A Preliminary Study of the Vacuum System for the Beamtubes of the Cosmic Explorer Third Generation Gravitational Wave Detector

R.Weiss January 20, 2019, June 6, 2019 Includes changes and suggestions coming from Vacuum Workshop

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ABSTRACT A concept study for the beamtube vacuum system of a third generation gravitational wave detector with 40km arms is presented. The concept is a derivative from the successful design and operation of the current 4km detectors but with the intent of reducing the initial construction costs per km as well as (hopefully) the running and maintenance costs. The residual gas pressure requirements are more stringent than those for the initial detectors, they are close to the goal values which were actually achieved in the initial detectors.

The concept trades on the idea that there are engineering and operational advantages to separating the functions of maintaining a space against the atmospheric pressure load and reducing the residual gas to the levels of ultra high vacuum. The concept is to use a nested vacuum system with an outer shell of extruded standard steel tubing with an inner tube of thin wall aluminum. The system is divided into 10km long modules which can be evacuated independently. The modules are further divided into 2km long sub-modules isolated by low differential force valves ("soft " close valves). Each 2km sub-module includes an annular valve that separates the inner and outer system (again a "soft" closed valve structure).

The nested system has more tolerance to leaks and weld workmanship than the standard vacuum system and may even have advantages in reduced diagnostic time and maintenance costs. However, the assembly costs if not done with good engineering design could eliminate the cost advantages. The assembly and installation, especially of the inner system, would benefit from special tooling designed for in-field manufacture and assembly.

The study includes model pumping curves for a specific configuration that meets the scientific requirements. The model shows that even for a nested system the most significant vacuum problem is the control of water which sets the costs and the pump down times. An investment in reducing the adsorbed water prior to pump down would pay off handsomely.

Introduction

One of the most direct ways to increase the sensitivity of interferometric gravitational wave detectors and bring the new field of gravitational wave astronomy into cosmology is to increase the arm length of the detectors. The gravitational wave signal increases as the arm length while many of the competing noise terms are length independent or grow only slowly with the length. A detector with 40km arms, a factor of 10 increase over the first generation gravitational wave detectors that have open the field, will allow measurements of compact binary sources such as black holes and neutron stars to the epoch of the first formation of stars in the universe.

The main challenge is the increased cost of the arms which grows somewhat faster than linear in the length. The cost is tied up with construction of the vacuum system – tubes, pumps, valves, outgassing, surface preparation, vacuum hardware and fittings, control of corrosion - and the civil construction – alignment, berms, cut and fill or tunneling, enclosures, roads, power distribution. Some operations costs will also grow with length but are not studied here except to note the need to leak hunt and maintain the system against corrosion, power costs to maintain the vacuum and security need to be evaluated

In the appendix on costs, the beamtube costs for the two 4km LIGO detectors constructed in 1994 dollars is shown to be $74.6M . The length dependent costs for the 16km of beamtube was $56.8M about $3.55M/km. A straightforward extrapolation for 80km of comparable beamtube constructed in 2025 using a 2.3% per year inflation would give a total cost of $603M and a length dependent cost of $7.1M/km. The aim of the workshop is to establish if there are practical ideas to reduce this cost and still satisfy the scientific and engineering requirements for the beamtubes. It is worth noting that natural gas pipelines of the same diameter and length are estimated to have a total cost of $270M and a length dependent cost of $3.38M/km. A preliminary estimate using the concept described in this note gives a total cost of $380M and a length dependent cost of 4.47M/km.

The concept explored in this note is to look at a beamtube system in which the structural demands to withstand the atmospheric pressure and simultaneously the requirements to maintain ultrahigh vacuum conditions are satisfied by a nested system – an outer tube of commercial material such as ordinary steel or a composite and an inner tube with low outgassing properties such as thin wall sheet aluminum, see **Figure 1**. The nesting relaxes the demands on both tubes. It allows cost savings in both material and in the vacuum components as well as in the procedures to attain the partial pressures and other system requirements such as cleanliness and optical properties. The nesting also enables optimization of the pumping system to achieve the pressure requirements. For example, it allows use of getter pumps which have a finite total gas capacity to maintain the inner UHV system. However, a cost driver could be the additional complexity in assembly.

Vacuum requirements for the 40km beamtubes

The primary requirement is on the column density of the gas (average pressure over the length of the tube). The pressure in the system is low enough everywhere to be in mean molecular flow. The principal issues in the beam tubes are the phase fluctuations in the optical beam due to forward scattering by the residual gas (refractive index fluctuations). The largest price is paid for molecules with a large optical polarizability (large molecular volume) and which have low thermal velocities (large masses which have longer residence time in the optical beam). Atomic hydrogen is one the least perturbative while a heavy hydrocarbon is the most damaging.

The noise power spectrum of the gravitational wave strain due to gas column density fluctuations is given by:

$$h^2(f) = \frac{4\rho\left(2\pi\alpha\right)^2}{L^2 v_0}\int_0^L e^{-\frac{2\pi f w(z)}{v_0}}\frac{dz}{w(z)}$$

$$v_0 = \sqrt{\frac{2kT}{m}}$$

ρ = particle density #/cm^3 , α = optical polarizability cm^3

v_0 = thermal velocity cm/sec k = Boltzmann's constant

T = temperature K, m = mass of particle gm

L = arm length cm, w(z) optical beam radius at z cm

f = frequency of gravitational wave, h(f) = gw strain/$\sqrt{\text{Hz}}$

Table 1 The average pressure requirements for a 40km detector with a sensitivity of h(f) ~1 x 10^{-25} strain/$\sqrt{\text{Hz}}$ at 300K and an optical wavelength of 1 micron.

Gas species	ratio to H_2	40km req torr	Gas species	ratio to H_2	40km req torr
He	0.32	9.8 x 10^{-9}	Kr	8.27	1.4 x 10^{-11}
Ne	0.89	1.3 x 10^{-9}	Xe	14.9	4.5 x 10^{-12}
H_2	1.0	1.0 x 10^{-9}	AMU 100HnCm	38.4	7.0 x 10^{-13}
H_2O	3.3	1.1 x 10^{-10}	AMU 200HnCm	88.8	1.4 x 10^{-13}
N_2	4.2	6.5 x 10^{-11}	AMU 300HnCm	146	5.0 x 10^{-14}
A	4.51	4.9 x 10^{-11}	AMU 400HnCm	208	2.5 x 10^{-14}
CO	4.6	5.0 x 10^{-11}	AMU 500HnCm	277	1.4 x 10^{-14}
CH_4	5.4	3.0 x 10^{-11}	AMU 600HnCm	345	9.0 x 10^{-15}
CO_2	7.1	2.3 x 10^{-11}			

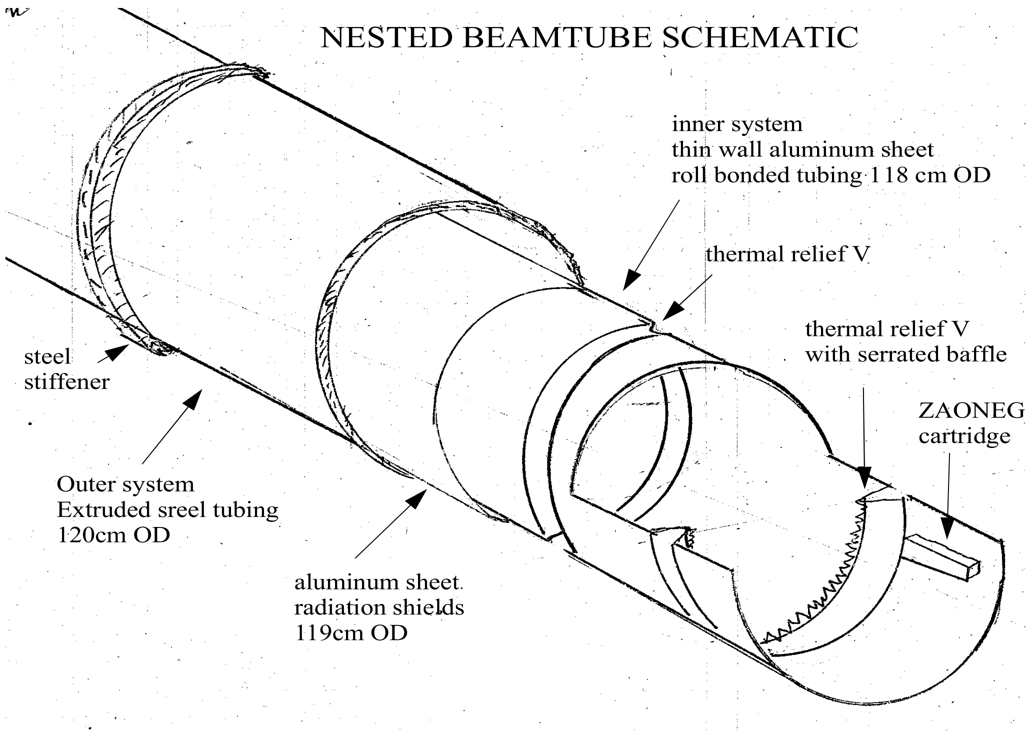
Note: Pressure requirement are set so that the noise from any single gas species can be no larger than 1/3 of the allowed strain noise. “ratio to H_2” means $\frac{\alpha}{\sqrt{v_0}}$ for the gas relative to that of Hydrogen.

Summary of the design concept including other system requirements

Table 2 Design concept and other requirements

Concept		
	geometry	40km arm is broken up into four independent 10km modules with gate valves able to withstand atmospheric loads at each end. The *inner* system modules are further broken up into five 2km sub-modules with separating gate valves between them that do not withstand atmospheric loads ("soft close gate valves"). Inner and outer systems in each sub-module are separated by "soft" close annular valves. See **Figure 2** and **3**.
Vacuum		
	leaks assumed in the model	outer system -> inner system: F =1 liter/sec/km atmosphere -> outer system: F =10^{-7} liters/sec/km, Q = 10^{-4} torr liter/sec/km
	pumps in 10km module	Rough pumping: Blowers and turbos on movable trailers to be used on all the10km modules at the ends and the middle. Permanently mounted pumps: Outer system : 2000 liter/sec ion pump mounted at the middle of each 2km sub-module. Inner system: 500 liter/sec ion pump mounted at the middle of each 2km module. ZAO getter pumps distributed at 250 meter intervals inside the inner system. See **Table 3** of ZAO properties and **Figure 2** and **3**
	valves in 10km module	Two standard hard closed gate valves one at each end of a 10km module. Four "soft" close separator valves between the 2km sub-modules. Five "soft" close annular separator valves **Figure 4** between the inner and outer systems in the middle of each 2km sub-module
	pump out	Inner and outer systems rough pumped together. Carried out on 10km modules with pumps on the ends and the middle of the module. At 10^{-4} torr begin 360K bakeout of inner system. At 30days with $3x10^{-5}$ torr, start outer system 2000 liter/sec ion pumps on each 2km sub-module. At 53 days 3 x 10^{-6} torr, activate ZAO getters, after pressure surge close the "soft" close annular separator valves on each 2km module. At 10^{-6} torr in the inner system start the 500 liter/sec ion pumps. At 140 days (depends on the initial adsorbed water load) turn off the bakeout power. For model pressure curves vs time see **Figure 5** and **6**.
	bakeout	Assume initial 150 monolayers of water on surfaces of both inner and outer system with a Dubinin –Raduskevich (DR) skewed Gaussian adsorption peak of 10^4K and a repulsive potential factor of r=0.7. No bakeout of outer system, a 360K bakeout of the inner system for 3 months. Power requirement 30kW/km with two radiation shields between inner and outer system. Bakeout done in all 2km sub-modules of a 10km module simultaneously. See **Figure 3**

	pump down time	Several months primarily due to water desorption. Can be significantly speeded up by reducing the initial adsorbed water .
	reliability	20 year lifetime. Ability to maintain and service: fully isolatable 10Km modules and at low pressure < 10^{-3} torr isolatable 2km sub-modules. Enables diagnostics for leak hunting.
	contamination	< 1/10 monolayer/month of hydrocarbon deposition from the beamtube onto the optics at the ends of the 40km arms
	dust	Less than 1 one micron "diameter" dust particle falling through the optical beam/km/hour. Needs further study.
Mechanical and optical		
	clear aperture	current design is 110cm diameter; needs more study for 1 micron light and, especially, with use of 2 micron light in the interferometer in a later phase
	scattering and diffraction from walls and baffling	@ 1 micron wavelength reflectivity of wall < 0.1 at 45^0, BRDF($\theta_{\text{incident}} > 45^0$)<10^{-3} /steradian randomly serrated edge baffles mounted in inner tube. Needs more study with use of 2micron light.
	vibration	inner tube mounted to move no more than twice seismic motions above 5Hz. Baffles mounted with f > 5Hz isolators; both need more study.
Temperature		
		inner system needs to accommodate a low temperature bake upto 360K, outer system needs to accommodate 260K to 330K depending on location. Inner system has relief V expansion bends every 2 meters, outer system has 5 bellows expansion joints/2km
Safety		
	maximum pressure difference inner/outer system	A concern expressed at the workshop was the crushing of the inner system by excess pressure in the outer system. Using the stability equation in the appendix, the maximum excess pressure in the outer system over the inner one is about 0.1 torr for 0.5mm inner wall thickness of aluminum. The allowed pressure difference grows as thickness cubed. The there needs to be an automatic opening system for the annular valves in the case of a sudden large leak to the outer system.



Getter cartridge needs to be mounted on thicker surface such as 5mm thick cylinder to take the activation power

Figure 1 Schematic of the nested system. The outer tube is extruded standard 48" OD steel tubing . Two concepts are being carried, one uses 3/16" wall with periodic stiffening rings on the outside to avoid collapse. The other is to use 3/8" wall, the standard size for the natural gas industry, without stiffening rings. Later in the design, depending on the site, the thicker wall may have a cost advantage as it allows less secure enclosures for the tube (more economical, more easily punctured by bullets). The hydrogen outgassing for the outer system at 300K is assumed to be 10^{-11} torr liters/sec/cm^2 and the water load at construction is assumed as 150 monolayers (5×10^{-3} torr liters/cm^2). The inner system is composed of aluminum sheet ½ mm thick. It is spiral roll bonded (or by other cold welding techniques) in a continuous helix at the detector assembly site. A thermal relief V is rolled into the tube every 2 meters. The V helps to stiffen the inner tube but also provides places to mount serrated edge baffles to reduce diffracted propagation of the laser light in the tube. The V also provides places to hide ZAO getter pumps and wiring to avoid scattering of the laser light. The inner wall of the aluminum needs to have low reflectivity for 1 and 2 micron light. The outer wall of the aluminum tube should remain a low emissivity surface but be insulated electrically to avoid electrical shorts to the outer structure. The water loading is expected to be the same as for the outer system but the hydrogen outgassing is expected to be less than 10^{-14} torr liters/sec/cm^{2}. During the pumpdown the inner aluminum tube is heated to 360K by passing 1000 amperes directly through the tube to reduce the adsorbed water. Two aluminum radiation shields both 1/2 mm thick (or sheets of super insulation) are placed between the inner aluminum system and the outer steel tubes.

SCHEMATIC OF A 10 KM MODULE

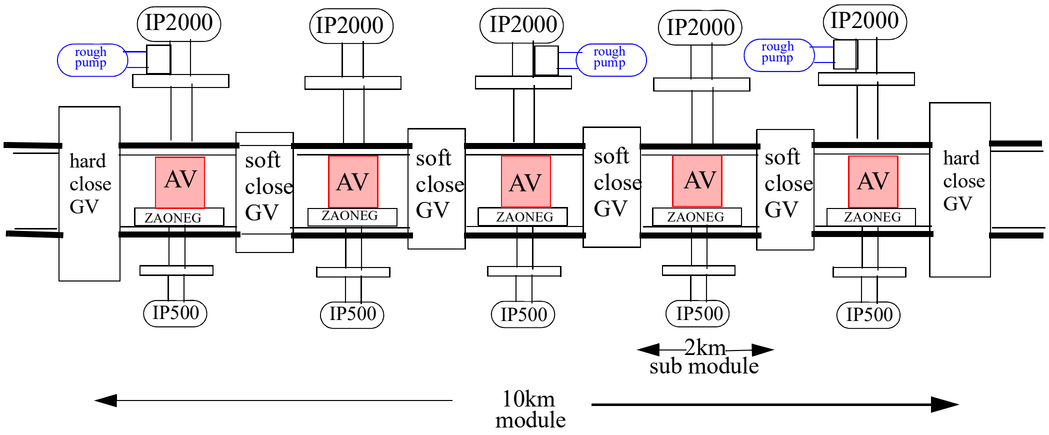


Figure 2 Schematic of a 10km module of the beamtube. For ease of construction, testing, commissioning and service; it is necessary to divide the arms into independent modules. The concept uses 10km modules which can be pumped down independently. Full hard close gate valves, able to withstand atmospheric loads, are placed at the ends of the 10km module. The 10km module is further divided into five 2km sub-modules. The 2km sub-modules can be isolated from each other by “soft” close valves which are not designed to take atmospheric loads. The “soft” close valves maintain isolation between the inner and outer systems. These valves are useful in making operations and diagnostics easier . For example, one does not have to try to get UHV conditions in all inner system sub-modules simultaneously (note: if these valves are difficult to design and costly one could forgo them). After rough pumping the entire module (both inner and outer systems), the outer system is maintained by 2000 liter/sec ion pumps placed at the center of each 2km sub-module. The inner system is heated to 360K when the pressure has reached 10^{-4} torr (see figure 3). The inner and outer systems are isolated by “soft” close annular valves. The “soft” close annular valves are open during the pump out until the pressure in the system has dropped to 3×10^{-6} torr. At this pressure the ZAO getters are activated followed by the closing of the “soft” close annular valves. The pump speed and capacity of the getter for the different residual gas species is described in **Table 3**. The getter is distributed in the inner tube at intervals of 250 meters with a total getter mass of 12kg per 2km module. The 500 liter/sec ion pumps that pump the inner system are turned on. The pressure vs time of the outer system is shown in **Figure 5** and that of the inner system in Figure 6.

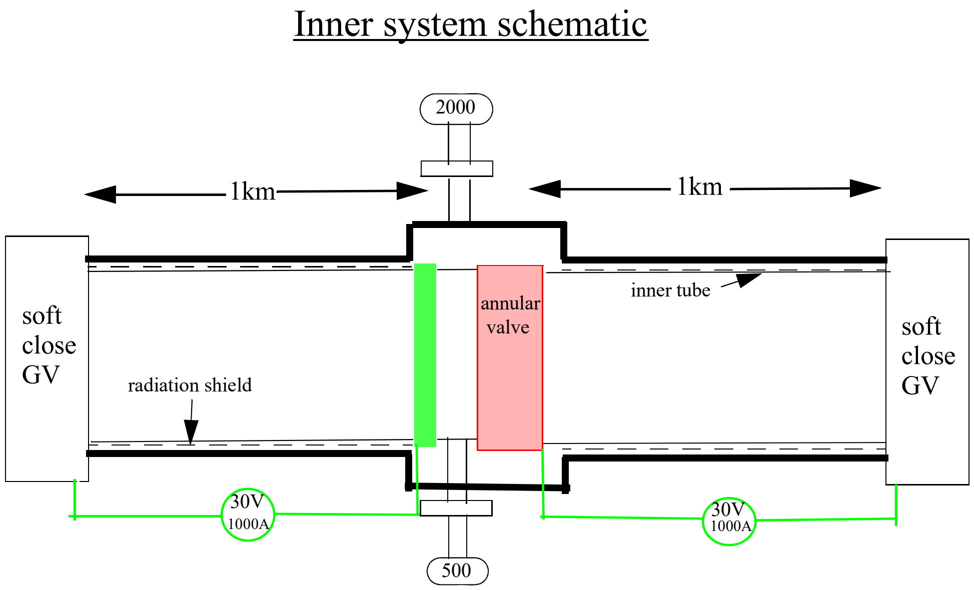
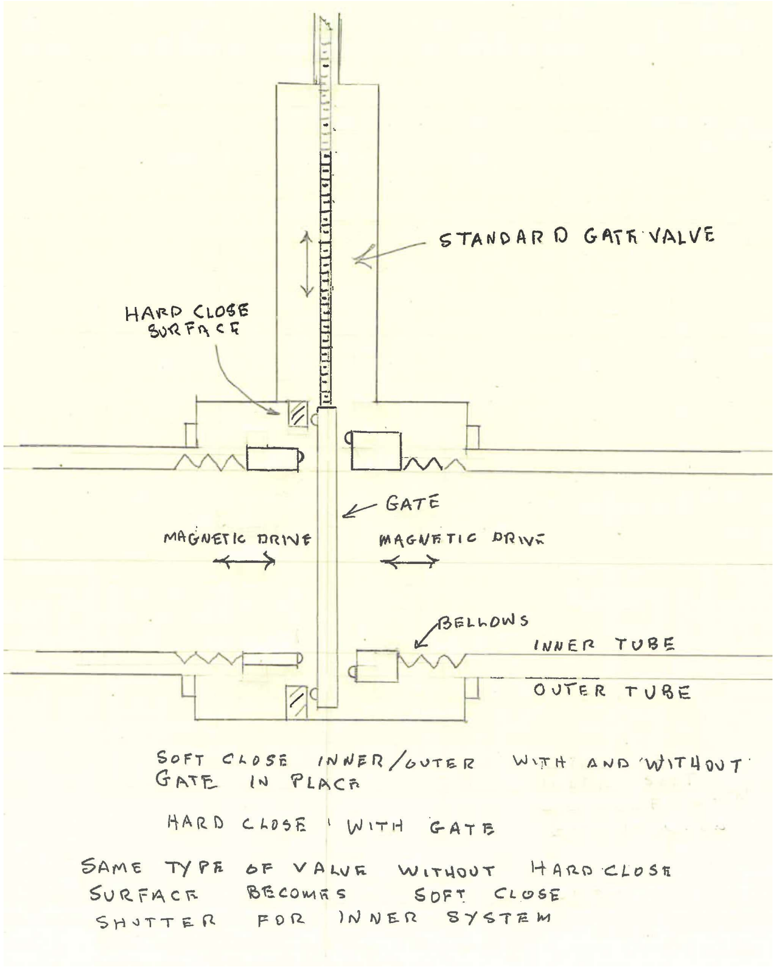


Figure 3 Schematic of a 2km sub-module. The figure shows the concept for the bakeout at 360K. Contact to the circumference of the inner system aluminum tube is made at the valves. The “soft” close valves are grounded while the annular valve is floating. DC power supplies deliver 1000A at 30V to the inner aluminum tube in 1km long circuits. After the picture was drawn it became apparent that one could use the outer tube as the current return as it will most likely be a 3/8” wall steel tube without insulation on it. (Do not need the long external cables). Radiation shields composed of 2 sheets of thin wall aluminum (or superinsulation) reduce the power requirement to attain the bakeout temperature. **Figure 4** shows a concept for the “soft” close annular valves. The outer wall of the inner system aluminum tube needs to be coated with an electric insulator that does not increase the infrared emissivity. The inner wall needs to be coated with a low reflection surface for 1 micron to 2 micron wavelength radiation to absorb the scattered laser light.

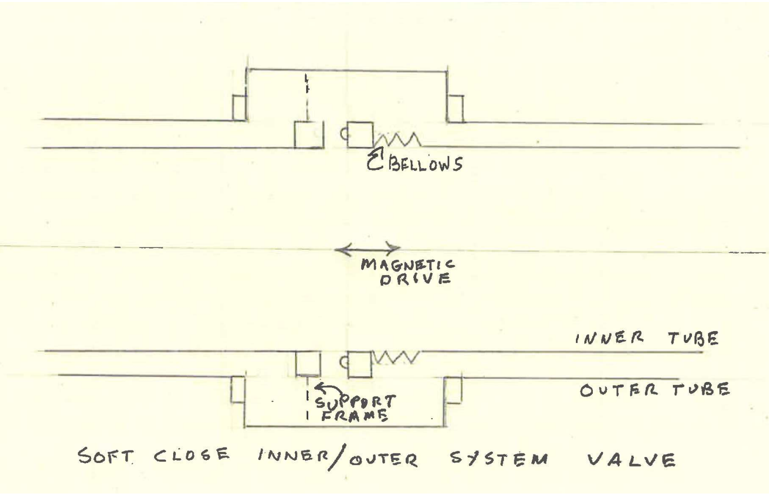


SOFT CLOSE INNER/OUTER WITH AND WITHOUT GATE IN PLACE

HARD CLOSE WITH GATE

SAME TYPE OF VALVE WITHOUT HARD CLOSE SURFACE BECOMES SOFT CLOSE SHUTTER FOR INNER SYSTEM

Figure 4a Soft close inner/outer and hard close outer valve concept



SOFT CLOSE INNER/OUTER SYSTEM VALVE

Figure 4b Soft close annular inner/outer valve concept.

Figure 4 Concepts for the “soft” close annular valves and shutter. The pumping speed between the inner and outer system when open should be greater than 6000 liters/sec. The leakage through the valve when closed should be less than 1 liter/sec. No lubrication or vacuum grease is permitted in the valve.

Pump down

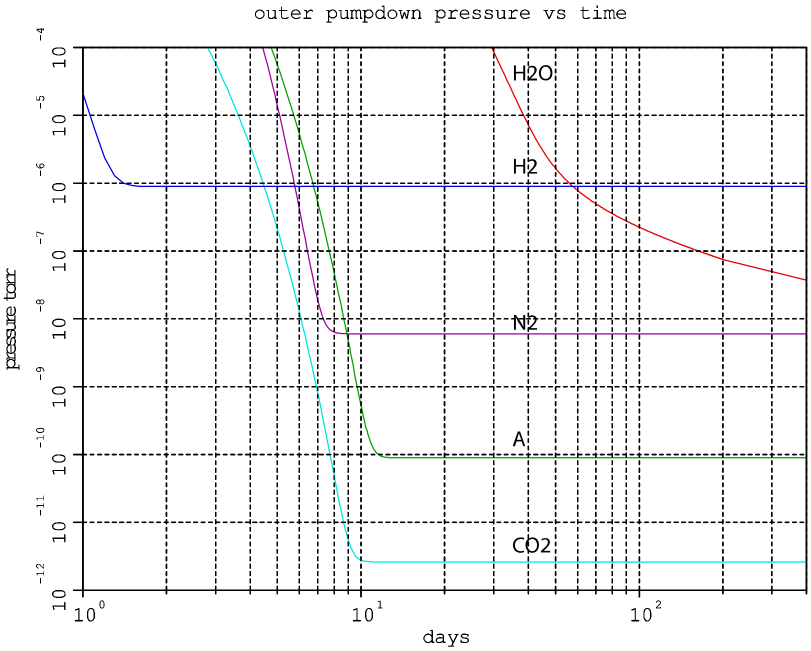


Figure 5 Pumpdown of the 10km module outer system

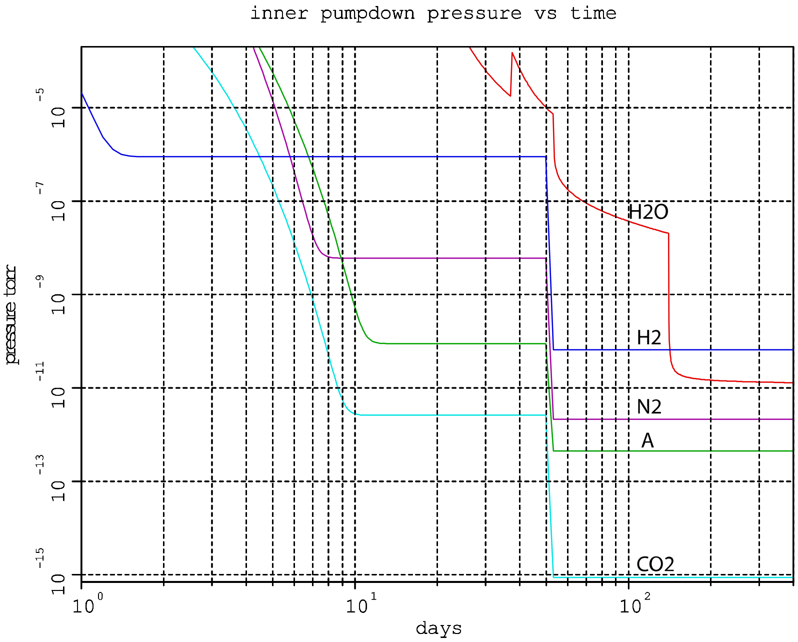


Figure 6 Pumpdown of the 2km sub-module inner system

The pump down curves were calculated with a finite element program that included the diffusion in the long tubes and the outgassing by the walls as a function of temperature. Water pressure is determined using the Dubinin-Raduskevich adsorption theory with emission and readsorption. Leaks between the inner and outer systems as well as leaks of the outer system to the external atmosphere are included. The symbolic equations below (valid only for a steady state) show the various terms in the model for each gas species indicated by the index k.

$$P(k)_{\text{inner}} = \frac{J_{\text{inner}}(k,T)A_{\text{inner}} + F(k)_{\text{inner-outer}}P(k)_{\text{outer}} + F(k)_{\text{inner-external}}P(k)_{\text{external}}}{F(k)_{\text{inner}} + F(k)_{\text{inner-outer}}}$$

$$P(k)_{\text{outer}} = \frac{J_{\text{outer}}(k,T)A_{\text{outer}} + F_{\text{inner-outer}}P(k)_{\text{inner}} + F(k)_{\text{outer-external}}P(k)_{\text{external}}}{F(k)_{\text{outer}} + F(k)_{\text{inner-outer}}}$$

Pumping

Outer system 10km module: five 2000 liters/sec ion pumps

Inner system 2km module: 12kg SAO getter@473K distributed in 250meter intervals, properties given in **Table 3**, one 500 liters/sec ion pump

Outgassing

Outer system

Hydrogen: $J(H_2, 300K) = 1 \times 10^{-11}$ torr liters/sec cm^2

Water: Dubinin –Raduskevich (DR) 150 monolayers T_0 =10000K, r= 0.7

Inner system

Hydrogen: $J(H_2,300K) = 1 \times 10^{-14}$ torr liters/sec cm^2

Water: Dubinin –Raduskevich (DR) 150 monolayers T_0 =10000K, r= 0.7

Leaks

$F_{\text{inner-outer}}$ 1 liter/sec/km

$F_{\text{outer-external}}$ 10^{-7} liter/sec /km

Tube

outer: radius= 62cm 10km module: area=$3.9\text{x}10^8$ cm^2 , volume = $1.2\text{x}10^7$ liters

inner: radius= 59cm 2km sub-module: area = $7.4\text{x}10^7$, volume = $2.2\text{x}10^6$ liters

V thermal relief on inner tube: height from inner wall = 6cm

Table 3 Getter properties

Properties assumed for 12kg of ZAO getters held at 473K in the 2km sub modules

gas species	lit/s/gm	torrlit/gm	torr lit 2km	lit/s 2km	Preq torr	sat yr
H_2	2	15	$1.8\text{x}10^5$	$2.4\text{x}10^4$	$1.0\text{x}10^{-9}$	240
H_2O	2(assume)	15(assume)	$1.8\text{x}10^5$	$2.4\text{x}10^4$	$1.1\text{x}10^{-10}$	2400
N_2	0.43	2.14	$2.6\text{x}10^4$	$5.2\text{x}10^3$	$6.5\text{x}10^{-11}$	2650
CO_2	0.46	0.17	$2.0\text{x}10^3$	$5.5\text{x}10^3$	$2.3\text{x}10^{-11}$	570
O_2	0.8	12.9	$1.5\text{x}10^5$	$9.6\text{x}10^3$	$5.0\text{x}10^{-11}$	9930
nobel gases	0	0	0	0		

ZAO are not regenerated at 400C

Note for costs: Assume ZAO cost $15/gm in large quantities which corresponds to $180K/2km sub module and $7.2M/40km detector (2025yr dollars)

Pumpout procedure

The pumpout described is not optimized in terms of the time required nor the number of pumps used. This optimization is work for a real engineering study and will involve tradeoffs between the allowed leaks, the number and location of the pumps and pumpdown time.

The procedure used in the **Figures 5** and **6** is presented here.

Rough down in 10km modules at both ends and in the middle with portable roughing pumps and turbos; in the models assumed 2000 liters/sec at each of the three ports. Begin with the "soft" close gate valves and the "soft" close annular pumps open. All ion pumps are off and getters not activated. At day 30 the water pressure is 3×10^{-5} torr . Remove the portable roughing pumps and begin ion pumping with the 2000 liter/sec pumps on each 2km sub-module. At day 37 begin heating the inner tube to 360K. At day 53 activate the ZAO getters. After the surge of gas has pumped away close the "soft" close annular valves and the "soft" close gate valves between the 2km sub-modules. Turn on the 500 liter/sec ion pumps on the inner system. At this point there are 16 monolayers of water left on the inner system walls. On day 140 stop the heating of the inner tube. When the system returns to 300K the pressures satisfy the requirements. The adsorbed water on the inner surface is 12 monolayers. The equivalent of 4 monolayers have been taken up by the ZAO getter (10^4 torr liter/2km of the inner tube which has 12kg of ZAO, a water load of about 1 torr liter/gm of ZAO) If the ratio of pumping speed to stored water could be increased, the amount of ZAO getter needed could be reduced. Another finding is that the pump down time is dominated by the readsorption of the water. The pump down time is close to proportional to the initial water loading on the surface and, with these model parameters, is still effected by the pumping speed, not only by the outgassing rate.

Appendices: calculations, other findings, preliminary costs

Pressure distributions along the modules for various conditions

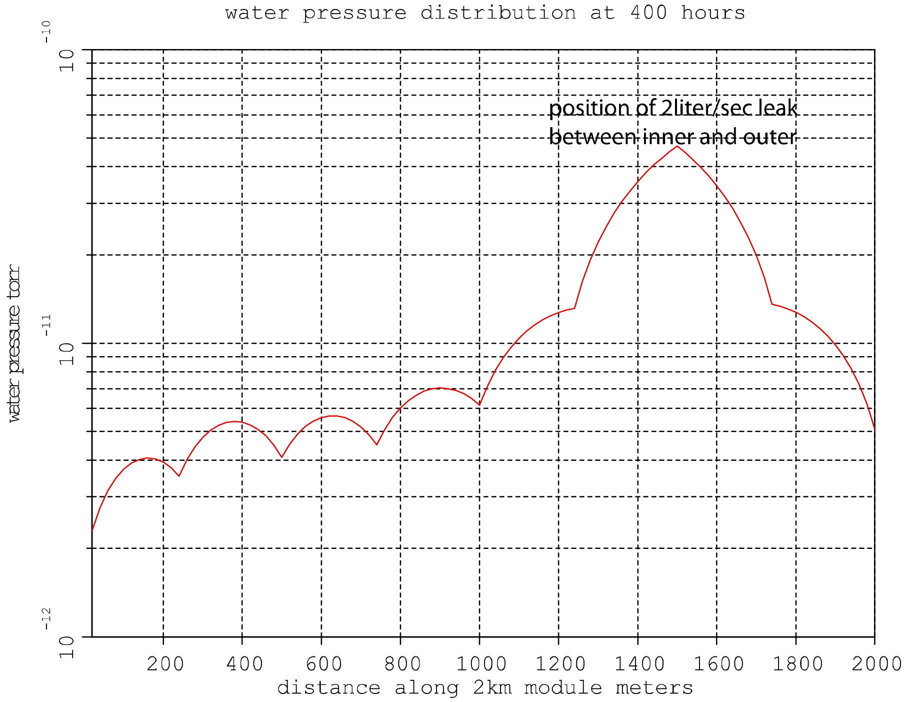


Figure 7 Water pressure distribution in a 2km sub-module for a 2liter/sec leak between the inner and outer systems.

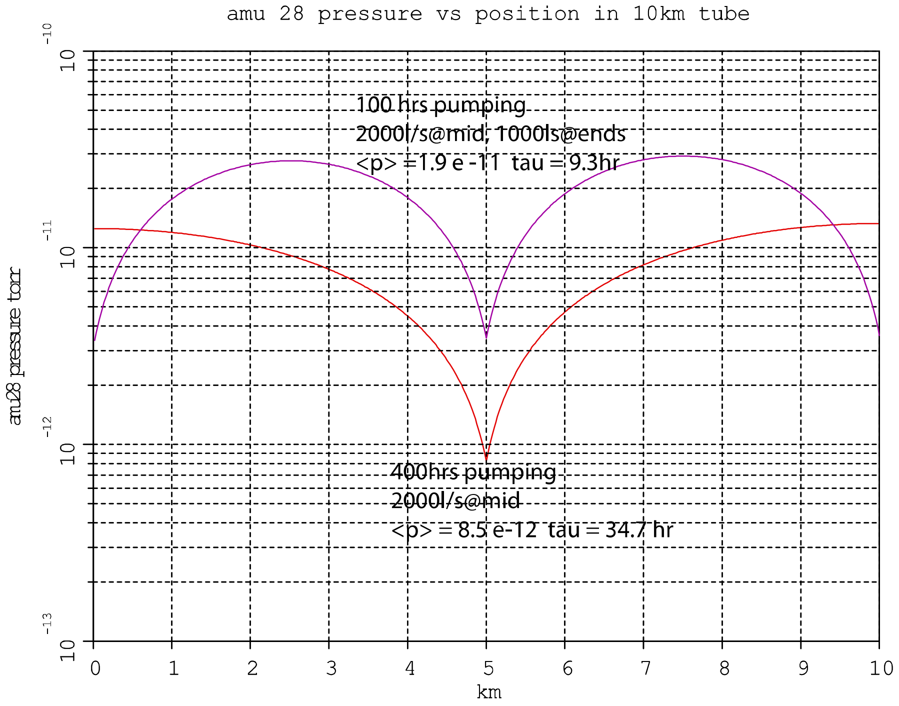


Figure 8 Nitrogen pressure distribution as a function of pumping strategy in a 10km module.

Testing the bakeout strategy

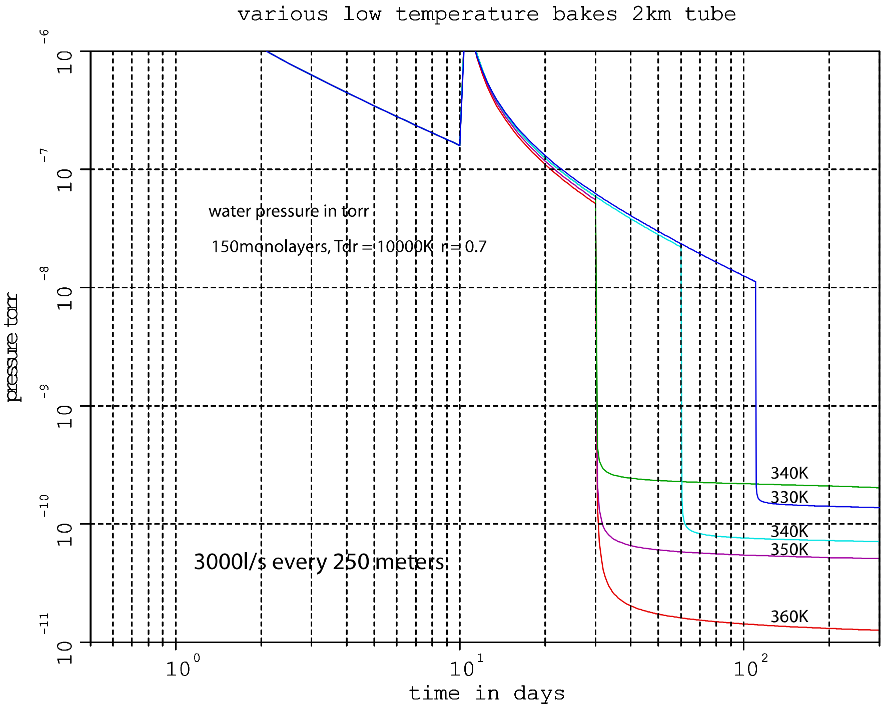


Figure 9 Bakeout to eliminate water for different bakeout times and temperatures. All sample bakes are for initial surface adsorption of 150 monolayers, have the same DR parameters and the same system pumping speed. The bake begins at 10 days after the start of pumping and return to 300K at the downward discontinuity in the 1/t dependence. The results show the longer the bake and the higher the bake temperature the lower is the final water pressure when the system returns to 300K. Runs were made with initial water load of 15 monolayers of adsorbed water (curves are not shown). These were all about a factor 10 lower than the curves plotted.

Pumping speed of 1km of 62 cm radius beamtube for different gases

Useful for quick estimates to determine if pump speed or the beamtube diffusion limits the pressure.

Table 4 Pumping speed of 1km long 62cm radius tube at 300K

gas	amu	v thermal	F liters/sec
H_2	2	1.8×10^5	910
H_2O	18	5.9×10^4	295
Ne	20	5.6×10^4	280
N_2	28	4.7×10^4	240
A	40	4.0×10^4	200
CO^2	44	3.8×10^4	190
Kr	84	2.7×10^4	135
Xe	132	2.2×10^4	108

Tube diameter and wall thickness for stability against crushing, no stiffeners

$$\frac{\text{thickness}}{\text{diameter}} = \left[\frac{\left(1-\upsilon^{2}\right)P_{c}}{2Y}\right]^{\frac{1}{3}}$$

$\upsilon =$ poisson ratio

$P_c =$ crushing pressure

$Y =$ Young modulus

Table 5 Tube wall thickness , diameter and mass/ kilometer for 2 atmospheres crushing pressure: material mass/length and cost/length

material	thickness/diameter	diameter inches,cm	thickness inches,cm	kg/km	2025yr $/km
S steel with stiffeners initial LIGO	stiffeners 1.3X10^3/km 4.45x0.47cm^2	48”, 122cm	0.13”, 0.3 cm	9.96 x 10^4	0.352M
steel with stiffeners	stiffeners 1.3X10^3/km 4.45x0.47cm^2	48”,122cm	0.13”, 0.3cm	9.96 x 10^4	0.120M
tube steel	7.717 x 10^{-3}	48” ,122cm	0.37”, 0.939cm	2.81 x 10^5	0.338M
tube steel		60” ,152cm	0.46”, 1.17cm	4.36 x 10^5	0.524M
aluminum	1.094 x 10^{-2}	48” ,122cm	0.53”, 1.33cm	1.37 x 10^5	0.563

Note: Commerically formed tubing typically costs 2.2 times the material costs.

Bakeout parameters

For pressure less than 10^{-4} torr the thermal conductivity is close to being only radiative. The power radiated between an inner surface at temperature T_2 with infrared emissivity ε_2 and an outer surface at temperature T_1 with infrared emissivity ε_1 separated by N radiation shields with infrared emissivity ε_{sh} is given by

$$\frac{P}{A} = \frac{\sigma\left(T_2^4 - T_1^4\right)}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1 + N\left(\frac{2}{\varepsilon_{sh}} - 1\right)}$$

$P =$ power

$A =$ area of surface

$\sigma =$ Stefan – Boltzman constant = 5.7×10^{-8} w/m^{2}K^4

Table 6 Power required to heat aluminum inner tube for a variety of temperatures. T_1 = 300K. ε_2 and $\varepsilon_{sh} = 0.05$ and $\varepsilon_1 = 1$, radius of the aluminum tube 59cm, thickness 0.5mm, electrical resistivity of aluminum at 300K is 3 x 10^{-8} ohm meter.

T_2 K	P/A w/m^2 N=0	V volts/km N=0	A amp N=0	P/A w/m^2 N=2	V volts/km N=2	A amp N=2
330	10.7	25	1577	2.2	11	715
340	15	30	1872	3.1	13	840
350	19.7	34	2147	4.0	15	970
360	25	38	2418	5.1	18	1070

Extrapolation of costs from 4km LIGO to 40km Cosmic Explorer and estimates for natural gas lines with comparable tube lengths and sizes

Table 7 LIGO beamtube costs 1994 dollars

References: LIGO Cost Book, L.Jones notes, F.Assiri notes

item	total cost $M	length dep cost $M
Management	5.5	~1.0
Design	0.83	
Tube factory	8.05	
Tube material	9.02	9.02
Bellows	0.77	0.77
Assembly	1.66	1.66
Leak check	0.87	0.87
Anchors+supports	3.05	3.05
Pump ports	1.83	1.83
Handling/shipping	0.92	0.92
Moblization/demobilization	0.46	
Installation in field	7.2	7.2
Insulation and bake	7.0	7.0
Acceptance tests	1.1	
CB&I profit (10%)	5.2	3.3
Beamtube enclosure design	0.64	
BTE QA and survey	0.32	0.32
BTE, berm, slab construction	18.6	18.6
TOTAL 1	72.4 16.8 fixed	55.5 3.47/km
Vac equipment for beamtube		
gate valves	0.72	0.72
ion pumps	0.24	0.24
cryo traps	0.80	
roughing pumps	0.24	0.16
turbo pumps	0.18	0.12
gauges, electronics	0.02	0.02
Total vac equip for beamtube	2.2 0.94 fixed	1.26 0.08/km
TOTAL 2	74.6 17.7 fixed	56.8 3.55/km

Projection for a single 40km interferometer in 2025 dollars using an inflation rate of 0.023/year, a factor of 2. Fixed costs = $35M, length dependent costs = $7.1M/km. Total cost for 80km of arm length = $603M Note: The vacuum equipment costs for all of LIGO were not part of the beamtube contract. The fraction of the costs associated with the beam tube and have been estimated by me.

Costs of a 40km interferometer based on industry experience with natural gas pipelines

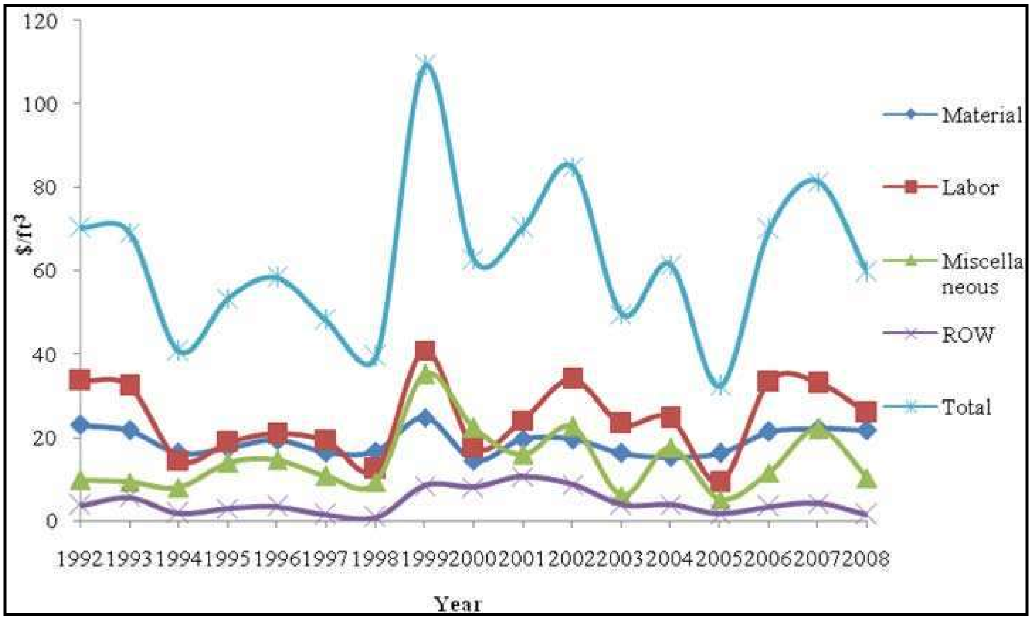
Standard schedule cold rolled steel tubing with corrosion resistant covering used in natural gas pipelines in sizes 24" and larger has a 3/8" wall. The total costs for pipeline installation and construction using shallow burial in "normal" sites was $60/ft^3$ in 2011 dollars. Large fluctuations in installed pipeline costs are common see **Figure 10** .

Table 8 :The costs breakdown for natural gas pipelines

item	fraction of total
Labor	0.4
Material	0.31
Survey,engineering,freight taxes	0.23
right of way costs	0.07

Using the inflation rate of 0.023/year, the estimated total cost in 2025 dollars for installed 48" diameter tube/km is $3.38M/km. Total costs for 80km of tube length are about $270M .

Figure 10 Annual Average cost of pipeline elements in $/ft^3$ installed.



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Cost estimate and discussion

Table 9 Preliminary 2025 costs and discussion

item	cost/	#	cost	discussion
outer tube	0.64M/km	80km	51M	Extruded 48" diameter standard steel tubing 3/8" wall to stop (most) bullets and take atmospheric load with out stiffening rings. Fabricated tube 2.2* material cost which is \$0.45/lb
expansion bellows	15K/bellows	5/2km	3M	LIGO cost x inflation. Fewer needed /km since the bakeout does not heat the outer tube and is lower temperature
inner tube	0.02M/km	80km	1.6M	Aluminum sheet 0.5mm thick made into tubing at the site with thermal relief V. Material cost only
in field machine to fabricate tubing			3M	Forms tube by spiral roll welding, bends V thermal relief, prepare inner surface for low reflectivity and outer surface with electrical insulator, possibly reduce the adsorbed water
radiation shields	0.04M/km	80km	3.2M	Aluminum sheet 0.5mm thick formed into cylinders or superinsulation (need to establish the water adsorption of the superinsulation)
Anchors @supports	0.37M/km		30M	LIGO cost x inflation
pump ports	10K/port	1/km	0.8M	Ken Mason estimate
bake out	\$0.1/kwh \$3K/supply	5.8Gwh 10 sup.	0.57M 0.03M	10km modules (5 sub-modules) heated simultaneously, circuit consists of aluminum inner tube and current return through the outer steel tube. Costs are 10 power supplies to be moved between the modules and the power 30kw/km for 100 days
installation			86M	LIGO cost * inflation * 1.2 (increased complexity)
road 3m	0.161M/km	80km	13M	asphalt road at \$5/ft^2
berm 4m	0.301M/km	80km	24M	concrete berm 6" thick at \$7/ft^2
cut & fill 4m			<42M	Site dependent. Assume flat (curved with earth radius) site, vol.cut = vol.fill, 30 degree slope on side walls. midpoint of tube 21 meters below ground with ends 12 meters above ground on a trapezoidal berm. Horizontal base of the trapezoid 4m. Needs optimization to the site contours. A bowl with the right curvature could greatly reduce the cost. Estimate earth moving cost \$7/m^3 .
cover 3m	0.45M/km	80km	36M	8 ft high steel Quonset hut along berm. Assume outer tube is 3/8" steel wall able to stop hunter's bullets
getter pumps	12kg/2km \$15/gm		7.2M	ZAO cartridges, cost projected for large purchase
ion pumps inner	10K/pump	1/2km	0.4M	500 liter/sec
ion pumps outer	25K/pump	1/2km	1M	2000 liter/sec
gate valves	100K/GV	2/10km module	1.6M	VAT valve or equivalent
soft close GV	40K/GV	5/10km	1.6M	guess
annular GV	20k/GV	5/10km	0.8M	guess
leak check	0.1K/10m	8000 sections	0.8M	look for bubbles in each steel tube section, 10 m lengths
handling and shipping			9M	LIGO cost x inflation
Quality assurance and survey			3.2M	LIGO cost x inflation
Length dep management			10M	LIGO cost x inflation
Length independent costs	15.8M			LIGO cost * inflation for those items that remain in the concept

The cost is $346M before profit. With 10% profit for the contractor, the total cost is $380M. The length dependent cost is 4.57M/km

Tunneling rather than cut and fill construction

Given the large cost associated with cut and fill and the even larger costs for excavation, it is worth looking at the current cost of tunneling. When LIGO was first being considered tunneling in the United States was far behind the rest of the world technically and correspondingly extremely expensive. It has not changed much though a company started by Elan Musk, The Boring Co, to build underground transportation is trying to make a significant change. **Table 10** shows the tunneling costs delivered and projected by The Boring Co as well as the results from a paper "*Assessing and Bench Marking the Construction Cost of Tunnels*" by A. Bernardos delivered at a GEOPhysics meeting in Montreal in 2013.

TABLE 10 Tunneling costs

method	$/m^3	$/km 4m diameter	$/80km
cut@fill	9 ± 7	0.1M	8M
trapezoidal cut&fill ,equal volumes cut and fill (costed in **Table 9**)	9 ± 7	depends on site topography	<42M
excavation	16 ± 9	0.2M	16M
TBC current	440	5.5M	440M
TBC projected mid 2020s	220	2.8M	224M
Mean Europe (Bernardos)	180	2.2M	176M

Tunneling looks unpromising except for short lengths where the earth moving may have peak cost. The accounting of cut and fill is not the same as in **Table 9** where the trapezoidal shape of the structure required to maintain stability of cut channels and built up berms is accounted for. There is a 33meter height difference between the center of the beamtube and the ends 20 km away. This is due to the Earth's curvature.

Why is the extrapolated initial LIGO cost for cosmic explorer different than the preliminary estimated cost?

Items that are less costly/km
1) The use of a quonset hut and thicker steel tubing rather than the concrete enclosure
2) Use of commercially fabricated steel with less stringent requirements on hydrogen outgassing
3) Standard steel tubing rather than stainless steel
4) Reduced cleaning requirements of the outer system and easier to attain cleanliness of the inner system
5) Bakeout costs are smaller: no insulation , lower tempertures and power costs
6) Reduced leak requirements on fabrication and less sensitive testing needed
7) Reduced cleaning
8) Reduced number of pumpout ports due to internal getter pumps
9) Improved match of pumps to requirements
9) May have left out some critical costs

Items that are more costly/km
1) Assembly of the nested system (assumed 20% increase of infield assembly costs)
2) Use of getter pumps
3) Use of "soft" close longitudinal and annular gate valves

Topics for further work and tests to do

Gas bursts: Is a nested system more likely to make short (1 to 0.01 sec) gas bursts that would be confused with gravitational wave signals?

"Soft" close valves: Possible concepts for the annular soft close valves and shutters as well as the combined hard close valves with additional annular valves are shown in the **Figure 4a** and **4b**. Need to put more work into an actual design. The costing assumes $100K for each hard closed valve, $40K for the "soft" closed and $20K for the annular "soft" close valves

Pump down time and costs: Run more cases to optimize the pump down time and costs. Determine the scaling for the adjustable parameters: the water load, the number of pumps, their location and the size of the leaks. Most critical is probably pumping out the water as it recombines with the surface.

Water: Adsorbed water is a major cost driver in both the nested system as well as in conventional designs with a single tube. Research on reducing the adsorption is well worth the effort. Some examples: non adsorbing coatings, removal by UV of sufficient energy to break up the water into its atomic components, microwave discharge, dry purge surface scrubbing systems…….

A useful idea might be to rid the surface of moderately bound water, water that at 300K requires longer than weeks to be emitted. This would change the 1/t depends to a faster rate. It is not as crazy as one might think, tightly bound water, say with an emission rate of a century or longer does not contribute to the outgassing rate (in part also because of the reduced number of high binding energy sites). The repopulation rate of the sites depends on the density of water molecules hitting the surface but also inversely on the adsorption binding energy.

We need to test the idea of recovering from a vacuum disaster with a backfill very low in water to avoid having to rebake. This was part of a vacuum recovery and research proposal made to the NSF by LIGO but which was only partially funded. Jon Feicht, LIGO vacuum engineer can tell about the planned research and test. Getting this right is critical for current LIGO due its problems with the gate valves and the stainless steel corrosion and will affect decisions that need to be made for 3rd generation detectors.

Getter tests: An assumption made in the concept is that an unsaturated ZAO getter does not outgas water. The outgassing of a getter as a function of accumulated water needs to be measured.

Optical properties: A problem specific to interferometric gravitational wave detectors is to avoid scattered and diffracted light from being recombined with the main optical beam sensing the gravitational wave. Besides baffling to avoid multiple bounce paths from propagating in the beamtube, it is necessary reduce the stray light by absorption

on the beamtube walls. Many optically absorbing coatings tend to increase the surface area of the tube and could have poor outgassing properties.
Research is needed into coatings or surface treatment of the inner wall of the aluminum tube that satisfies both the optical and vacuum requirements.

Acoustic and mechanical noise: Need to think about the motion of the structures driven by thermal expansion and seismic vibrations. Need to avoid stick/slip noise as the temperature changes that can communicate to the structures that support the mirrors. Need to avoid poorly damped oscillations in the inner system in the frequency band of the gravitational wave observations (5Hz to 5kHz). Depending on current optical calculations, it may even be most economical to (crudely) vibration isolate the inner tube from seismic and acoustic noise.

Assembly: A key element for a nested system using the concept described here is to learn how to fabricate and assemble the inner aluminum system. Bonding does not need to be done to the usual UHV leak requirements. It is worth looking at techniques such as roll bonding, laser welding, ultrasonic pressure welding - techniques that can be done in the field as part of assembly. One can imagine an assembly system starting with a machine (much like CB&I used in LIGO) to convert coil stock to tubing by spiral joining followed by a sheet metal forming press to make the V thermal relief bends. The formed tube cleaned, coated, and dried in a final stage of the movable assembly system. A technique needs to be developed to join sections of the aluminum tube with the valves that can still seal around a step discontinuity in the tube wall (places where the sheet metal overlaps). Given the overall cost of making a cosmic explorer, an investment of several millions dollars into such an assembly system would be cost effective. $3M is assumed for this in the preliminary budget.

Metrology: Optical column density gauges using laser beams with wavelengths specific to the individual gases would be a good way to determine the amount of residual gas left in the tubes. Tunable pulsed UV lasers tuned to the strong molecular electronic lines could make the species determination while total absorption on and off resonance could provide column density measurements. Timing of the scattered light could also provide some information of the location of leaks in the system.

Over all tests: Once concepts have survived more critical engineering study, the surviving ideas need to be tested in prototype. This was absolutely critical in the development of the beamtube vacuum system for initial LIGO which was tested twice. Once in a small 20 meter prototype and then again at CB&I in a full fledged prototype using the dimensions and practices to be employed in the field construction. Unless there are good reasons developed at the workshop otherwise, a prototype commercial standard 48" extruded steel tube should be tested for leaks and outgassing followed by the insertion of a thin wall tube to make a nested system allowing an inner system bakeout.

TABLE 9.7— ANSI PIPE SCHEDULES
(courtesy of Natural Gas Processors Suppliers Assn.)

UPPER FIGURES INDICATE WALL THICKNESS IN IN.

LOWER FIGURES INDICATE WEIGHT PER FOOT IN LBM

PIPE SIZE	O.D. in IN.	5	10	20	30	40	STD.	60	80	XH	100	120	140	160	XXH
⅛	.405	.035 .1383	.049 .1863			.068 .2447	.068 .2447		.095 .3145	.095 .3145					
¼	.540	.049 .2570	.065 .3297			.088 .4248	.088 .4249		.119 .5351						
⅜	.675	.049 .3276	.065 .4235			.091 .5676	.091 .5676		.126 .7388	.126 .7388					
½	.840	.065 .5383	.083 .6710			.109 .8510	.109 .8510		.147 1.088	.147 1.088				.187 1.304	.294 1.714
¾	1.050	.065 .6838	.083 .8572			.113 1.131	.113 1.131		.154 1.474	.154 1.474				.218 1.937	.308 2.441
1	1.315	.065 .8678	.109 1.404			.133 1.679	.133 1.679		.179 2.172	.179 2.172				.250 2.844	.358 3.659
1¼	1.660	.065 1.107	.109 1.806			.140 2.273	.140 2.273		.191 2.997	.191 2.997				.250 3.765	.382 5.214
1½	1.900	.065 1.274	.109 2.085			.145 2.718	.145 2.718		.200 3.631	.200 3.631				.281 4.859	.400 6.408
2	2.375	.065 1.604	.109 2.638			.154 3.653	.154 3.653		.218 5.022	.218 5.022				.343 7.444	.436 9.029
2½	2.875	.083 2.475	.120 3.531			.203 5.793	.203 5.793		.276 7.661	.276 7.661				.375 10.01	.552 13.70
3	3.500	.083 3.029	.120 4.332			.216 7.576	.216 7.576		.300 10.25	.300 10.25				.437 14.32	.600 18.58
3½	4.0	.083 3.472	.120 4.973			.226 9.109	.226 9.109		.318 12.51	.318 12.51					.636 22.85
4	4.50	.083 3.915	.120 5.613			.237 10.79	.237 10.79	.281 12.66	.337 14.98	.337 14.98		.437 19.01		.531 22.51	.674 27.54
4½	5.0						.247 12.53			.355 17.61					.710 32.53
5	5.563	.109 6.349	.134 7.770			.258 14.62	.258 14.62		.375 20.78	.375 20.78		.500 27.04		.625 32.96	.750 38.55
6	6.625	.109 7.585	.134 9.289			.280 18.97	.280 18.97		.432 28.57	.432 28.57		.562 36.39		.718 45.30	.864 53.16
7	7.625						.301 23.57			.500 38.05					.875 63.08
8	8.625	.109 9.914	.148 13.40	.250 22.36	.277 24.70	.322 28.55	.322 28.55	.406 35.64	.500 35.64	.500 43.39	.593 50.87	.718 60.63	.812 67.76	.906 74.69	.875 72.42
9	9.625						.342 33.90			.500 48.72					
10	10.75	.134 15.19	.165 18.70	.250 28.04	.307 34.24	.365 40.48	.365 40.48	.500 54.74	.593 64.33	.500 54.74	.718 76.93	.843 89.20	1.000 104.1	1.125 115.7	
11	11.75						.375 45.55			.500 60.07					
12	12.75	.165 22.18	.180 24.20	.250 33.38	.330 43.77	.406 53.53	.375 49.56	.562 73.16	.687 88.51	.500 65.42	.843 107.2	1.000 125.5	1.125 139.7	1.312 160.3	
14	14.0		.250 36.71	.312 45.68	.375 54.57	.437 63.37	.375 54.57	.593 84.91	.750 106.1	.500 72.09	.937 130.7	1.093 150.7	1.250 170.2	1.406 189.1	
16	16.0		.250 42.05	.312 52.36	.375 62.58	.500 82.77	.375 62.58	.656 107.5	.843 136.5	.500 82.77	1.031 164.8	1.218 192.3	1.437 223.5	1.593 245.1	
18	18.0		.250 47.39	.312 59.03	.437 82.06	.562 104.8	.375 70.59	.750 138.2	.937 170.8	.500 93.45	1.156 208.0	1.375 244.1	1.562 274.2	1.781 308.5	
20	20.0		.250 52.73	.375 78.60	.500 104.1	.593 122.9	.375 78.60	.812 166.4	1.031 208.9	.500 104.1	1.280 256.1	1.500 296.4	1.750 341.1	1.968 379.0	
22	22.0		.250 58.07	.375 86.61	.500 114.8		.375 86.61	.875 197.4	1.125 250.8	.500 114.8	1.375 302.9	1.625 353.6	1.875 403.0	2.125 451.1	
24	24.0		.250 63.41	.375 94.62	.562 104.8	.687 171.2	.375 94.62	.968 238.1	1.218 296.4	.500 125.5	1.531 367.4	1.812 429.4	2.062 483.1	2.343 541.9	
26	26.0		.312 85.60	.500 136.2			.375 102.6			.500 136.2					
28	28.0		.312 92.26	.500 146.8	.625 182.7		.375 110.6			.500 146.8					
30	30.0		.312 98.93	.500 157.5	.625 196.1		.375 118.6			.500 157.5					
32	32.0		.312 105.6	.500 168.2	.625 209.4	.688 230.1	.375 126.7			.500 168.2					
34	34.0		.344 123.7	.500 178.9	.625 222.8	.688 244.8	.375 134.7			.500 178.9					
36	36.0		.312 118.9	.500 189.6	.625 236.1	.750 282.3	.375 142.7			.500 189.6					
42	42.0						.375 166.7			.500 221.6					
48	48.0						.375 190.7			.500 253.6					

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