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NSF Workshop on Large Ultrahigh-Vacuum Systems for Frontier Scientific Research Instrumentation

LIGO Livingston Observatory

January 29-31,2019

H.F. Dylla, R. Weiss and M. E. Zucker, eds.

California Institute of Technology
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Workshop Proceedings:
NSF Workshop on Large UHV Systems for Frontier Scientific Research*

LIGO Livingston Observatory, LA
January 28 - 31, 2019

H.F. Dylla, R. Weiss and M.E. Zucker, Proceedings Editors

Executive Summary

The **NSF Workshop on Large Ultrahigh Vacuum Systems for Frontier Scientific Research Instrumentation** was held at the LIGO Livingston, LA site on Jan. 28 - 31, 2019. The purpose of the workshop was primarily focused on the need to identify cost effective technologies for the design, construction and operation of the large vacuum systems that would be required for gravitational wave observatories that are a factor of ten larger than the current generation systems in the U.S. (LIGO), Europe (Virgo) and Japan (KAGRA).

The technologies that were developed and employed in the existing gravitational wave observatories have been shown to meet the stringent requirements of vacuum integrity, very low hydrogen and heavy molecule outgassing, minimal particulate generation, low vibration, and appropriate stray light optical absorbance for successful operation. However, straightforward extrapolation of the costs for extending the interferometer vacuum beam enclosures from the current lengths of 3-4km/arm to 40km/arm indicates the need for investigation of a wide range of technologies and materials that could significantly lower the final cost of next generation observatories such as the Cosmic Explorer in the U.S. and the Einstein Telescope in the E.U.

The workshop participants were confident that technical solutions could be developed that would have non-trivial impact on the cost of the design, construction and life-cycle operation of vacuum systems for the proposed next generation gravitational wave observatories. Two classes of solutions for the vacuum enclosures were examined: the first design concept is an extrapolation of the single-wall vacuum pipe in use in the present generation of detectors (at LIGO, Virgo, and KAGRA). The second design concept involves double-walled or nested vacuum pipes that would separate the atmospheric load problem from the stringent UHV properties needed for the inner wall. Vacuum pumping solutions and surface treatments were examined for both concept designs with an emphasis on potential hardware and treatments that could lower total costs but still meet the stringent requirements for next generation gravitational wave interferometric detectors.

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Introduction

The **NSF Workshop on Large Ultrahigh Vacuum Systems for Frontier Scientific Research Instrumentation** was held at the LIGO Livingston, LA site on Jan. 28 - 31, 2019. The workshop was primarily focused on the need to identify cost effective technologies for the design, construction and operation of the large vacuum systems that would be required for planned future scientific research facilities, including next-generation gravitational wave observatories (GWO) that are a factor of ten larger than the current systems in the U.S. (LIGO), Europe (Virgo) and Japan (KAGRA).

The technologies that were developed and employed in the existing GWOs have been shown to meet the stringent requirements of vacuum integrity, very low hydrogen and heavy molecule outgassing, minimal particulate generation, low vibration, and appropriate stray light optical absorbance for successful operation. However, straightforward extrapolation of the costs for extending the interferometer vacuum beam enclosures from the current lengths of 3-4km/arm to 40km/arm indicates the need for investigation of alternative technologies that could significantly lower the final cost of next-generation observatories, such as Cosmic Explorer (CE) [1] in the U.S. and Einstein Telescope (ET) [2] in the E.U.

Concurrent with the need for new technologies for next generation GWOs, the international particle physics community is developing concepts and initial proposals [3-5] for next generation accelerators involving long length vacuum systems. The design and estimated costs of these proposed frontier scientific instruments would also benefit from incorporation of new materials, treatments and construction technique for vacuum systems. Because of this symbiosis of needs, this workshop also included the U.S. accelerator and CERN community representation to help identify common research and development interests in vacuum science and technology. Given the workshop's interdisciplinary nature of the topic, invitees included representatives of the three large GWOs (LIGO, Virgo and KAGRA) along with vacuum science and technology experts from the accelerator, fusion, and materials science communities (see Appendix A).

The workshop was made possible by financial support provided by the National Science Foundation's Gravitational Physics Program and by the LIGO Laboratory, which is operated for NSF by Caltech and MIT.

Goals and structure of the workshop

The primary goals of the workshop were twofold: 1.) to examine a range of concepts that could have significant impact on the estimated cost of next generation gravitational wave observatories and 2.) to generate a prioritized list of technologies that should be investigated with detailed engineering and cost studies that will follow the workshop. In order to stimulate preparatory work for presentation and discussion at the workshop, a brief document was circulated to all attendees listing the basic concepts for the design of a 40km interferometer vacuum enclosure, on consideration of a double or nested vacuum enclosure to separate the atmospheric loading problem from the more stringent UHV requirements of an inner vacuum vessel, and a second design concept involving the more traditional single-walled vacuum vessel in use in the current generation GWOs. This concept document also includes a preliminary list of key design drivers that would have to be evaluated for each of the two classes of design concepts, such as basic requirements for hydrogen and heavier residual gas outgassing, optical properties of the inner wall, propensity for particle generation, fabrication, operational and maintenance issues-all of which effect procurement and lifetime operational costs.

Since this workshop precedes any formal conceptual design phase that will necessarily follow for next generation GWO such as the Cosmic Explorer and the Einstein Telescope, the workshop organizers felt it was important to provide a very open structure for the workshop to encourage wide ranging and unconstrained discussions for potential solutions to the two basic design concepts.

With this scheme in mind, the organizers proposed a two-part structure to the workshop agenda [see Appendix B]. A call was issued to all attendees to submit topics for brief (~10 minutes) "blue sky" presentations to cover any topic that was deemed relevant for either or both design concepts. Following these presentations, four working groups (WG) were organized. The first two addressed each of the two basic design concepts. WG1 examined potential new solutions for the straight forward extrapolation of the single vessel design currently in use at LIGO, Virgo and KAGRA with all constraints lifted in choice of vessel material, structural design, fabrication, surface preparation and in-situ preparation. WG2 examined the double walled, or nested vacuum vessel concept. Again, few constraints were applied to encourage a wide range of potential solutions.

Two other working groups were organized to examine important topics that would need to be incorporated within the design process of the two vessel concept classes. WG3 addressed novel surface treatments for both conventional and new UHV compatible materials. These treatments provide the primary means of meeting hydrogen and water outgassing and other residual gas requirements, in addition to being able to meet minimal particulate generation and desired stray light reflection requirements. WG4 addressed vacuum pumping for conventional and nested vacuum system concepts. Topics included gettering options within the beam pipe UHV sections and means of maintaining differential pressures in the nested system concepts.

The workshop agenda provided time for the working groups to meet individually and also with the entire workshop attendees. In the closing session of the workshop, working group chairs provided a preliminary summary results that were subsequently expanded by post-workshop communications for the working group summaries presented in the following sections of this report.

This report concludes with an overall summary, high level recommendations for work to follow, and a statement endorsed by all participants that a follow-up workshop should be scheduled within the next year.

Design requirements

The design targets for this workshop are driven by the current concepts for the next generation gravitational wave observatories: the Cosmic Explorer (CE) in the U.S. and the Einstein Telescope (ET) in the E.U. An overview of the field of gravitational wave detection based on interferometric detectors was given at the beginning of the workshop by M. Zucker from LIGO [6]. Gravitational wave detectors based on laser interferometry observe the metric strain ($h = \Delta L/L$) induced by a passing gravitational wave. The differential displacement, ΔL registered between orthogonal interferometer arms of mean length L as a result of a passing wave with strain amplitude h is given by:

$$\begin{aligned}\Delta L &= hL \sim L\cdot\frac{4\pi^2 GMR^2 f_{orb}^2}{c^4 r}\\ &= 4\cdot 10^{-19}\, m\cdot\left(\frac{L}{4000m}\right)\left(\frac{M}{M_\odot}\right)\left(\frac{f_{orb}}{400\,Hz}\right)^2\left(\frac{R}{20\,km}\right)^2\left(\frac{100\,Mpc}{r}\right)\end{aligned}$$

where we've taken, as an example source, a compact binary system with two equal component masses M separated by R, orbiting each other at frequency f_{orb} ,at distance r from Earth. When expressed in terms of apparent ΔL, the limiting noise terms in detectors of this type are either independent of, or vary only weakly with, overall instrument size. As a result, the most direct way to improve the distance r at which sources can be observed is to increase the arm length L. It's important to note here that the number of detectable sources varies with the *volume* observed, and thus the rate of event detections initially scales as L^3 (neglecting cosmological evolution of sources). Thus, the distance to which the proposed CE and ET could see would exceed the horizon where stars first formed in the early universe.

Residual Gas Noise

The power spectral density[1] of gas-induced fluctuations in the optical path length is given by:

$$S_L(f) = \frac{(4\pi\alpha)^2}{v_0}\int_0^L \frac{\rho(z)\,\exp\left[-2\pi f\, w(z)/v_0\right]}{w(z)}\,dz$$

where f is the signal frequency, L is the physical length, $\rho(z)$ is the number density of the molecules, α is each molecule's optical polarizability (proportional to n-1, where n is the bulk refractive index of the gas at standard pressure), $v_0 = (2k_BT/m)^{1/2}$ is the most probable speed for the molecules given their mass m and ambient temperature T, and $w(z)$ is the laser beam's Gaussian radius parameter [6-8]. The calculated limits for residual gas partial pressures are given in Table 1, showing that required partial pressures of H_2 are 10^{-9} Torr, for water 10^{-10} Torr and lower for heavier hydrocarbons.

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[1] Defined as mean-squared deviation per unit bandwidth.

Parameter	**Achieved in LIGO**	**Required for CE (1 μm)**
L (m)	4,000	40,000
w_0 (mm)	62	83
h_{gas} ($Hz^{-1/2}$)	$< 5 \times 10^{-25}$	$< 5 \times 10^{-26}$
P[H_2] (Torr)	$< 10^{-9}$	$< 10^{-9}$
P[H_2O] (Torr)	$< 10^{-10}$	$< 10^{-10}$
P[CO_2] (Torr)	$< 2 \times 10^{-11}$	$< 2 \times 10^{-11}$

Table 1 Key parameters and resulting beamtube gas pressure requirements for a possible Cosmic Explorer (CE) concept, employing 1 μm laser wavelength, compared to vacuum performance achieved in the existing LIGO beamtubes. Here w_0 is the minimum Gaussian "waist" radius of the laser beam and h_{gas} is the maximum allowable amplitude spectral density[2] of residual gas noise (assuming a factor of 3 safety margin with respect to the total noise allowance). [7]

For the proposed Cosmic Explorer, the interferometer length is increased a factor of 10 over LIGO's current 4 km arm to 40 km, for a total vacuum vessel length of 80 km for a two-arm, right-angled interferometer. Two identical but widely separated Cosmic Explorer interferometers are planned, requiring in total 160 km of beamtubes for the project. The Einstein Telescope configuration is triangular with total arm length of 3 x 10 km for a total vacuum vessel length of 30km. For either facility, the design is driven by finding affordable production methods for much longer beamtubes of large diameter (~1.2m) that are capable of achieving the ultra-high vacuum (UHV) of Table 1. UHV conditions are necessary to reduce scattering losses in residual gas molecules to levels such that such these losses do not affect the interferometric signals.

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[2] Defined as the square root of the power spectral density; the gas-induced RMS strain noise in a bandwidth B is $h_{RMS}(B) = h_{gas}B^{1/2}$.

The workshop goal is to examine design concepts and technologies that would feed into the first detailed design and engineering studies of the Cosmic Explorer and the Einstein Telescope. For the Cosmic Explorer, an approximate project time scale has been proposed. The formal design phase could begin in 2022, and the construction project could begin in 2026 for completion on or about 2035. Concurrent with the early phases of this project would be crucial testing of laser technologies at the Advanced LIGO (aLIGO) project including higher power lasers and optics to transition operation from 1µm to 2 µm. [9].

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Working Group 1 Report: Conventional Single-Wall Vacuum Systems

Co-chairs: Curt Baffes (FNAL) and Daniel Henkel (Rimkus Consulting Group, Inc.)

Charge

Investigate cost reduction options for conventional beamtube technology that could impact the design, construction and operation of the Cosmic Explorer, including the use of stainless steel, mild steel or aluminum single-walled tubing. The group was asked to look at novel applications of spiral welding and other pipeline technology.

Summary

Working Group 1 was charged with investigating cost-reduction options for conventional, single-wall vacuum systems. Material, fabrication, and processing (i.e. baking) techniques were discussed. Stainless steel, mild steel, and aluminum options were considered. The performance and behavior of stainless-steel systems is well established, but the material has a comparatively high cost. As such, our attention was focused on the lower-cost materials. However, raw material cost savings for the cheaper materials may be offset by reduced performance or increased cost/complexity in other parts of the system (e.g. beamtube expansion joints). A set of studies and tests to address the challenges of the lower-cost materials will be presented in the recommendations section.

Discussion Highlights

Geometry for a 3rd Generation Observatory

The straw-man geometry under consideration by this working group was as follows:

- Configuration - Single-wall metal tube
- Diameter - 1.2m (though diameters as small as 1m and as large as 2m were discussed)
- Arm length – 40km per arm

Material Choices

Stainless Steel

Austenitic stainless steel (e.g. 304L) is well understood, having been successfully used in all existing gravitational observatory beamtubes. As such, for the purposes of this report, it will be considered the straw-man against which other options are compared.

Carbon Steel

Carbon steel, sometimes referred to as “mild steel” or “plain carbon steel,” is proposed as a lower-cost alternative to stainless steel. Carbon steel becomes attractive as a beam tube material due to the availability of steel through Ruhrstahl-Hausen vacuum process during steel refining, resulting in very low hydrogen content and extremely low hydrogen outgassing [1]. Because of the unique requirements in this vacuum system, there are hundreds of alloys to consider, classified by several organizational standards such as American Society for Testing and Materials (ASTM) and American Petroleum Institute (API). Both focus on structural shapes and pipe. In addition to the composition and carbon content, other important factors must be considered. A few include the type of deoxidizing, grain size and shape (hot rolled or cold rolled), hardenability, weldability, and inclusion content. Closely controlled microstructures and the level of steel process cleanliness can have a profound influence on outgassing, surface finish, corrosion resistance and strength. Good weldability and high-yield strength can be controlled, not only by the carbon level, but also by microalloying, pre- and post-weld heat treatment and mechanical work-hardening. Appropriate surface treatment needs to be developed to avoid rusting and other forms of corrosion and to prevent water adsorption. Both plasma deposition and wet chemistry deposition of various coatings should be investigated to find the optimum type of coating (see Working Group 3 section).

The large amount of material required for this project provides the opportunity to go beyond commercially available carbon steels. The alloy does not have to be selected off the shelf. It can be designed as a low cost, corrosion resistant, weldable pipeline material with optimized properties of both carbon and stainless steel. There are U.S. mini-mills that could work with the collaboration in the development of the beamtube alloy and processes [2].

Aluminum

Aluminum offers low hydrogen outgassing and relatively low material cost. Fabrication of thick-wall Al pipes was discussed. Extrusion, forming and welding processes may be viable. Friction stir-welding, used internally by large commercial aluminum manufacturers for making long sections of rolled and welded pipe, is an option for aluminum. The welding of Al pipes to dissimilar-metal components, such as expansion joints and side port flanges, will need to be developed. Bi-metal transitions may be needed, with the added cost and risk, and must be evaluated.

Exotics

Other materials were suggested, most plausibly titanium. However, as will be discussed below, a back-of-the-envelope cost assessment quickly disqualifies titanium.

Material Thickness

For buckling stability and material robustness, a steel or stainless-steel tube should have material thickness $\geq$ ~3mm for pipes with meter-sized diameters. LIGO's beamtube is nominally 3.2mm thick, with Virgo and KAGRA having chosen to use thicker shells.

There have been occasions when the LIGO concrete enclosures have been hit by bullets. The concrete enclosures were sufficient to protect the beamtube. But for 3rd generation observatories, cheaper but less-robust enclosures are envisioned. There is a proposed requirement that the beamtube be thick enough to survive a bullet strike. It is estimated that a thickness in the neighborhood of 9mm (for a steel) would be needed. Raw material costs scale proportionally to thickness, and welding costs will have a positive correlation with thickness, so this proposed requirement will have significant cost implications, and should receive corresponding attention and debate. Costs associated with raw materials, which will be estimated below, can be weighed against the cost of providing physical barriers. For the above-grade sections of beamtube, a 2m-high earthen berm could perhaps be constructed from the cut material removed from the below-grade sections of beamtube. Such a berm might also reduce wind vibration of the structure.

For equivalent buckling performance and bullet-resistance, an aluminum tube would need to be thicker than a stainless one. To first order, buckling capability is proportional to (Elastic modulus * thickness^3). Therefore, an aluminum tube will require ~1.4X the thickness of its stainless counterpart. It is likely that bullet resistance does not scale up as strongly with thickness. A simple internet search on the bullet resistance of aluminum is not reassuring.

Raw Material Cost Comparison

For crude first-order comparison, commodity costs for representative mild steel (1008), stainless steel (304), and aluminum (3003) plate stock were retrieved from [3]. At this writing, stainless steel costs ~$3/kg, carbon steel ~$1/kg, and aluminum ~$3.5/kg. One can then compute material costs relative to material thickness. Results are shown in Figure 1. In order to facilitate comparison between materials of different elastic modulus, the X-axis is plotted as *equivalent* thickness, i.e. the thickness of stainless steel that gives identical buckling performance. In a future engineering study, this analysis should be refined by accounting for stiffening ribs.

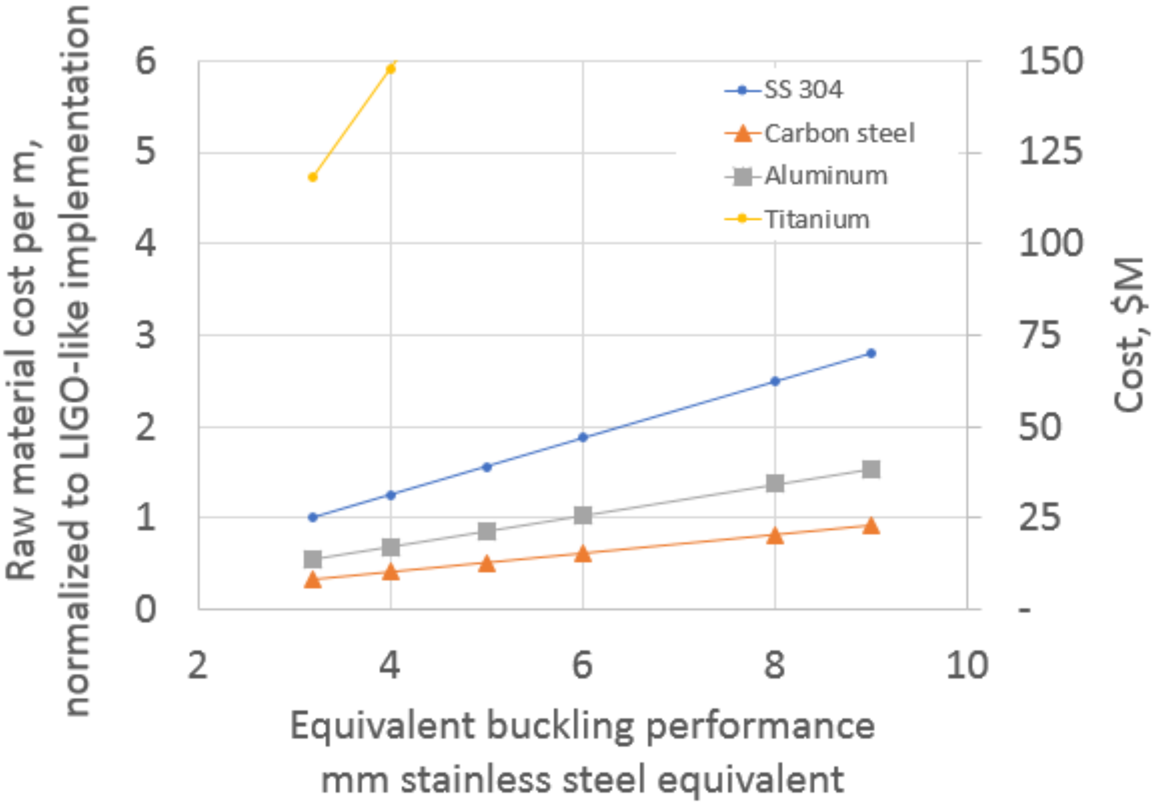


Figure 1: Raw Material Cost Comparison

At the low end of the thickness range, raw material costs are modest in relation to the likely cost magnitude of a 3rd generation observatory project. Cost advantages of aluminum, especially, could be counteracted by increased risk or complexity costs (e.g. in material transitions). This would recommend a conventional, proven implementation in stainless steel for a thin-wall system. If a higher wall thickness is desired, cost differences between the materials become more significant, and a broader systems trade study is recommended.

Fabrication Techniques

Spiral Welding

LIGO provided a demonstration of the feasibility of a spiral welding process. The only disadvantage of such a process is the comparatively long length of weld (~3X tube length in the LIGO implementation). The feeling of the authors is that spiral welding would be an option for any of the candidate materials, and fabrication cost would not be a strong function of material choice.

Longitudinal Welding

Both VIRGO and KAGRA demonstrated a successful longitudinal-seam implementation. This, also, is felt to be an option for any of the candidate materials. Fabrication costs would not be a strong function of material choice.

Seamless Piping (Stainless, Mild Steels)

It is believed that most leaks inherent in large-bore commercial piping (e.g. gas pipeline pipe) are associated with the weld seams. It is possible that seamless piping could mitigate this issue. Large-bore seamless piping is available from at least a few vendors, e.g. [4].

Custom Extrusion (Aluminum)

For aluminum designs, a custom extrusion could be considered. This approach has been used successfully for complicated beamtube shapes at many particle accelerators. Extrusion would be cost-effective, however, due to the large diameter and length, no extruders have been identified yet, and some amount of tooling development may be required. Due to the relative flexibility and ease of extruding aluminum, once could consider co-extruding other features beneficial to the application, for example stiffening ribs or channels for a water-driven bakeout (see also bakeout section below).

Commercial Off the Shelf (COTS) Products

Large-bore piping is readily available from the pipeline industry in a variety of materials. Anecdotally, these materials are said to have welds unsuitable for UHV service. This should be investigated and verified. In any case, it seems overwhelmingly likely that a dedicated production run with UHV-suitable process control will be required. Linde offers a 1.2m spiral-welded aluminum tube as a standard product [5]. Spiral rolled mild steel piping is available from Korea. Pricing is approximately $220US per meter for the steel tube only [6], with specifications as follows:

- 1.2 m(Dia.), 8 mm (t), 5 m tube from a hot-rolled coil
- Applied spiral welding to from the steel tube, which is cheaper than the seamed tube from thick, hot-rolled plate. The total welding length is longer than the latter. We believe applying this technique may be applicable for forming the tube. But evaluations for leak tightness and outgassing are necessary.
- including descaling (either ice bead blasting or acid pickling)
- excluding joints (flanges) + joining welding,
- excluding vacuum-cleaning
- excluding anti-corrosion painting for the outer surface
- $1030 + $60 (transportation to Houston) per each steel tube

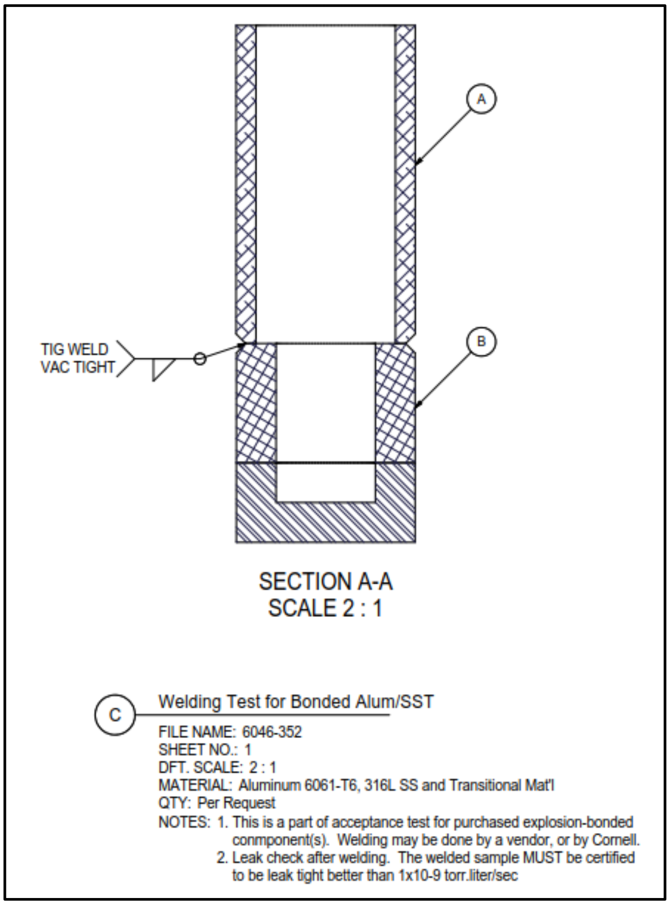
Joining of Dissimilar Materials

For a non-stainless system, a need may arise to join dissimilar materials with stainless. This can be avoided in some applications (for example, aluminum systems with aluminum Conflat™ flanges and soft aluminum gaskets). However, in other cases it may not be feasible or economical to avoid a transition. It is likely that the most challenging application is at the beamtube expansion joints.

In an aluminum system, hydroformed aluminum bellows may not be viable due to reliability and fabrication concerns. One could perhaps avoid a transition by accommodating a large-diameter diaphragm (essentially a single-convolution edge-welded bellows). However, it seems unlikely that a material transition can be avoided. Assuming a bake out at 120°C and a 20m section of beamtube between expansion joints, the 3rd generation observatory would need 4,000 expansion joints, each of which would need to provide >40mm of stroke during the bake. To meet this, one would likely choose to transition to a stainless steel expansion joint. 4,000 expansion joints would require 8,000 1.2m diameter Al-SS transitions, a considerable number and considerable cost. This cost would be weighed as a penalty against raw material cost savings. (Note-that the potential for lower temperature bake outs under discussion for the required water removal would relax the expansion joint requirements.)

When using aluminum alloys as beam tube material, functional components (such as flanges, bellows, etc., usually made of stainless steels) may be welded to the beam tubes using cladded bi-metal transitions. There are two types of bi-metal transition materials commonly used in the particle accelerator vacuum systems: explosion bonded (ExB) and hot isostatic pressing (HIP). Very large parts (exceeding 48"x48") are usually made of ExB materials, while the size of the parts from HIP material may be limited by the available vessels at HIP vendors.

For ExB parts, machining would be necessary to create weld interface geometry. Reliability experience with this type of transition has been mixed. Parts made of ExB materials may develop a leak during the welding process. Most of the leaks are likely due to filament fractures in interlayer sheet (Ti, Cu, Nb, Ta, etc.) used in the bonding (from the violent shock-wave), owing to insufficient interlayer thickness. (Our experiences showed that the interlayer sheet needs to be more than 0.5-mm in thickness.) Thus, adequate quality assurance tests need to be in place for the ExB parts or/and plates. The most effective QA test is to have a weld test specimen as shown below (Figure 2). A Cornell ExB plate technical specification is also supplied as an appendix.



Welding Test for Bonded Alum/SST
FILE NAME: 6046-352
SHEET NO.: 1
DFT. SCALE: 2 : 1
MATERIAL: Aluminum 6061-T6, 316L SS and Transitional Mat'l
QTY: Per Request
NOTES: 1. This is a part of acceptance test for purchased explosion-bonded conmponent(s). Welding may be done by a vendor, or by Cornell.
2. Leak check after welding. The welded sample MUST be certified to be leak tight better than 1x10-9 torr.liter/sec

Figure 2: Explosion-bonded transition weld test coupon

Transition components made of HIP material are commonly used in many accelerators in Asian countries, such as Super KEKB in Japan, Taiwan Light Source in Taiwan. The experiences of these accelerators have been very positive. One of the advantages of HIP transitions is that it can bond the dissimilar materials into the final form of the components, thus no post-bonding machining is required. Most HIP vendors in the US have HIP vessels less than 30" in diameter. However, a Japanese company, Metal Technology Co. Ltd, has HIP capacity to a maximum size of 2 m in diameter x 4 m in height. The cost of the HIP transitions is compatible with ExB transitions, if multiple transitions can be produced per batch.

For large components, such as beamtube bellow assemblies, adhesive bonding may also be considered. A concept design is shown below, in which the epoxy-bonded Alum/SST transitions could be mass produced with simple tooling.

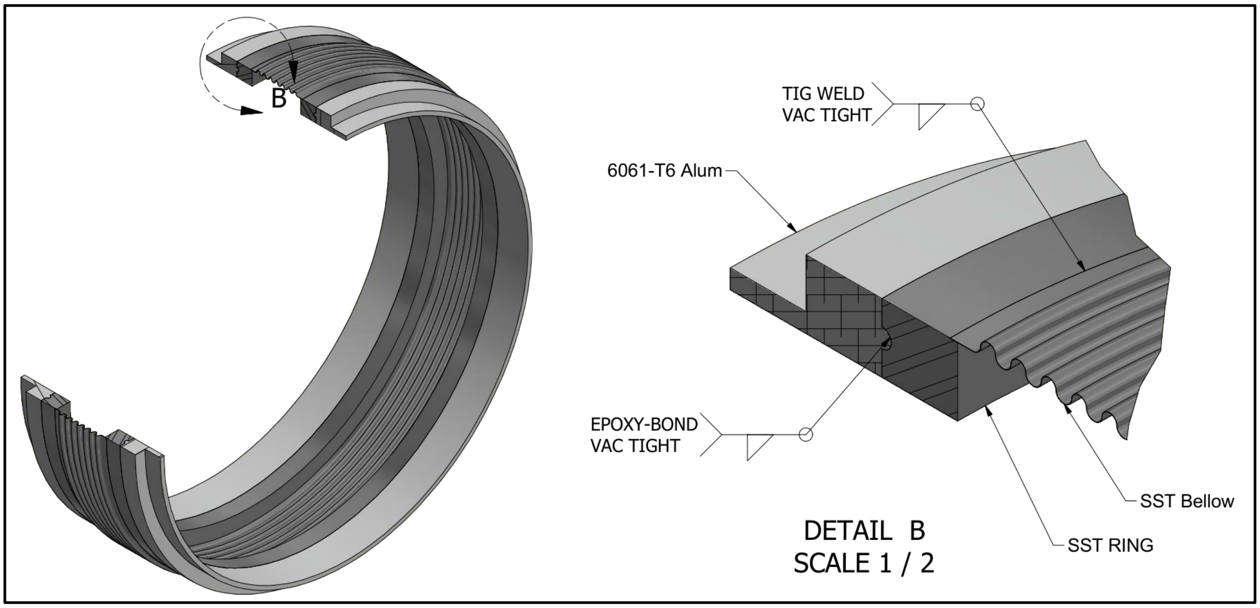


Figure 3: Adhesive-bonded transition concept

In a mild steel system, transitions could potentially be avoided by using a steel expansion joint. Alternately, weld techniques and filler materials are readily available to join mild and stainless steels, with appropriate process controls steel-stainless steel transitions should not pose a problem.

Surface Considerations

To minimize stray light, a smooth, specular, reflective beamtube surface is undesirable. For optimum vacuum performance, a smooth surface is very desirable. Under the presumption that a clever baffle design and/or coating can relieve stray light requirements on the beamtube surface, we consider here techniques that can be used to optimize vacuum performance. Surface degradation such as micro-crack, residual stress, microscopic defect may act as an absorption/desorption site, causing higher outgassing rate. KAGRA chose an electrolyte-polishing finish, after the production process of tube-forming (pressing and one-seam weld) and welding of bellows and flanges: hydro-formed bellows (0.8 mm thick) are chemically wet-cleaned in advance. In case of KAGRA stainless–steel tube, a few tens of micrometer in outermost surface should be removed so that non-degraded surface results. In order to passivate the electrolyte-polished surface, it is necessary to bake out a tube in vacuum and to be kept sealed off by dry-air, until jointing tubes on-site.

An alternate approach to remove surface defects and smooth the internal surface is barrel polishing with abrasive media (i.e. tumbling). This has been employed successfully to remove internal surface and weld defects in niobium accelerator cavities (Figure 4). Environmental/safety hazards are much lower than with chemical approaches.

IB4 High centrifugal barrel polishing tool repairs 1.3 GHz inner surfaces when defects appear. Two 9-cell 1.3 GHz cavities can be tumbled simultaneously.

Figure 4: Barrel Polishing Setup (courtesy A. Rowe, FNAL)

Bakeout Considerations

For any single-wall system, a bakeout in the neighborhood of ~100°C is desirable to reduce adsorbed water. A LIGO-like approach, with large (~ a few km) sector of beamtube being isolated and baked would clearly be feasible. Discussion here will focus on less conventional ideas with the opportunity to reduce the cost or complexity (e.g. elimination insulation, gate valves). One idea proposed at the workshop was a traveling bakeout system, which would bake a comparatively short section of beamtube without the isolation of adjacent areas. Such a system might reduce the costs correlated with instantaneous power delivery. A “hot tent” could relieve the need to insulate the beamtube itself.

One disadvantage of this approach is the possibility for water to reabsorb on cooler sections of beampipe. This could potentially be mitigated by making several passes along the beampipe. Another approach would be to establish a viscous flow of ultra-dry air (~ppb water content). Water liberated by the bake could become entrained in the flow and flushed out of the vacuum system. It is plausible that this process could be executed at a pressure of a few torr. Dry air systems of appropriate capacity have been developed to service the semiconductor industry [7].

Due to high thermal conductivity, an aluminum beamtube offers additional options for bakeout without uniform heat deposition. For example, co-extruded water channels could be used in conjunction with a hot-water bake system. This technique has been used at CLASSE [8]. Discrete, inexpensive resistive heaters could also be affixed to the beampipe.

Conclusions

Options for materials, fabrication techniques, and processes were considered. In this early phase, the greatest opportunity for cost reduction of conventional single-wall systems appears to be the investigation of alternatives to stainless steel as a beampipe material. Recommendations will address specific tests and studies to improve our understanding of the costs, benefits and pitfalls of a mild steel or aluminum beamtube.

Recommendations for Next Steps

Bullet-resistance field testing

It is clear that a bullet-resistance requirement may drive cost. It will not be possible to design a system that can withstand any plausible condition. However, a straw man requirement should be proposed. An afternoon of coupon testing may augment intuition and provide guidance for such a requirement.

Mild Steel Literature Search

A mild steel system looks attractive. An initial task should be a thorough literature search to identify promising alloys and/or processes. The result should be an identification of perhaps 5-10 alloys to test further.

Mild Steel Coupon Testing

Identified alloys should undergo a test program to quantify performance. Water adsorption and hydrogen content are of particular interest. NIST, JLab, CERN, Virgo and LIGO have expressed interest in participating in this test program.

Aluminum-System Expansion Joint Study

The largest challenge to an aluminum system is believed to be the implementation of the expansion joint. An engineering study to more formally assess the feasibility and quantify the costs of the identified options would be very informative.

Investigate COTS options

COTS seamless piping is available in large diameters and spiral-welded products are available. If initial discussions and investigation do not disqualify the various COTS products, a more formal discussion with potential vendors should occur to gather cost information and identify opportunities for tests.

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Working Group 2: Non-conventional vacuum technology

Co-Chairs: John Noonan (ANL) and Dennis Manos (William and Mary)

Charge

Examine cost reductions options using non-conventional vacuum pipe technology for the design of the Cosmic Explorer including the use of nested vacuum systems with a thin, bakeable inner vacuum system and potential use of coated substrate systems

Summary

Alternative conceptual designs for the 80km beamtube for Cosmic Explorer were considered. One variant would be to use a single tube, as the current LIGO does, but use advances in metal manufacturing in an attempt to reduce the cost. Single-tube examples as discussed by WG1 include using low-cost aluminum alloys that can be made into suitable piping using advanced in-situ techniques. It might also be possible to extrude such alloys in long sections with a large-diameter. Such an approach needs new methods for fabrication and would also require finding methods to bond these alloy tubes to dissimilar metals, also using field-worthy methods. Another variant discussed by WG1 included the use of so-called "mild" steels to reduce cost, which likely would require advances in surface treatments to reduce water, carbon oxide, and hydrogen outgassing to acceptable levels. The workshop identified a need for updated data on the vacuum performance of mild steel, especially on materials that are in current production. The topics of treatments and coatings in connection with vacuum improvements were taken up WG3. WG2 worked closely with this group since we believe that any design will require significant development of final surface treatments in fabrication, and careful consideration of the use of in-situ treatments for routine maintenance, replacements, and repairs that will be required during the multi-decade life of the device.

A two-concentric-tube variant design was examined in detail. The primary requirement for this option is that the outer vessel must have very low manufacturing costs. Material choices for these designs included consideration of both steel and plastics. The two-tube design calls for the use of a thin-walled inner tube for laser beam transport, situated coaxially inside a lower-cost outer tube which provides the needed mechanical support against radial air pressure. Two main (mechanical) subsets of this design are presented below. Time did not permit equally careful examination of designs wherein the inner tube might provide some degree of resilience against (local) partial loss of vacuum in the outer tube.

Two-tube concept 1: Inner and Outer vacuum spaces are coupled.

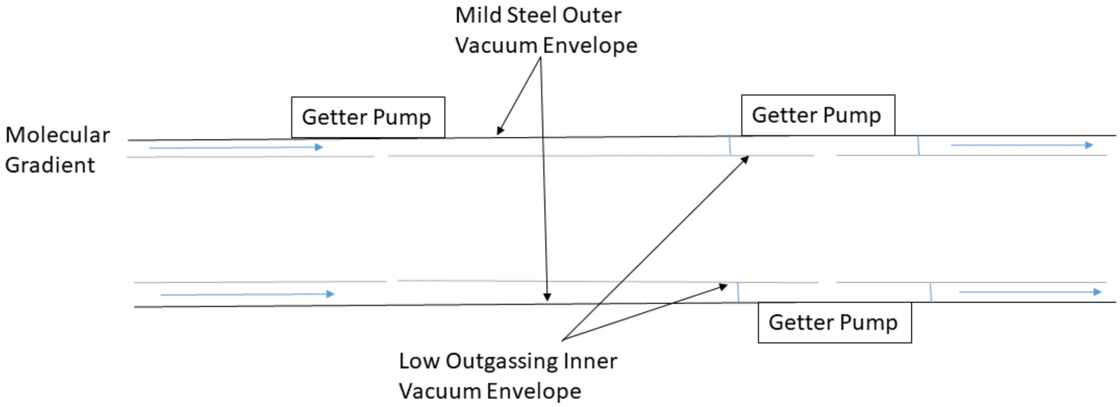
This design was analyzed in detail by R. Weiss [1] and summarized in his presentation at this workshop. The key features of the concept are described below. Extended discussions by WG2 and other groups using this design as a benchmark identified several key items for further analysis and examination. These are described briefly in the next few paragraphs.

As mentioned, the selection of an aluminum alloy and means to bond it will be important. The discussion of the use of soft-seal valves for vacuum isolation led to the proposal for devising shutters to limit conductance between the inner and outer vacuum spaces. This approach allows a somewhat wider latitude in considering bonding and joining methods for the alloy tubes, since a controlled amount of leakage is allowable. This extends to designs for a lattice of pumping rings along the length of the arms, and the placement of non-evaporable getter pumps and other internal hardware.

A careful analysis of thin-walled inner tube vibration is required to design methods to support and isolate the inner pipe. For this purpose, suggestions were made to use sliding supports made of Teflon™ (or other materials) between the tubes . The use of non-evaporable getter (NEG) pumps introduces the need for relatively high-temperatures (~400C) for their activation. The limited total capacity of NEGs for water uptake also requires recurrent high-temperatures for their regeneration. Annealing or other effects on the local structures in the aluminum around the NEGs requires analysis. The possibility of adding more pumping (additional NEGs or other pumps) near joints to allow the reduction or elimination of sliding joints also requires analysis. As discussed above, the use of coatings or other surface treatments to suppress water outgassing might reduce the need for regenerative heating.

Concern arose about the stability of the inner tube in the event of a major compromise of the outer vacuum housing. The extreme example considered was of one or more holes being made in or around a joint section of the outer pipe. Even for a small difference between the diameter of the inner and outer tubes, there would be a sufficiently large volume in the annular space between the tubes that a localized leak would take a significant amount of time (many hours) for the pressure to rise to values needed to deform the inner tube. Rapid repair technologies for the outer envelope may need to be developed.

One possible alternative to using annulus valves is the use of pumps located on the outer vacuum envelope and allowing for access of the inner vacuum envelope through a small gap in the inner shield. This could be made consistent with the pumping speeds described in the earlier part of the vacuum description if the size of the slit and the area of the getter pump have the appropriate ratio.



A critical aspect of this design is the conductance of the molecular flow in the annular volume between the inner and outer shield. One possibility is to effectively seal this volume near the getter pump, as illustrated to the right set of getter pumps. In this case, a low vacuum can be readily created in this volume that allows effective pumping of the inner vacuum envelope. The small conductance of this zone coupled to a high-speed pump will pump the inner volume. This will require a moderately low outgassing material, like mild steel, for the outer vacuum envelope. Both these ideas need additional design calculations to document their effectiveness.

A brief summary of attributes and cost for concept 1 are table here:

- Inner aluminum wall thickness of ½ mm
- Use of mild steel reduces material costs
- More tolerant than a single system to leaks to the atmosphere
- Allows optimal pumping strategies
- Reduces cost and complexity of bakeout
- Easier to clean and maintain surface conditions for the detector
- Tolerant to leaks between inner and outer systems
- Regulation of shared vacuum using "soft-sealing valves" or shutters.

The estimated cost for concept 1 is:

Outer tube	$51M
Inner tube	$1.6M
In field fab	$3M
Total:	$55.6M

The cost estimate is for the beam pipe only in order to make the cost comparison to equivalent lengths of plastic pipe.

Two-tube concept 2: Independent inner and outer vacuum space.

This variant of the two-tube concept calls for a sealed inner UHV vacuum tube for laser beam transport, concentrically disposed inside an independent outer "guard" vacuum tube. The inner thin-wall tube is proposed to be fabricated of either aluminum or mild steel, approximately 1.5 mm thick. The outgassing of mild steel, as it is currently being manufactured to reduce carbon, is thought to be sufficiently low to permit this; as we mentioned above, further tests may be required. In this design, the inner tube is thicker than the 0.5 mm of concept 1. A tube 1.5mm thick, should be sufficient to give either Al or steel tubing some mechanical strength to sustain significant loss of guard vacuum. For aluminum 1.5 mm is probably not thick enough to serve as an independent single-tube against a full 1 atmosphere pressure differential.

WG2 examined the prospect of making the outer tube from a fiber-glass reinforced plastic (FRP) [2]. Manufacturers have been identified who can fabricate an FRP tubes with up to 1.6m ID with a wall thickness of 6.5cm, sufficient to withstand 1 atm [3 – 4]. The cost of such a structure has not been carefully analyzed, but some material savings may be made by reducing the wall thickness to ~ 4cm by adding stiffeners every 0.6m along the length.

Such an FRP tube can be evacuated to ~10^{-6} torr, at which pressure a water-permeation barrier on the inner wall may not be needed. Since the main residual gas is water, a desiccant might be used to further reduce the partial pressure. A differential pressure ratio of guard to beam tube chambers of >10,000 is sufficient to protect the operation of optical components in the inner beam tube, allowing moderate conductance of gas between the tubes. Alternative plastic piping materials were examined. Discussions with pipe and vessel manufacturers [5 - 7] and conversation with users of large-scale plastic vacuum components [8] led us to reject unreinforced (extruded) plastic vacuum materials. The following extruded materials were rejected as either being weaker, or more expensive, or both: PE (polyethyelene) [10 – 11], PPE (polyphenylene ether), PVC (polyvinyl chloride) [2], FEP (fluorinated ethylene propylene), PTFA (polytetrafluoroethylene), and PFA (perfluoroalkoxy).

One supplier [7] has prepared a preliminary cost [12] estimate for 80 km of the guard vacuum pipe. The estimate was based on an FRP pipe with a 1.6 m I.D., assuming a 1 atm. pressure differential, at ambient temperature, also assuming that the entire installation would be above-ground. Each outer pipe section is assumed to be 12 m in length, with wall thickness of 6.5 cm. (270 kg/m) for the unstiffened case, yielding a cost of $13,140 per section. As an alternative, each 12m section may have a wall thickness of 4 cm with stiffeners as above (200 kg/m), for a cost of $12,260 per section. The estimated total cost for 80 km of outer plastic tubing is between $81M and $86M dollars, An inner steel vessel is estimated to cost $2.5M in materials plus ~$3M in fabrication for a total of $5.5M. The combined total rough estimate is: Stiffened: $86.4M; Unstiffened: $92.2M. The cost estimates for the plastic guard chamber and the inner beam chambers include only the cost of the pipe materials, and do not include assembly or other related charges.

It is important to note that this outer FRP tube cost is higher than the cost of steel for nested concept above [1]. Detailed comparison of steel versus plastic from the standpoint of lifetime operating costs, including maintenance and repair has not been performed. Substantial industrial experience exists to compare the environment degradation of metal versus plastic pipelines as a result of exposure to temperature cycling, geo-environmental weathering, biological agents, and sunlight.

Surface Treatments

The above considerations do not include surface treatments to improve outgassing of the inner tubes or absorptive or other coatings that might be necessary or desirable to improve performance of the optical interferometer. WG2 undertook discussions with coating suppliers and manufacturers to evaluate a possibility that emerged in the workshop. Certain styles of deposited, or electrochemical conversion, coatings are used to create “blues” and “blacks” and other low-reflection finishes on metals. These finishes, including nitrides [13], aluminides [14], metal oxides [15], glass [16], in addition to standard carbides, oxynitrides, and others, have also been used for “passivation”, reducing corrosion by creating barrier layers against incoming oxidizing species at the surface. Such barrier layers also may reduce the diffusion of lighter molecular gases coming from the deeper structures on the metal that are released as outgassing components.

Many of these coatings require activation to overcome energy barriers to their formation and so are produced by plasma or electrochemical means, or alternatively, are produced at elevated temperature. The idea was to take advantage of the high temperature associated with mill hot-rolling of the sheet stock to be used for the inner chamber. At various points in that process, the metal temperature is between ambient and the melting point, and by controlling exposure to reactive compounds, contact time, pressure, and other process variables, one might produce an optically absorptive surface layer on the stock that could also serves as a diffusion barrier, thereby lowering the outgassing. Possible materials that might be produced on a mild steel as it comes off the rollers might be magnetite-like (Fe_3O_4), TiN, or other such layers.

Such a process might be difficult to develop since the tolerance of the interferometer system for suspended particles is nearly zero. Hot rolling produces undesirable surface layers (scale) that are often removed by harsh chemical means or post-treatments of stock, like electropolishing to smooth the surface and reduce the depth of grain boundaries. These processes, which include high-temperature bakes, electropolish, chemical-mechanical polish, and other passivation treatment do indeed reduce the depth of grain boundary crevices, remove visible defects, and leave mirror-like surfaces that have much better appearance than the mill finishes. Such high-cost treatments are frequently used in semiconductor manufacturing and other processing chambers where they may give a wider latitude in handling and operation for processes that cycle to air frequently. However, there is little evidence that the vacuum performance of these expensive finishes improves the short-term outgassing performance compared to properly cleaned mill-finished metals [17].

Conversion coatings created using the inherent heat of a hot-rolling step during production of the metal would require a cooperative arrangement between a steel-mill and a national lab, or perhaps with a university, but such an effort might return dividends for this project in the long-term in developing a process to enhance the sensitivity of the instrument. So, the possibility for production of a deposited layer or a conversion coating was discussed at length with technical personnel at a major supplier of architectural glass and with a supplier of large-scale coated flexible films.

The current practice in the glass industry [18] to produce proprietary coatings (mostly multilayer stacks) on architectural glass panels produces a very wide variety of coatings. Such coatings are done mainly by sputtering or PECVD on (optically smooth) flat glass panels, that begin the coating processes at room temperature. The float glass from which panels to be coated are cut, comes off a molten tin float-line as a ribbon with a width of at least 130 inches (3.3m). Larger float-glass ribbon widths sufficient to produce a 1 – 1.5m diameter rolled tube can be coated by existing equipment. In the roll-coated film industry [19], plastic substrates are processed in equipment capable of coating similar widths. The most common equipment for these films is sputtering or reactive sputtering to continuously produce multilayer stacks in roll-to-roll coater geometries. The energy required to overcome the reaction barriers is supplied by largely charged particle (plasma) bombardment, allowing lower temperatures to be used where necessary. The adaption of these methods to using afterheat in a mill rolling environment was thought to be interesting to both sets of manufacturers.

The specifications and equipment choices for processing are proprietary to industrial manufacturers, as are the detailed process conditions required. Standard practice for large-scale box or roll-to-roll, in the film and plate markets is dominated by a small number of European firms [20-22]. Each makes equipment that could process sheet steel or aluminum in widths large enough to fabricate a coating on the inner wall of the inner tube.

Conclusions

The purpose of the WG2 group was to evaluate whether nested chamber [1] designs are viable and cost effective. The two-chambered coupled vacuum design is more completely described and discussed extensively. The group concluded that it is a viable design. However, several issues need more research. Soft seal shutters, pump rings as an alternative to annular valves, and activating ZAO getter modules in an aluminum chamber need more study.

The two-chamber design with an inexpensive inner beam tube and an independent, guard vacuum chamber needs more study. At the time of the workshop, several plastics, e.g. PVC [2], HDPE[3], fiber reinforced plastic [5-8], were discussed. One question, whether an encapsulating coating was needed to achieve base pressure, was answered. Many plastic vacuum materials that are properly cured achieve a base pressure ~10^{-6} torr, which is more than adequate. However, water is the main residual gas. Additional pumps for water would improve the guard chamber base pressure.

Subsequent to the workshop, technical discussions on the various plastics determined that PVC, HDPE, and simple plastics would require a wall that would be too thick to make the guard chamber economically viable. Fiber reinforced plastics are a viable alternative, however. A cost estimate of only the pipe is included in the report. Since both construction and operating costs are a major concern for Cosmic Explorer, detailed cost analyses, to include pipe, flexible joints, flanging, and other component and their required assembly, should be performed as part of choosing one of the candidate vacuum chamber geometries. The choice of a single-wall beam pipe, or a coupled two-chamber system [1] or a two-chamber system with independent vacua needs to be made. If an independent two-chamber system is preferred, then cost analysis will be needed to determine whether the material for the outer chamber should be plastic or metal.

Recommended action items

- Develop a conceptual design for soft close shutters
- Analyze pump rings versus annular valves
- Design work to reduce the heat load on the aluminum beam tube during NEG activation
- Fabricate two-sections of the FRP guard vacuum chamber. Perform vacuum system testing to evaluate joining techniques, base pressure, and vacuum integrity against atmosphere
- Studies of anti-reflection, outgassing barrier coatings may be useful for the Cosmic Explorer

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Working Group 3 Report: Novel surface treatments for conventional and UHV materials

Co-Chairs: James Fedchak (NIST), Jon Feicht (LIGO)

Charge

Working Group 3 (WG3) led a discussion of novel surface modifications and/or surface coatings to meet the design requirements for hydrogen, water and contaminant outgassing in addition to meeting particulate and reflection requirements for the vacuum enclosures for the Cosmic Explorer.

Summary

The charter for Working Group 3 was to discuss beamtube surface processing, coating materials, surface cleaning techniques, acceptable particulate contamination levels and outgassing requirements for gravitational wave detectors. We were asked to review any novel surface coating materials for the potential to achieve faster (water) pump downs and lower hydrogen diffusion rates, and perhaps exhibit good IR (1µ) optical properties as well. Many potential candidates were posited but two results that stood out were those of Park *et al.* (2014) [1] on the hydrogen outgassing rate of mild steel, and Saito *et al*. (1999) [2] on TiN coated stainless steel being used to preclude (water vapor) baking.

Park reported that H_2 diffusion in mild steel produced by vacuum degassing was substantially lower than that produced by older foundry techniques. Park's data suggests that mild steel could be used for the Cosmic Explorer without having to perform thermal processing such as the air-bake that the LIGO stainless steel required. The downside of mild steel is corrosion, however it was suggested by D. Henkel that conversion coating the steel with Fe_3O_4 (magnetite) or other coatings may mitigate this issue and might improve the surface optical scattering properties using bidirectional reflectance (BRDF) at 1µ wavelength.

Y. Saito reported that a 1µm thick TiN coating on surface-smoothed 316 stainless steel is effective in minimizing water adsorption during air exposure[2]. He reported that micro-polishing techniques were applied to TAMA300, a prototype gravitational wave interferometer similar to LIGO, due to the inability of the TAMA300 system to be baked out following assembly. Micro-polishing alone was found to be effective, however the surface quickly recharged with water when vented to atmosphere. Saito noted that an additional TiN (or (TiOx) coating would be a better option but requires development for large-scale application. Poelker reported on their comparative outgassing studies [3] that showed TiN was very effective, reducing the apparent total outgassing rate by about four orders of magnitude vs. uncoated stainless steel, but cautioned that residual gas pumping by the Ti based coating is likely occurring, thus skewing the data.

One outcome of the WG3 session was an offer to arrange for additional investigations into the outgassing of mild steel and coated chambers, to include TiN and diamond-like carbon (DLC) using the standardized chamber geometry of Fedchak *et al*. (at NIST) via the spinning rotor gauge (SRG) technique.

Optical measurements indicate DLC films perform well at 1µ wavelength [4]. LIGO also has recent experience with 304 stainless steel baffles coated with DLC, including in-house BRDF measurements that indicate the material has excellent optical properties. A plasma CVD process was used to coat the LIGO baffles, but since the process is proprietary to the vendor the exact method is not publicly available. Amorphous silicon (a-Si) was another candidate material discussed, however recent [3] testing suggests that this material does not reduce outgassing but may preserve a low rate if the substrate is first thermally processed.

Discussion Highlights

The implied ground rule was that any process being considered had to be competitive with the existing state of the art (i.e., ~450C air prebake followed by in-situ water degas of the 304 stainless steel beamtube demonstrated at LIGO). Any new proposed process has to reduce the hydrogen and water outgassing rate per the stated requirements and be cost competitive. A new process could possibly be cost justified if it provided a unique property, such that a larger initial cost would be acceptable. For example, could a DLC coating eliminate the need for system bakes following air exposures?

The hydrogen outgassing of mild steel measured by Park *et al.* [1] was mentioned repeatedly, including some historical notes by Dylla on (his) work on outgassing [5] of this material. Dylla further noted that historical data has errors that has precluded mild steel systems from being further investigated and considered.

Regarding vacuum requirements for residual gas species, R. Weiss mentioned that LIGO "overdid it" by requiring such low H_2O rates, so in the future a more modest bake might be sufficient. Updated maximum rates may possibly be higher depending on detailed calculations of the H_2O adsorption-desorption dynamics based on the LIGO model developed by Weiss. The key metrics for residual molecules are their polarizability and thermal speed. Large molecules such as hydrocarbons must be eliminated almost entirely.

TiN Coatings: A variety of physical vapor deposition (PVD) techniques are used to apply TiN coatings. A brief search of coating vendors shows that substrates can be successfully coated at substrate temperatures in the range of 450C [6]. Reactive sputtering and arc coating can be applied at near ambient temperatures. Process parameters have to be carefully controlled to insure proper bonding and pure TiN stoichiometry. [7] It was suggested that the steel would be coated first, then manufactured into a tube. Processing (web coating) machinery similar to flat panel or glass coating lines that include differential pumping input/output stages for processing sheet stock are in wide use and may be applicable [8].

DLC Coatings: The group spend considerable time discussing diamond-like carbon (DLC) films. They appear to have good outgassing characteristics, are relatively easy to apply, also have good optical properties. KEK has reviewed the coating properties from several relevant parameters [9]. LIGO also has recent experience coating baffles with DLC. The data will be provided as follow-up information to this workshop.
Wet (chemical solution, electroplating) processing of steel with copper was discussed, but this system needs a Ni-strike layer for adhesion, and possible thermal treatment post-plating. There are both electrode and electro-less Ni systems. This approach was discounted as impractical due to costs and risks.

D. Henkel mentioned that Fe_3O_4 (magnetite) may be a good coating candidate for mild steels. It is typically an "oxide + water" treatment or it can alternatively be applied with a non-aqueous process at higher temperatures (>550C). Called "conversion coating", these coatings help steel resist corrosion. The process creates a diffuse black surface that may have good optical properties. The material would need BRDF measurement on samples for further qualification of the required optical properties.

A brief review of the magnetite process [10] indicates that the plated surface may have loose particles called "smut" that needs to be removed by mechanical means. The plating smut would require evaluation since LIGO is sensitive to particles falling through the beam path creating random noise, or if deposited on optics, the particles can cause localized heating.

Alternate Materials and Processes

An alternate approach to reduce outgassing is mechanical surface modification. Surface smoothing (surface area reduction) can be done by diamond turning and honing. Both processes were mentioned as very effective, although the surface recharges with multi-monolayers of adsorbed water during atmospheric venting (like all surfaces) but in proportion to the real surface area. Therefore, surface smoothing does have a quantitative effect of net water outgassing [11] when other surface and exposure conditions are controlled. A comparison of many of the surface smoothing and chemical processing techniques used to process stainless steel and aluminum for UHV service was done by Dylla, et al [12] with net outgassing after air exposures and surface analysis as the metrics. Small differences were noted among any of the more extreme treatments (mirror and electropolished surfaces) compared to now standard alkaline detergent cleaning followed by hot, clean water rinsing. (Note: a version of the latter processing was used for LIGO beamtubes).

Grain refined steel. D. Henkel mentioned low-alloy steels may have beneficial low H_2 outgassing rates. This option requires more study of candidates, also a review of any other problems associated with using this material. Cor-ten® steel was mentioned as an example, but it was also noted as having corrosion issues, even though grain refining typically helps with corrosion. This topic initiated another discussion on the type of steel for fabrication of test samples. The selection of a tentative list will require additional literature review and discussion of candidate materials.

R. Weiss mentioned that water molecules with adsorption activation energies in the range of 10,000-15,000 Kelvin are the fraction of adsorbed molecules that are important to go after (desorb), but doubts "energy windowing" is possible. The thought behind this discussion was to remind the group that higher energy sites have such long residence times that trying to desorb them is not worth the energy input.

UV light sources were considered as potentially useful for outgassing water following air exposures but discounted as difficult to employ with the LIGO's beam tube geometry. The energy level of typical commercially available devices (Hg resonance lamps, Xe arc) is too low. A source on the order of 5-10eV is required to induce dissociation and desorption. A study by Koebley, Outlaw, and Dellwo [13] indicated good results (see the figure below), desorbing 22 monolayers with a 30 minute exposure to 185 nm (6.7 eV) radiation, with the caveat that the radiation needs to be primarily line-of-sight from the source. Examples of practical deep UV sources suitable to the LIGO beamtube geometry were not identified by the working group during the course of the workshop.

There are examples of electrodeless geometries (using dielectric barrier, RF, or microwave excitation) running on inert gases or inert-halogen mixtures to create excimer emissions that have been demonstrated to produce kilowatts of light in the range of 173 – 225 nm.[14] However, practical concerns of the cost of delivering sufficient RF power and handling expensive inert gases may tip the scale to novel vessel heating and dry gas purging techniques for cost-effective water removal techniques.

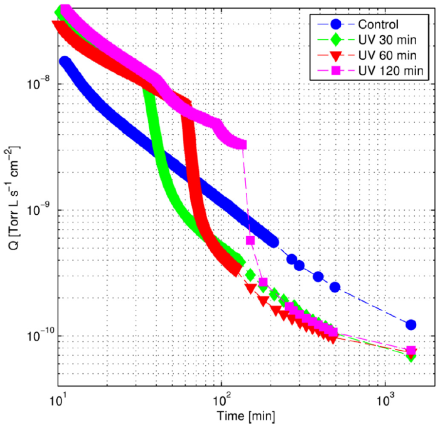


Figure 1. Water desorption rate (from Koebley, Outlaw and Dellwo [13]) of a stainless-steel chamber showing an increase in throughput during exposure to 6.7 eV UV radiation. Control indicates rate without radiation.

A dry purge cleaning process (primarily prior to hydrocarbon sensitive processes) was mentioned as a technique used by vacuum hardware suppliers in the semiconductor industry. Dry purge was noted to be nearly as effective as a mild bake-out for water removal, [15] and may offer unique advantages for hydrocarbon and particulate contamination. Dylla mentioned that a viscous flow, dry gas purge was effectively used to remove oil and dust contamination with a contaminated Nb superconducting RF cavity at Jefferson Lab. His experience indicated that the technique can be very effective. Another benefit of using a dry purge is the improved conductance of the system. A "cycle-purge" method of outgassing is described in a US patent filing [16], in which the system is cycled between rough and high vacuum, the purge cycle overcoming the limited conductance due to molecular flow.

A follow-up request by R. Weiss that dry gas purging systems be installed for immediate on-call use at LIGO due to recent problems with leaking gate valves, was discussed. Such a system would likely use dry air rather than nitrogen, primarily for personnel safety. Examples of this technology exist in the semiconductor and flat panel manufacturing industries, with both industries requiring large amounts of dry gas for cleaning parts and processing. At LIGO, such a system could be used to quickly backfill or purge the beamtube with extremely dry air, potentially reducing pump-down time A typical molecular sieve system is manufactured by SAES [17]. These systems can provide air with sub-ppb moisture content. The feed air needs to be dry, (-50C dewpoint) and oil-free. LIGO's existing compressors can meet the feed air requirement. Regeneration of the sieve is done by the manufacturer or can be done on-site if proper equipment is available.

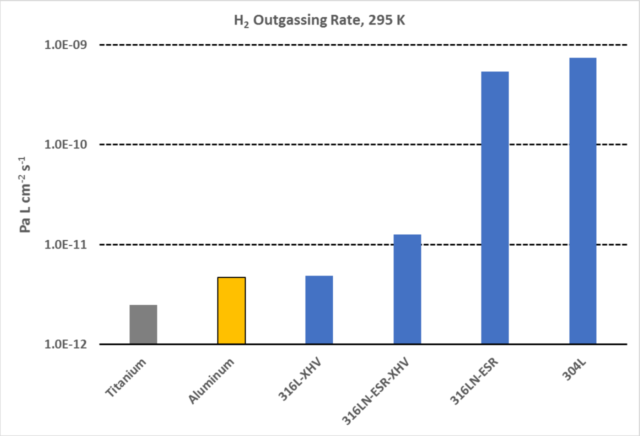
Ozone cleaning was mentioned as effective on removal of hydrocarbon contamination when delivered as a flowing gas. Typical units use Hg lamps or corona discharge chambers to generate the gas.

Outgassing Rate of Uncoated Metal Vacuum Chambers

Stainless Steel, Aluminum, Titanium. For comparison, it is useful to note the H_2 outgassing rate of uncoated materials. The following table was presented by J. Fedchak, and represents measurements made at NIST on chambers baked for atmospheric water removal for a minimum of 2 days at 125-150 °C.

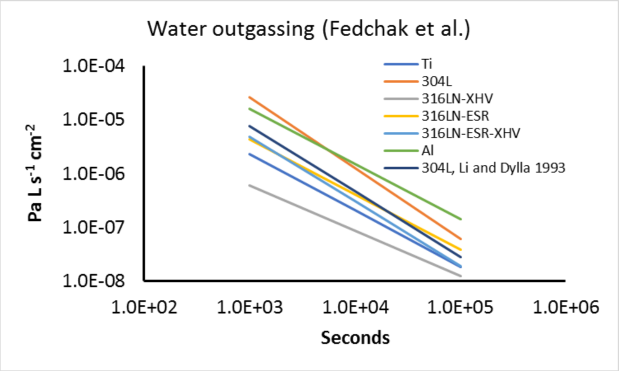
The data is preliminary but should be ready for publication within the year. Chambers designated by -XHV have been vacuum fired at 950 °C for a minimum of 24 hours in accordance with steel thickness. The outgassing rate of vacuum fired 316L is similar to the LIGO 400 °C air-bake outgassing rate of 6.7 × 10^{-12} Pa L s^{-1} cm^{-2}, as noted in the workshop presentation by M. Zucker. The units in the table are [Pa L s^{-1} cm^{-2}] = 133×[Torr L s^{-1} cm^{-2}].

	Activation Energy		**Outgasssing Flux (295 K)**	**Relative improvement facctor**
	eV	**K**	**Pa L s^{-1} cm^{-2}**	
Titanium			2.50E-12	295
Aluminum	0.4	4251	4.70E-12	157
316L-XHV	0.7	8078	4.89E-12	151
316LN-ESR-XHV	0.6	6892	1.26E-11	58
316LN-ESR	0.6	7445	5.39E-10	1.4
304L	0.6	6880	7.37E-10	1



For water outgassing, the outgassing rate as a function of time was determined for each chamber. In this case, no bake for water removal was performed. The data was fit to $At^{-\alpha}$. For comparison, Li and Dylla obtained A= 3.56 × 10^{-2} Pa L s^{-1} cm^{-2} and α=1.22 for a 304L chamber vented with air. [18]

Chamber	**Pa L s**$^{-1}$ cm^{-2}	**α**	**10^4 seconds** [Pa L s^{-1} cm^{-2}]	**10^5 seconds** Pa L s^{-1} cm^{-2}
Ti	3.20E-03	1.05	2.06E-07	1.85E-08
304L	2.31E-01	1.32	1.25E-06	6.05E-08
316LN-XHV	1.97E-04	0.84	8.66E-08	1.25E-08
316LN-ESR	5.26E-03	1.03	4.05E-07	3.79E-08
316LN-ESR-XHV	1.97E-02	1.20	3.04E-07	1.90E-08
Al	1.93E-02	1.03	1.52E-06	1.43E-07



Mild Steel. The mild steel or low-carbon steel outgassing rates has been measured by Park *et al.* (2014),[1] They chose 3 grades of mild steel for their study, as given in the table below. We summarize their measurements in this section.

TABLE I. Materials tested in this study were low-carbon steels ($0.1 \leq C \leq 0.2$ wt. %). Listed are three impurity elements that are relevant to vacuum outgassing.

Material (Korean standard)	Shape	Recommended service	Impurities (wt. %) C	P	S	Equivalent grades
D3752	Round Bar	Machine structural use	0.2	0.021	0.007	AISI 1020 JIS G 4051 (S20C)
D3507	Pipe/ Plate	Ordinary piping	0.1	0.008	0.004	ASTM A53 Gr. A JIS G 3452
D3562	Pipe/ Plate	Pressure service	0.09	0.01	0.012	ASTM A53 Gr. A JIS G 3454 STPG370
STS304	Pipe/ Plate	Structural use General purpose	0.08	0.045	0.03	AISI 304

For H_2 outgassing, they measured the outgassing rate of the material without heat treatment and with a 850 °C vacuum fire. The results are summarized in the table below. Note that that [Pa m^3 s^{-1} m^{-2}] =(1/10)* [Pa L s^{-1} cm^{-2}] = (1/133)×[Torr L s^{-1} cm^{-2}]. For D3507, unbaked, the outgassing rate is 3.1×10^{-13} Torr L s^{-1} cm^{-2}, about 10 times worse than the present LIGO.

TABLE II. Total outgassing rates (H_2 equivalent) after bakeout. *d*, thickness of the chamber.

Material	Sample no.	*d* (mm)	Preheat treatment	*In situ* bakeout	*q* (Pa m^3 s^{-1} m^{-2})	Comments
D3752	1	10	—	150 °C, 48 h	2.6×10^{-10}	
			850 °C, 12 h	150 °C, 48 h	8.8×10^{-11}	
		8	—	150 °C, 48 h	6.3×10^{-11}	After honing[a)]
			850 °C, 12 h	150 °C, 48 h	6.2×10^{-11}	
D3507	3	5	—	150 °C, 48 h	4.1×10^{-10}	
			850 °C, 12 h	150 °C, 48 h	6.8×10^{-11}	
D3562	4	5	—	150 °C, 144 h	1.4×10^{-10}	
			850 °C, 12 h	150 °C, 48 h	7.8×10^{-11}	
	5	5	—	150 °C, 48 h	1.0×10^{-10}	
			850 °C, 12 h	150 °C, 48 h	7.2×10^{-11}	
STS304	6	3.3	—	150 °C, 48 h	5.1×10^{-9}	

The water outgassing rates of mild steel without the 850 °C vacuum fire are about 3-10x worse than those of 304L stainless steel. With the vacuum fire, the water outgassing rate significantly improves, as shown below.

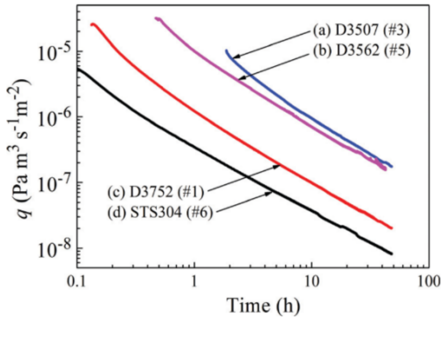


FIG. 3. (Color) Total outgassing rates (N_2 equivalent) during pump-down without a high temperature heat treatment. Outgassing was measured at 24 °C after 48-h *in situ* bakeout followed by a 5-h N_2 exposure.

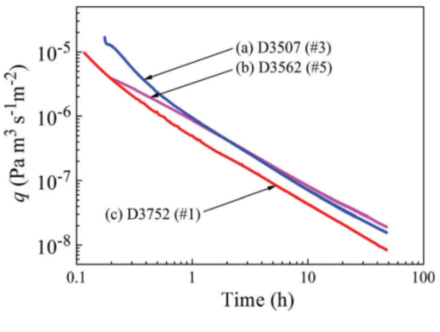


FIG. 4. (Color) Total outgassing rates (N_2 equivalent) during pump-down: after annealing for 12 h in vacuum at 850 °C. Outgassing was measured at 24 °C after 48-h *in situ* bakeout followed by a 5-h N_2 exposure.

[Above figures and tables from C.T. Park, et al, JVST A34, 021601 (2016), Ref. 1]

Outgassing Rate of Coated Surfaces

***Amorphous Silicon* (a-Si).** Unpublished data from the manufacturer's website suggests a factor of 9 improvement on water outgassing during the first 80 minutes for a-Si coated stainless-steel chamber compared to uncoated. The outgassing rate of a stainless-steel chamber coated with a-Si and baked 30 hours at 90 °C was measured to be 2.3 × 10^{-12} Torr L s^{-1} cm^{-2} by the JLab group [3]. Significant improvement was noted by these authors as the stainless-steel chamber was first subjected to a 400 °C heat treatment. These results are summarized below. As seen, a good outgassing rate is obtained if a bake of 150 °C or above for water removal is first applied, but the measured H_2 outgassing is still a factor of 2 to 3 above that of LIGO. More work should be done to conclude if an a-Si coating yields a sufficient H_2 outgassing rate, and if the water outgassing characteristics are significantly improved. In addition, the cost of applying this coating and other properties of the resulting surface that are important for Cosmic Explorer applications need to be evaluated (i.e., optical properties, mechanical toughness, and particulate generation).

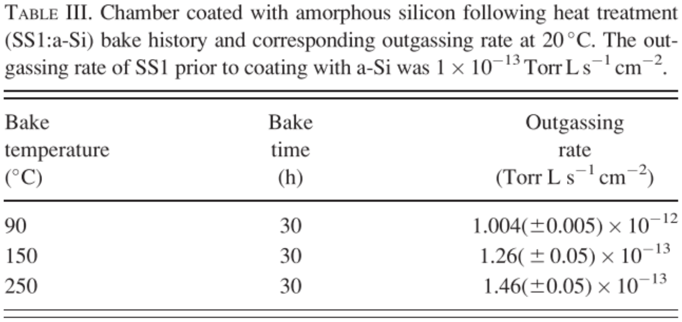


TABLE III. Chamber coated with amorphous silicon following heat treatment (SS1:a-Si) bake history and corresponding outgassing rate at 20 °C. The outgassing rate of SS1 prior to coating with a-Si was 1×10^{-13} Torr L s^{-1} cm^{-2}.

Bake temperature (°C)	Bake time (h)	Outgassing rate (Torr L s^{-1} cm^{-2})
90	30	$1.004(\pm 0.005) \times 10^{-12}$
150	30	$1.26(\pm 0.05) \times 10^{-13}$
250	30	$1.46(\pm 0.05) \times 10^{-13}$

[Table from M. A. A. Mamun et al, JVST A32,021604,(20140, Ref.3]

TiN coating. The water outgassing of TiN coated stainless steel chambers was measured to be 6.0 × 10^{-11} Torr L s^{-1} cm^{-2} at 10^4 s, and 6.0 × 10^{-12} Torr L s^{-1} cm^{-2} at 10^5 s by Saito et al. [2]. P. He, et al. [19] found a modest 15%-30% improvement in outgassing of coated stainless steel with a 450 °C heat treatment. The JLab group measured an H_2 outgassing rate of 6.3 × 10^{-12} Torr L s^{-1} cm^{-2} for stainless steel with no heat treatment but baked at 90 °C for 30 hours [3]. They suspected that the TiN coating may have had a small pumping speed, and this accounts for the apparent small outgassing. Akimichi and Hirata [20] also measured an extremely low outgassing rate of 1 × 10^{-13} Pa m^3 s^{-1} m^{-2}, but this was for a 316L vacuum re-melt chamber that already had an extremely low outgassing rate before the TiN coating. More work needs to be done to see if the TiN coating actually reduces the outgassing rate of un-treated chambers.

Diamond-like Carbon (DLC) coating. Takahashi et al. [9] measured outgassing rates from an unbaked DLC coating of, 1.9x10^{-11} Torr L s^{-1} cm^{-2} after 10 hours and 3.0x10^{-12} Torr Ls^{-1} cm^{-2} after 50 hours, as can be seen in the figure below. This is excellent, about two orders of magnitude better than stainless steel surfaces. There does not seem to be information on the H_2 outgassing rate of this surface. However, their numbers imply that the H_2 outgassing rate at 50 hours is less than 3.0x10^{-12} Torr L s^{-1} cm^{-2}, or 4.0x10^{-10} Pa L s^{-1} cm^{-2}, which is better than unbaked stainless steel (see above table and histogram).

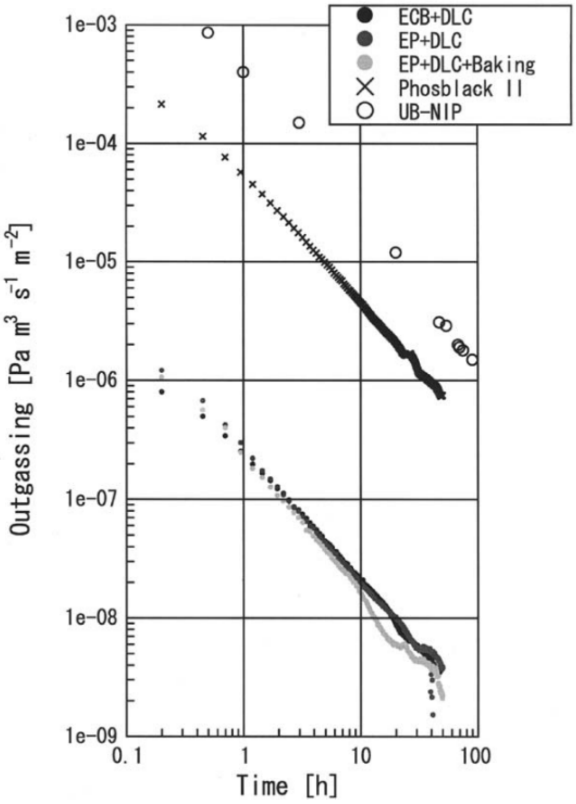


Fig. 1. Measured outgassing rates of various black surfaces.

[Figure from Reference 9]

Recommendations and Action Items

NIST (Fedchak) has offered to perform outgassing tests on additional chambers, specifically a DLC-coated chamber, a mild steel chamber (using a particular alloy to be determined from a low carbon or some type of grain-refined mild steel), and a chamber coated with TiN. These tests would be an extension of the outgassing work that NIST has previously done (as reported above and is scheduled for near term publication).

LIGO will investigate funding for test chambers and coatings. In feedback from the chamber supplier to NIST, the vendor mentioned a reluctance to manufacture a mild steel chamber in their stainless steel fabrication facility. This is due to the potential for contamination of the tools and raw stock used for stainless steel fabrications. This contamination is Fe transfer from mild steel to stainless steel, which causes corrosion. Typically called carbon contamination (misnomer), the “free iron” transfer causes rust spots on stainless steel surfaces.

A magnetite (Fe_3O_4) conversion coating was considered worth investigating. This coating is typically applied to steel and stainless steels using a wet-chemical process. For steel it improves corrosion resistance and produces a matte black surface. Due to the potential for corrosion of a mild steel beamtube, a magnetite type coating was raised for consideration. It was suggested that the mild-steel chamber be conversion coated following as-received testing. This option will be added to the NIST outgassing testing list.

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Working Group 4 Report: Vacuum pumping for conventional and nested systems

Co-Chairs: Yulin Li (Cornell) and Paolo Chiggiato (CERN)

Charge

Consider vacuum pumping schemes and pumping scenarios for obtaining UHV conditions within the beamtube enclosures keeping in mind concerns for maintaining differential pressures within nested vacuum system solutions.

Summary

The Working Group 4 (WG4) convened to discuss vacuum pumping for the Cosmic Explorer's (CE) 40-km beamtubes. The pumping system was considered for two CE beam tube designs, i.e. a conventional single wall tube similar to the one of LIGO as considered by during this workshop by WG1, and a nested double-wall tube as presented by Rainer Weiss [1] and further considered by WG2. There are three phases of vacuum pumping to be considered: 1). Roughing phase to evacuate atmospheric gas; 2). Bake-out phase to remove several monolayers of water from inner walls; 3). Steady-state phase to maintain UHV conditions required for physics runs, namely in average $P_{H2O}<10^{-10}$ Torr and $P_{H2}<10^{-9}$ Torr. The goal of the discussion was to give guidelines for the choice of the pumping system, taking into account cost reduction, operational efficiency, reliability and margin for each of the pumping phase.

Pump-down process

Roughing phase

Generalities

Given the reasonable design assumption of large gate valve incorporation able to withstand one bar differential pressure, the 40-km long beamtubes can be sectorized in four 10-km long segments; each of them pumped down separately. The process would bring the tube segment from atmospheric pressure down to a few 10^{-2} Torr (roughly a factor 10 above the ultimate pressure of the pumps). We consider limiting pressures to this range to be a precaution with respect to the risk of gas back-streaming and contamination. An accidental 'hydrocarbon' contamination of the tube walls would be very difficult to recover by the foreseen mild bake-out, and it appears as one of the major risks to be prevented.

The time duration of the evacuation should not be a critical parameter; one-week long pumping, for instance, could be acceptable. For the nested tube design, the following requirements will have to be considered:

- The inner cylinder should be kept permanently at a slightly higher pressure than the outer one. The first reason is purely mechanical: the inner cylinder could suffer buckling at a quite low differential pressure, potentially at < 1 Torr depending on the detailed design. In addition, it is important to ensure that the inner tube does not become contaminated by gases desorbed from the outer pipe.
- The same constraints would apply for the venting process.
- Pumps able to manage a relatively high load of water vapor should be adopted in case of use of multilayer thermal insulation in the inner space between the two vacuum pipes.

Equipment choice and procedures

Single wall design: Different options could be evaluated for the choice of pumps:

- several dry pumping systems (20 to 40 units) could be connected to the beam tube by gate valve ports spaced at 250-m to 500-m intervals;
- just two units providing large throughput could be used, since the spacing of pumps has relatively low importance in this phase. For example, roots pumps with pumping speeds of the order of 1000 m^3hr^{-1}, backed by proper dry pumps, could be used.

A series of suitable pressure gauges will monitor the pressure gradient over the tube length. An interlock system will provide the immediate isolation of each pump in case of faults and or loss of power.

Maintaining differential pressures in the nested tube design: In the nested tube design, inner tubes and outer tubes may be connected via 'soft annular' valves installed at 2 km interval as proposed by Weiss. During the roughing phase, these valves will be kept in open position to allow the simultaneous evacuation of the two volumes. The requirement is to avoid gas flux mixing and to maintain a given overpressure in the inner pipe over its entire length (the allowed overpressure range needs to be determined).

A similar procedure is being applied for the evacuation of the Virgo 'towers' that include two contiguous compartments separated by a relatively thin Kapton™ membrane. In this case the allowed overpressure is a few mbar.

The geometry of the annular valves and the size and position of pumps need to be optimized with a computational fluid dynamics (CFD) study, simulating the gas flow distribution in the system by accounting for the different volume and gas impedance of the two coaxial vessels. Should it turn out not to be practicable to meet the requirements, the other option would be to pump the two volumes separately, controlling actively the differential pressure (i.e. with a positive pressure of a few mbar in the inner pipe). Note that normally there will be no strict mechanical constraints to have the inner tube at relatively higher internal pressure.

Subjects to be researched and analyzed

Single wall tube: A relatively large leak would delay the pump-down and it would not be easily localized in viscous and transition regime flow. All welds should be fully qualified in advance via the proven method already developed by LIGO; a similar pre-qualifying procedure should also be studied for the several 'minor' flanged joints (for location of pumps, gauge, etc.).

Nested tube system: the inner pipe would be mechanically vulnerable to an accidental gas inlet in the outer vessel (for instance due to a failure of a mechanical pump or to an improper operation during the mechanical evacuation phase). A venting setup could be automatically operated in case of such 'emergencies' to increase the inner pipe pressure.

Intermediate phase and bake-out

Intermediate

In this stage the 10-km long segments should be broken down further to 2-km long sections by means of closing the 'soft gate' valves or a shutter mechanism that would limit conductance. The shorted sectors simplify the process control; allow a reduction of necessary equipment (movable from one section to another); and reduce the electrical power needed for the bake-out.

The considered option is to make use of portable turbo-molecular pumping groups to evacuate the tubes from the 10^{-2} Torr down to the 10^{-5} Torr range, draining the residual air and getting the tubes into regime limited by the 1/t water outgassing. Hybrid turbos are an option. They can provide pumping speed higher than 1000 Ls^{-1} and are able to start working at 0.1 Torr inlet pressure. Magnetic bearing suspension should be preferred for cleanliness reasons.

For the nested tube case, the 'soft annular' valves are kept open and both chambers are evacuated by the same pumping groups. As an alternative, the two volumes could be pumped independently. The CFD study will help to support the final choice.

Bake-out

Once the pressure is in the 1/t regime, the bake-out process can commence. For the single wall tube, it shall be convenient to exploit its large conductance and use high pumping speed pumps for water vapor. Cryopumps may be used for such a service, size DN 250 mm, with typical nominal pumping speed larger than 4000 Ls^{-1} for water vapor, as already experienced by LIGO. For the nested case, large ion pumps and distributed NEG (ZAO type operated around 200°C) would be a valid option in combination with or in alternative to cryopumps. Simulations in the latter pumping configuration were also presented by Weiss [1]. In both cases it will be advantageous to have the 'soft gate' valves closed to limit the processed tube length, reducing the amount of pumping and heating equipment that will have to work concurrently and easing a trouble-free conclusion of the bake-out.

Pump spacing and other parameters

The process parameters are temperature, time duration, and pump spacing. The water load on surfaces will be given depending on choices of materials and conditioning treatments. The Weiss model [2] for water outgassing should be the main tool used to evaluate the best tradeoff for the design in order to attain the desired water outgassing rate (nominally < $1x10^{-15}$ Torr $Ls^{-1}cm^{-2}$) since it has been benchmarked with LIGO performance. The choice of the baking temperature will require iterations concerning the design of the tube structure, the location and speed of the pumps, the design of the baking system and the pre-conditioning of the beam pipes.

The pump spacing should be driven by the necessity to limit the peak water partial pressure; probably a reduced pump interval (250m for instance) will be needed in the case of the choice of a lower bake-out temperature. Finally, the time duration would probably be less critical provided its compatibility with the overall project schedule.

Some considerations

The ports used for connecting pumps during the bake-out could be equipped with valves with Viton™ seals on gates for reliability reasons and for reducing the cost. Once the baking is finished, the valves should be closed with blind flanges and kept unused. Because of a possible threat of leaks in the long-term operation, the number of pumping ports should substantially more than the minimum needed in the optimum situation as prescribed by simulations. During the baking process it should be possible to monitor the level of the organic contaminants present among the residual gases; the time duration of the baking process should be driven also by their evolution.

NEG – ZAO management during bake-out

ZAO based pumps [3] can be used during the bake out thanks to their high capacity for hydrogen, water vapor and other active gas species compared to standard SAES NEG alloys used in vacuum systems (e.g. St707™ and St172™). There are advantages in using such NEG pumps during bake-out, in combination with sputter ion pumps. As passive pumps with no moving parts, ZAO-based NEG pumps have no risk of releasing contaminations in cases of loss of vacuum accidents and power outages; therefore, they do not need isolation valves. In addition, thanks to their limited costs, they can be more tightly distributed along the tube ensuring a more efficient pumping than cryopumps or turbomolecular units.
In order to use the ZAO pumps during the bake-out, the following procedure must be considered:

- Roughing down the system to less than 10^{-2} Torr by auxiliary pumping system.
- Ramp up the NEG activation temperature in 30 minutes.
- Keep the activation temperature at 550°C for 3 hours.
- At the end of the activation, keep the ZAO pump temperature at 150~200°C throughout the baking.

The pressure to start NEG activation and the working temperature after the activation can be tuned depending on the geometry of the pump and the gas load. This family of pumps can be implemented in the nested tube solution as well as in the single tube approach. Being a passive pump, the ZAO pumping system offers an important advantage with respect to the other pumps; it works even if electrical power is off. More studies should be conducted to better clarify if this aspect is an advantage for use with the Cosmic Explorer conditions.

In figure 3, a comparison of the pumping speed versus sorbed gas quantity of the SAES CapaciTorr™ HV200 at room and 200°C working temperature is shown.

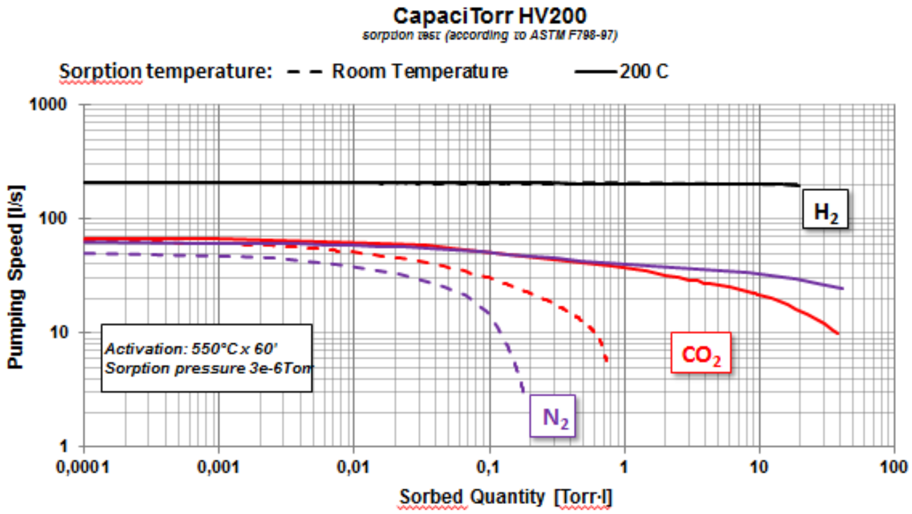

Figure 3. Pumping speed versus sorbed quantity of CapaciTorr™HV200 at room temperature and 200°C. (data courtesy SAES)

LN$_2$ panels

A possible upgrade of the current cryopump models used at LIGO and Virgo (LN$_2$ bath panels pumping water vapor) could enable them to also pump N$_2$, O$_2$, and Ar coming from the 'optics chambers' (from materials, leaks, permeation, etc.). This would shorten the recovery after optic chambers maintenance interventions (venting) and possibly improve the vacuum level in the beam tubes. Such an upgrade could be perhaps realized by adding a colder section working with Ne-He cycles or adsorbent materials (able to work at 77K).

Pumping for Steady-State Operations

Ideal steady-state operations

After a proper pump down and a bake-out, the outgassing rate from interior walls (in single beam tube and nested beam tube designs) is expected to be very low, of the order of 10^{-15} and 10^{-14} Torr·L/s·cm^2 for H_2O and H_2, respectively. Simulations showed that pumps of pumping speed of 1000 L/s spaced at 1-km intervals are sufficient to maintain the required UHV conditions for the beam tubes, namely average partial pressures less than 10^{-10} and 10^{-9} Torr for H_2O and H_2, respectively. In the ideal steady-state operation, it is assumed that these limiting pressures can be obtained both with a single wall design pipe free of air leaks, or a nested pipe design with sufficiently low annular pressure (less than 10^{-8} torr).

Single wall beam tube design

NEG pumps are suitable for the steady-state operation. ZAO-type NEG pumps have very large pumping capacities for H_2 and H_2O to handle years of operation without re-activation. The yearly gas loads are relatively minor (of order of magnitude of 10 Torr-L per year per km for H_2, and ten times lower for H_2O) when compared to NEG gas capacities. For instance, the UHV1400™ module from SAES (1360 L/s for H_2 and similar for H_2O) has a single-run capacity of 7200 Torr-L for H_2 and likely at least 10 Torr-L for H_2O. The high vacuum version of the pump, HV800™ delivers 10,500 Torr-L for H_2 and some hundreds of Torr-L for H_2O. Therefore, the hydrogen capacity does not need to be regenerated and the pumps should be reactivated every few years to refresh the water capacity. As usual, auxiliary ion pumps should be installed to pump traces of noble gases and methane. The distance between the pumps would depend on potential sources of such gases that should be attentively quantified.

Nested beam tube design

The pumping in the inner tube can have a similar configuration as in the single wall design, though implementation of the NEG pumps requires significantly more design work.

Relatively large gas loads to the annular space is expected, from either the unbaked outer tube and air leaks. If the total gas load could be limited to less than 10^{-4} Torr L/s/km, 2000-L/s, ion pumps every km would produce an annular pressure on the order of 5 x 10^{-8} Torr. However, pressure profiles in the annular space must be analyzed in detail to understand the impact of very high pressure 'bumps' between ion pumps taking into consideration of the thermal radiation shield. Therefore, the required conductance limitation of 1 L/s from annular space to inner tube would produce a gas load of 5 x 10^{-8} Torr L/s/km inside the innermost region, which is equivalent to the water vapor outgassing rate of the baked inner tube.

Pumping with contingencies

For long-term operations, various contingency situations must be taken into account such as small leaks or dry-air venting of the beam tubes (with no subsequent baking). More closely spaced pumps (less than 1 km) should be included, especially considering that the pumping system constitutes only a relatively small portion of the facility costs.

Titanium sublimation pumping (TSP) may be considered as a lower cost option for distributed getter pumping for handling contingencies. The unique feature of the LIGO beam tubes is the availability of a large interior surface for deposition of Ti thin films. For H_2O pumping, TSP can provide very high pumping speed with comparable pumping capacity to NEG pumps. For instance, 1-m^2 of Ti film can provide H_2O pumping speeds of 70,000 L/s with a single-run capacity of 10 Torr·L [4]. In contrast to the NEG re-activation process, re-deposition of a Ti film is a much faster process (minutes vs hours) and produces much less pressure excursions to the vacuum system. Long-term operations of TSPs had been successfully deployed in particle accelerators, such Fermi Lab and CESR [5, 6]. Optimal integration should be studied for the CE project. The long-term risk of dust production must be experimentally assessed.

Vacuum Instrumentation

Distributed vacuum gauges (100 to 250-m interval) should be installed to monitor the pressure profile in the beam tube and provide means to localize leaks.

Conclusions

The Working Group 4 has proposed a strategy for the pumping of the 40-km long beam tubes of the CE. The pumping process leading to the required pressures has been subdivided in three phases: pump down, bake-out and steady state operation. For each of them there is no showstopper; a choice of pumps based on previous experience has been presented. However, some crucial points should be investigated in detail:

- The needed pumping speed depends on the outgassing rate, which in turn depends on the effectiveness of the bake-out and material choice. Today, the effect of the bake-out is based on positive experiences of LIGO and Virgo. Dedicated simulations and experimental validation are an important step to validate the new chosen tube design and the global pumping scenario. The outgassing properties of the chosen materials should be reliably measured after different surface treatments.
- The pump down in the nested tube approach needs special attention to avoid buckling of the aluminum liner. Dedicated calculations are recommended.
- The NEG pumping configuration and properties should be optimized for the specific case of the CE's beam tube. The integration in the nested tube has to be evaluated in detail.
- A deeper functional and cost analysis of the Ti sublimation pumps should be tackled.

References

1. R. Weiss, "*A preliminary study of the vacuum system for the beamtubes of the Cosmic Explorer*", January 2019, presented at this workshop, LIGO Document T1900023-v1.
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5. N. B. Mistry, *et at*, "*Massive titanium pumping in the CESR interaction region*", *Proceedings of the 1997 Particle Accelerator Conference*, Vancouver, B.C, (IEEE, New York,1997) p.3559

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Workshop Conclusions and Recommendations

The workshop participants were confident that technical solutions could be developed that would have non-trivial impact on the cost of the design, construction and life-cycle operation of vacuum systems for the proposed next generation gravitational wave observatories. The two potential projects being discussed presently by the gravitational wave community are the Cosmic Explorer in the U.S. and the Einstein Telescope in the EU. Both projects incorporate interferometer arms with UHV-quality vacuum enclosures that are 10-40 km in length — up to an order of magnitude larger than the present generation of gravitational wave detectors.

Two classes of solutions for the vacuum enclosures were examined: the first design concept is an extrapolation of the single-wall vacuum pipe in use in the present generation of detectors (at LIGO, Virgo, and KAGRA). The second design concept involves double-walled or nested vacuum pipes that would separate the atmospheric load problem from the stringent UHV properties needed for the inner wall. Vacuum pumping solutions and surface treatments were examined for both concept designs with an emphasis on potential hardware and treatments that could lower total costs but still meet the stringent vacuum, vibration, particulate and optical characteristics required for next generation gravitational wave detectors.

Conclusions

- Both design concepts (single-walled and nested vacuum pipes) should be carried to the next level of detailed design, engineering and cost studies. The workshop identified no serious issues that would disqualify either design concept at this early stage.
- For the single-wall vessel, two other additional materials should be considered for the vessel: a low carbon, mild steel alloy and aluminum, in addition to keeping the stainless steel as the comparison material based on the experience of first-generation installations. Both the mild steel and aluminum could offer significant cost savings. A number of concerns are raised for further study in the workshop report to quantify realized costs in a final system. These include choice of the mild steel alloy, potential surface treatments or coatings for the mild and stainless steel and the aluminum alloy, and the cost of incorporating the many transition elements (flanging and expansion joints) if aluminum is chosen as the base vessel material.
- For the nested vessel concept: aluminum is considered as the baseline material for the inner vessel because of the ease of in-situ bake out and the slightly better water adsorption characteristics compared to stainless steel. For the outer vessel material: the use of mild steel and a number of polymer composites were considered and both options for the outer vessel should remain under consideration during the initial design phase.
- In order to minimize the cost of in-situ bake out systems for removal of adsorbed water following the initial or subsequent exposure to air, a number of potential surface coatings were identified for stainless and mild steels including TiC, diamond-like carbon (DLC) ,amorphous Silicon (a-Si) and a class of conversions coatings such as magnetite (Fe_3O_4) that could be applied during the mill processing of the steel (so-called conversion coatings). A number of characteristics of these coatings were identified for further study before their cost effectiveness could be quantified including additional H_2O adsorption studies, coating deposition costs at scale, film toughness, particulate generation, interference with vessel welding, and optical characteristics.

- Viable first order pumping schemes were offered for both vacuum vessel concepts. Specific pump-down routines were identified from atmospheric pressure to UHV using pumps that would minimize or eliminate hydrocarbon or particulate contamination. The continued use of large area liquid nitrogen panels was recommended based on the high-water pumping speed and satisfactory performance in current generation systems. UHV performance can be maintained with periodically spaced getter pumps and ion pumps. The availability of the new getter alloy from SAES (ZAO) is particular useful for this application because of its large pumping speed and capacity for H_2O and H_2 . in addition, conventional titanium sublimation pumps (TSP) are not ruled out for consideration.

- The use of clean, ultra-dry (ppb water), warm gas purging systems could significantly affect the need for in-situ bake-out systems for removal of adsorbed water following the initial or subsequent pump-downs from atmospheric pressure. The incorporation for such systems for LIGO and the other first-generation gravitational wave observatories can significantly shorten downtime in the event of a loss-of-vacuum incident.

- The value of partnerships with industrial contractors with relevant expertise was demonstrated the successful design, installation and operation of the LIGO vacuum vessels (and similar partnerships are evident at Virgo and KAGRA). Such partnerships can be valuable in the pre-competitive phase to test the viability of concepts proposed in this workshop and they are certainly valuable in the final design and early constructions phases to test prototypes of full vessel segments.

Recommendations

- The two identified vessel schemes (single walled and nested) should be carried further to quantify the potential cost of construction, installation and operation at scale .
- A series of materials and surface studies should be undertaken to examine particular mild steel alloys and aluminum fabrication techniques that could be most advantageous and cost effective for gravitational wave detector vacuum vessel designs. (Specific recommendations on material, studies and surface treatments are given in the recommendation sections of the workshop working group reports.)
- The gravitational wave observatory community should take advantage of the offers from workshop participants from NIST, JLab and CERN to investigate the H_2O adsorption/desorption characteristics of the several potential surface coatings identified by the surface treatment working group (TiC, DLC, a-Si and conversion coatings).
- Recommendations for specific pump placements for either vacuum vessel concept would be dependent on vacuum model calculations based on more detailed vessel designs when available later in the design phase.
- Workshop participants recommend that a follow-up workshop with similar participation would be advantageous to take advantage of this group‘s expertise for guidance on continuing design studies and related tests. The Fall of 2019 is a suggested timeframe for the next workshop.
- A recommended goal for the next workshop is the layout of a research agenda for short term research projects that would focus on quantifying the cost-benefit of materials choices and surface treatments identified in this workshop.

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We acknowledge the active participation of all of the attendees during the Workshop and appreciate the efforts of our colleagues who travelled from Europe and Japan to participate. We give special acknowledgement to the Working Group Co-Chairs for their contributions, both during the workshop and afterwards with their input to this summary report.

Appendix A:

Participant List for the NSF Workshop on Large Ultrahigh Vacuum Systems for Frontier Scientific Instrumentation, LIGO Livingston Site, Jan. 28-31,2019

Attendee	Affiliation
Curtis Baffes	FNAL
Alex Chen	FNAL
Paolo Chiggiato	CERN
Bob Childs	MIT PSFC
Dennis Coyne	LIGO Caltech
Fred Dylla	AIP (retired)
James Fedchak	NIST
Jon Feicht	LIGO Caltech
Joseph Giaime	LIGO Livingston
Daniel Henkel	Henkel Consulting
Hsiao-Chaun (Dick) Hseuh	BNL
Albert Lazzarini	LIGO Caltech
Yulin Li	Cornell University
Yev Lushtak	Cornell University
Enrico Maccallini	SAES
Dennis Manos	William & Mary
Scott McCormick	LIGO Livingston
Gerardo Moreno	LIGO Hanford
Dave Morrissey	MSU
Tetsuro Nakamura	MiraPro
John Noonan	ANL
David Ottoway	Adelaide University
Richard Oram	LIGO Livingston
Harry Overmier	LIGO Livingston
Antonio Pasqualetti	Virgo
Matt Poelker	Jefferson Lab
Tommaso Porcelli	SAES
David Reitze	LIGO Caltech
Fulvio Ricci	Virgo
Chandra Romel	LIGO Hanford
Yoshio Saito	KAGRA
Bruce Strauss	DOE
Tom Swain	VAT
Ryutaro Takahashi	KAGRA
Martin Tellalian	McDermott
Takayuki Tomaru	KEK
Rainer Weiss	LIGO MIT
Michael Zucker	LIGO MIT

Appendix B: Agenda for NSF Workshop on Large UHV Systems for Frontier Scientific Research

DAY 1 – January 29, 2019

Start Time	Session Title	Speaker – Affiliation
8:00 AM	*Coffee*	
9:00 AM	**Introduction & Background**	
9:00 AM	Welcome	D. Reitze – LIGO
9:10 AM	Visitor safety briefing	R. Oram – LIGO
9:15 AM	Workshop goals	F. Dylla – AIP
9:25 AM	Vacuum Requirements for GW Interferometers	M. Zucker – LIGO
9:55 AM	*Discussion*	
10:00 AM	**Existing GW Interferometer Vacuum Systems**	
10:00 AM	KAGRA	Y. Saito – KAGRA
10:30 AM	*Discussion*	
10:40 AM	*Coffee*	
10:55 AM	Virgo	A. Pasqualetti – Virgo
11:25 AM	*Discussion*	
11:35 AM	LIGO	M. Zucker – LIGO
12:05 PM	*Discussion*	
12:15 PM	***Lunch***	
12:45 PM	*Lab Tour*	LLO Staff
2:15 PM	**Blue Sky Brainstorming: Options & Opportunities**	
2:15 PM	Example Cosmic Explorer concept illustrating key questions	R. Weiss – LIGO
2:35 PM	*Discussion*	
2:40 PM	Nested systems	J. Noonan – ANL
2:50 PM	*Discussion*	
2:55 PM	Comparative outgassing of XHV materials	J. Fedchack – NIST
3:05 PM	*Discussion*	
3:10 PM	Outgassing of prebaked and optically black materials	M. Poelker – Jlab
3:20 PM	*Discussion*	
3:25 PM	Outgassing of 304LN vs. cold-rolled carbon steel	F. Dylla – AIP
3:35 PM	*Discussion*	
3:40 PM	*Coffee*	
3:55 PM	Compact UHV optical vacuum gauge concept	J. Fedchack – NIST
4:05 PM	*Discussion*	
4:10 PM	Accelerator experience with Al alloy vacuum systems	Y. Li – Cornell
4:20 PM	*Discussion*	
4:25 PM	Experience & concerns with microbial-induced corrosion of SS	D. Henkel – Rimkus
4:35 PM	*Discussion*	
6:00 PM	**Day 1 Adjourn**	

DAY 2 – January 30, 2019

Start Time	Session Title	Speaker – Affiliation
8:00 AM	*Coffee*	
9:00 AM	Distributed getter pumping for very long vacuum systems	Y. Lushtak – Cornell
9:10 AM	*Discussion*	
9:00 AM	New NEG configurations and formulations	E. Maccallini – SAES
9:10 AM	*Discussion*	
9:15 AM	Options to improve vacuum performance of existing LIGO tubes	J. Noonan – ANL
9:25 AM	*Discussion*	
9:30 AM	Sharing technical risk with industrial partners	M. Tellalian – CBI
9:40 AM	*Discussion*	
9:45 AM	Black coatings	Tomaru – KAGRA
9:55 AM	*Discussion*	
10:00 AM	DLC Coatings	Takahashi – KAGRA
10:10 AM	*Discussion*	
10:15 AM	**Working Group Organization and Charters**	F. Dylla – AIP
10:45 AM	**Working Group Morning Session (2 concurrent groups)**	
10:45 AM	WG1: Cost reduction options for conventional beamtube technology	C. Baffes – FNAL D. Henkel – Rimkus
12:45 PM	WG2: Non-conventional pipe technology	J. Noonan – ANL D. Manos – CWM
12:45 PM	***Lunch***	
1:30 PM	**Working Group Afternoon Session (2+ concurrent groups)**	
1:30 PM	WG3: Novel surface treatments for conventional and non-UHV materials	J. Fedchack – NIST J. Feicht – LIGO
3:30 PM	WG4: Pumping for conventional and nested system	Y. Li – Cornell P. Chiggiato – CERN
3:30 PM	WG5: TBD	TBD
3:30 PM	*Coffee*	
3:45 PM	**Working Group Crosslinks and Preliminary Reports**	F. Dylla – AIP R. Weiss – LIGO
5:00 PM	**Day 2 Adjourn**	

DAY 3 – January 31, 2019

Start Time	Session Title	Speaker – Affiliation
8:00 AM	*Coffee*	
9:00 AM	**Working Group Reports (cont'd)**	F. Dylla – AIP
11:00 AM	*Coffe and Group Photograph*	
11:15 AM	**Future work prioritization, key recommendations, & writing assignments**	F. Dylla – AIP M. Zucker – LIGO
12:15 PM	***Lunch***	
1:00 PM	**Workshop wrap-up & free discussion**	F. Dylla – AIP M. Zucker – LIGO
2:00 PM	**Day 3 Adjourn**	