-f(m)*p(m))/(pi*al*a**2)
c
c
        use winteracter
        character fileout*100
        real*8 ystart,dydx
        dimension p(1000,8000),ystart(1000),time(8000)
        dimension fp(1000),alk(1000),dydx(1000)
```

```
        common /deriv/ pstart,aa,bb,cc,dd,ajt,nsec,tbon,tboff,tpon
        write(unit=*,fmt=601)
601     format(' enter # of sections :' $)
         read(unit=*,fmt=602)nsec
602     format(i6)
c set pump speeds and leaks in all sections to 0
         do 620 k=1,nsec
          fp(k)=0.0
          alk(k)=0.0
620      continue
          write(unit=*,fmt=1)
1       format(' enter pump speed lit/sec at x=0: ' $)
          read(unit=*,fmt=2)fpp1
          fpp1 = fpp1*1000.0
2        format(e15.6)
           write(unit=*,fmt=1111)
1111   format(' enter pump speed lit/sec at x = L:'  $)
        read(unit=*,fmt=2)fpp2
        fpp2=fpp2*1000.0
        write(unit=*,fmt=605)
605      format(' enter amu of gas : ' $)
         read(unit=*,fmt=4)amu
         write(unit=*,fmt=3)
3        format(' enter J, torr liters/sec/cm^2 : ' $)
          read(unit=*,fmt=4)ajt
          ajt=ajt*1000.0
4       format(e15.6)
c enter the fixed parameters
c beam tube radius cm
       a = 61.91
c thermal speed of gas in cm/sec
       v = (5.901e4)*sqrt(18.0/amu)
c module length cm
       al0 = 3.94108e5
c number of sections
        an = real(nsec)
c section length cm
       al = al0/an
       write(unit=*,fmt=9)
9        format(' enter starting pressure in torr : '$)
        read(unit=*,fmt=4)pstart
         write(unit=*,fmt=1202)
1202   format(' enter period in hrs to turn pumps at end on/off :' $)
          read(unit=*,fmt=4)tau
         tau=tau*3600.0
          write(unit=*,fmt=1301)
1301    format(' enter leak size (torr*lit/sec), sec# for leak ' $)
        read(unit=*,fmt=411)allk,nlksec
411       format(e15.6,i6)
        alk(nlksec)=allk*1000.0
        aa = (2.0*v*a)/(3.0*al**2)
        bb = 2.0/a
        dd = 1.0/(3.14159*al*a**2)
         do 1000 kt = 1,nsec
         p(kt,1)=pstart
```

```
1000     continue
9876     write(unit=*,fmt=7)
7        format(' time(hrs)/step, #steps total, #calsteps/step : '$)
           read(unit=*,fmt=8)tstep1,mstep,intstep
8       format(e15.6,2i6)
c convert time to seconds
         tstep = tstep1*3600.0
         x2=0.0
         nvar = nsec
         do 100 k=1,mstep
         x1 = x2
         x2 = x1 + tstep
         phase = 2.0*3.14159*x1/tau
         phase = sin(phase)
         if(phase.le.0.0)tbon = -1.0
         if(phase.gt.0.0)tbon = 1.0
         if(tbon.gt.0.5) then
         fp(1)=0.0
         fp(nsec)=fpp2
          end if
          if(tbon.lt.-0.5)then
          fp(1) = fpp1
          fp(nsec) = 0.0
          end if
           if(k.eq.1)then
           do 1002 n=1,nsec
            ystart(n)= pstart
1002     continue
         time(k)=x1/3600.0
         p(nsec+1,k)=pstart
         end if
         call rkdumb(ystart,x1,x2,dydx,intstep,fp,alk)
          do 1003 n=1,nsec
           p(n,k+1)=ystart(n)
1003    continue
      time(k+1)=x2/3600.0
c calculate the average pressure
          sum = 0.0
          do 400 n=1,nsec
           sum  = sum + p(n,k+1)/an
400     continue
        p(nsec+1,k+1)=sum
        write(unit=*,fmt=11)time(k),p(nsec+1,k)
11      format(' time (hours) = '1pe15.6,  'avg p (torr) = '1pe15.6)
100      continue

2000    write(unit=*,fmt=77)
77      format('enter fileout: '$)
          read(unit=*,fmt=78)fileout
78      format(a100)
           open(unit=2,file=fileout)
           write(unit=*,fmt=4001)
4001   format(' enter 1 for p vs x, 2 for p vs t : '$)
            read(unit=*,fmt=4002)ich
4002   format(i3)
```

```
           if(ich.eq.2)then
           write(unit=*,fmt=2001)nsec+1
2001    format(' enter #segment ('i4,' = avg pressure) : '$)
           read(unit=*,fmt=2002)ks
2002    format(i6)
           write(unit=2,fmt=79)mstep+1
79      format(i5)
          do 200 k=1,mstep+1
           write(unit=2,fmt=80)time(k),p(ks,k)
80      format(1pe15.6,1pe15.6)
200     continue
           close (2)
           end if
           if(ich.eq.1)then
           write(unit=2,fmt=4011)nsec
4011   format(i5)
          m=mstep+1
           do 4020 j=1,nsec
c set to center of section
           xs = al*(real(j-1)+0.5)/100.0
          write(unit=2,fmt=4021)xs,p(j,m)
4021   format(1pe15.6,1pe15.6)
4020   continue
          end if
           write(unit=*,fmt=2003)
2003    format(' enter 1 to write another file: '$)
            read(unit=*,fmt=2004)igo
2004    format(i3)
            if(igo.eq.1)go to 2000
3000    continue
            end

        subroutine derivs(y,dydx,fp,alk)
                   real*8 y,dydx
                  dimension y(1000),dydx(1000),fp(1000),alk(1000)
        common /deriv/ pstart,aa,bb,cc,dd,ajt,nsec,tbon,tboff,tpon
            do 100 n=2,nsec-1
            xy = aa*(y(n-1)+y(n+1)-2.0*y(n))+bb*(ajt)
            dydx(n) = xy + dd*(alk(n)-fp(n)*y(n))
100     continue
            dydx(1) = aa*(y(2)-y(1))+bb*(ajt)+dd*(alk(1)-fp(1)*y(1))
            xy = aa*(y(nsec-1)-y(nsec))+bb*(ajt)
            dydx(nsec) = xy+dd*(alk(nsec)-fp(nsec)*y(nsec))
            return
             end

        SUBROUTINE rk4(v,dydx,x,h,yout,fp,alk)
        INTEGER nsec,i
        REAL*8 dydx,yout,ystart,v,dv
        REAL*8 dym,dyt,yt
        real*4 x,h6,hh,xh,h
        dimension fp(1000),alk(1000),dydx(1000)
        dimension yout(1000),v(1000),dv(1000)
        dimension dym(1000),dyt(1000),yt(1000)
        common /deriv/ pstart,aa,bb,cc,dd,ajt,nsec,tbon,tboff,tpon
```

```
        hh=h*0.5
        h6=h/6.
        xh=x+hh
        do 11 i=1,nsec
        yt(i)=v(i)+hh*dydx(i)
11      continue
         call derivs(yt,dyt,fp,alk)
        do 12 i=1,nsec
        yt(i)=v(i)+hh*dyt(i)
12       continue
         call derivs(yt,dym,fp,alk)
        do 13 i=1,nsec
        yt(i)=v(i)+h*dym(i)
        dym(i)=dyt(i)+dym(i)
13      continue
         call derivs(yt,dyt,fp,alk)
        do 14 i=1,nsec
        yout(i)=v(i)+h6*(dydx(i)+dyt(i)+2.*dym(i))
14      continue
        return
        END
C  (C) Copr. 1986-92 Numerical Recipes Software 7%W3.



       SUBROUTINE rkdumb(ystart,x1,x2,dydx,intstep,fp,alk)
       INTEGER nsec,intstep
        REAL*4 x1,x2,x,h
        real*8 ystart,v,dydx,dv,yout
        dimension fp(1000),alk(1000),ystart(1000),dydx(1000)
        dimension yout(1000),v(1000),dv(1000)
CU    USES rk4
        INTEGER i,k
        common /deriv/ pstart,aa,bb,cc,dd,ajt,nsec,tbon,tboff,tpon
        do 11 i=1,nsec
        v(i)=ystart(i)
11    continue
        x=x1
        h=(x2-x1)/real(intstep)
         do 13 k=1,intstep
         call derivs(v,dv,fp,alk)
         call rk4(v,dv,x,h,yout,fp,alk)
         if(x+h.eq.x)pause 'stepsize not significant in rkdumb'
          x=x+h
         do 12 i=1,nsec
         v(i) = yout(i)
12      continue
13      continue
          do 14 i=1,nsec
          ystart(i)=yout(i)
14      continue
          return
          END
C  (C) Copr. 1986-92 Numerical Recipes Software 7%W3.
```