Summary of the Beamtube Workshop 3 held at LIGO Hanford,

Sept. 30-Oct.3, 2025

M. Zucker, F. Dylla, and Paolo Chiggiato, Co-Chairs

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This workshop was the third in a series that began in 2019 to investigate the scientific and technical problems associated with the design, fabrication and operation of the large, multi-kilometre long, large diameter (~1m) ultrahigh vacuum beamtubes that are required for the present generation and next generation gravitational wave observatories.

Dedication to Professor Rainer Weiss

The existence of the founding generation of gravitational wave observatories (LIGO, Virgo and KAGRA) would not have been possible without the inspiration and dedication of Professor Rainer Weiss. The community lost this brilliant and very personable pioneer of this field of scientific endeavour with his death in August of 2025. One of the workshop organizers, F. Dylla had the privilege of meeting Prof. Weiss when he began his undergraduate studies at MIT in 1967. Dylla opened the workshop with a brief remembrance of Prof. Weiss and dedicated the results of the workshop to his memory.

Context for the Gravitational Wave Observatory Beamtube Workshops

The first workshop in this series, entitled "*NSF Workshop on Large Ultrahigh Vacuum Systems for Frontier Scientific Research*" (P1900072), was held in January 28-30, 2019 at the LIGO Livingston Observatory. It was attended by ~ 40 participants from all the existing gravitational wave observatories (LIGO, Virgo, and KAGRA) with supporting vacuum experts from accelerator laboratories and industry in the US and Europe. The workshop was organized by M. Zucker (LIGO and F. Dylla (LIGO Consultant) and the workshop summary prepared by the two organizers is available on the LIGO archive site (P1900072). A useful addition to the program of the workshop was the inclusion of working groups that could analyse specific problems with a smaller group of participants with an open program to encourage "blue-sky" discussions. All the working groups provided specific action items for follow-up on key open items. The addition of working groups was incorporated in the two follow-up workshops.

It was the original intention to schedule the second workshop in the 2020–2021-time frame but the disruptions of the pandemic prevented this scheduling. In the mid-summer of 2021, a series of bimonthly teleconference calls were initiated and moderated by F. Dylla to continue these important discussions among the vacuum science and technology community. These calls included participants from CERN and groups in the US and Europe that were being organized to support early design studies for both the Einstein Telescope (ET) project in Europe and the Cosmic Explorer (CE) Project in the US. These teleconferences were hosted by CERN and continue a bimonthly basis since their inception. A summary of each teleconference prepared by F. Dylla with input from the presenters is archived on the CERN Indico site.

The second workshop in this series, entitled "*Beampipes for Gravitational Wave Telescopes 2023" was* held at CERN on March 27-29, 2023. This workshop was organized and chaired by Paolo Chiggiato. The workshop program continued to analyse the issues identified at the first workshop. Highlights included presentations by CERN participants and tours of on-going hardware projects that had been started at CERN to design and build prototype beamtube hardware for ET. This workshop also included working groups for more targeted discussions and formulation of specific action items for follow-up by the community. F. Dylla prepared an informal summary of the workshop which is available and archived on the LIGO archive site (P2400360-v1).

Outline of this Summary of the Third Beamtube Workshop

This document summarizes the key findings of the third beamtube workshop (BTW3) which was held on Sept. 30-Oct.2, 2025 at the LIGO Hanford Observatory site in Richland, Washington. site. The workshop was entitled "*Cosmic Explorer- Einstein Telescope Beamtube Workshop III*". It was organized and co-chaired by M. Zucker, LIGO, F. Dylla, LIGO and Paolo Chiggiato, CERN.

With the success of the follow-up on plans and action items that were delineated in the working groups from the first two workshops, the organizers also included working groups in this latest workshop. Two of the working groups followed similar topics as prescribed in the first two workshops: a working group on materials, vacuum properties and surface issues, and a second working group discussing design and fabrication issues of candidate beamtube designs. For this third workshop, the organizers decided to dispense with a working group on pumping and vacuum diagnostic issues (these being well in-hand) and designated the third working group in the Hanford BTW3 workshop to focus on the issue of the design, fabrication and installation of the critical light baffles that are needed in gravitational wave observatory beamtube designs to minimize scattered light.

The three Working Groups included in this third beamtube workshop were the following:

Working Group 1: *Materials, Surface Treatments and Outgassing*, co-chaired by Paolo Chiggiato (CERN) and Daniel Henkel (LIGO Consultant)

Working Group 2: *Design, Fabrication and Assembly*, co-chaired by Dennis Coyne, LIGO and Marco Marrone, CERN

Working Group 3: *Scattered Light Isolation and Baffles*, co-chaired by Matt Evans, MIT and Mario Martinez, IFAE, Barcelona

This report includes excellent summaries of all three Working Groups prepared by the respective Working Group chairs. Thus, there is no need to provide an overall summary of the workshop findings other than to set the following context for these detailed summaries.

At the start of the BTW 3, the situation with the design and selection of beamtubes could be summarized as the following:

Mild steel (and related alloys) are still viable candidates for beamtube materials. They have advantages in cost, manufacturing capability, and low H-content. The H_2O outgassing behavior is similar to the baseline material, 304L class stainless steels. Whether the installed beamtubes would require bakeouts at temperatures around 150C to remove absorbed H_2O is still a matter of study, but prudence at this point requires planning for 150C bakeout. Unfortunately, resistive bakeout is not possible because of the thickness of the proposed mild steel beamtubes. Ongoing studies at LIGO Caltech on travelling bakeout schemes and dry gas purge tests may lead to some cost advantages for bakeout systems, as well as the previous and potential new studies at multiple laboratories in this beamtube collaboration on possible passivation layers for mild steels.

Alternative beamtube designs are also well into prototyping based on thin-walled convoluted ferritic alloys. These designs have the advantage of lowering the materials cost of traditional thicker-walled ferritic alloys, long familiarity with the surface properties and adsorbed water degassing properties, and simpler and less costly bakeout systems. Ongoing work at CERN for the ET Prototype beamtubes and a planned beamtube protype at LIGO Hanford (the CEBEX project) will investigate the details and costs of beamtubes using this material and proposed fabrication schemes.

The addition of the third Working Group to this workshop to help integrate the design issues for beamtube baffles was a success. Their Working Group report (No.3) shows these issues are well in hand for both design and integration issues.

Acknowledgment: The organizers thank all the presenters for their active participations and the Working Group Chairs for their extra efforts in organizing and compiling their key findings. We also thank the LIGO Hanford Observatory staff for their superb hospitality and organizational abilities that led to a successful workshop. We also thank the NSF for funding the LIGO contributions and the CERN and ET organizations for supporting the ET presentations.

Content Outline:

Working Group 1: Materials, Surface Treatments and Outgassing

Co-Chairs: Paolo Chiggiato, CERN and Daniel Henkel, Consultant

Summary Report

The Working Group 1 activities brought together the teams of the Einstein Telescope (ET) and Cosmic Explorer (CE) to assess candidate materials, surface treatments, and processing paths for next-generation gravitational-wave detector beamtubes. The key objective is to meet ultra-high-vacuum (UHV) requirements while enabling scalable industrial production and minimizing lifecycle cost.

A strong and consistent outcome of the working group is the validation of ferritic stainless steels (FSS), in particular stabilized grades AISI 441 and 444, as highly promising beam-tube materials. Multiple measurements demonstrate hydrogen outgassing rates two to three orders of magnitude lower than AISI 304L, even without high-temperature vacuum firing. This performance is attributed to the intrinsically low hydrogen content of ferritic steels. Methane and CO outgassing rates are also significantly reduced. Welding studies confirm that stabilized FSS grades provide adequate mechanical properties and corrosion resistance, comparable to 304L, while avoiding martensitic transformation issues observed in AISI 430.

Mild (low carbon) steels were also shown to exhibit low hydrogen outgassing after appropriate bakeout. The benefit of surface conversion coatings such as magnetite remains unclear: while magnetite can reduce water outgassing at room temperature, it often degrades hydrogen performance after bakeout. At present, native oxide surfaces appear sufficient for vacuum performance, and further justification is required before adopting conversion coatings at ET-CE scale.

Corrosion studies highlight the need for environmental qualification, particularly with respect to stress corrosion cracking, residual welding stresses, and long-term exposure conditions. Salt spray tests alone are insufficient to represent realistic beam-tube scenarios; they give only comparison data with respect to the well-known AISI 304. Stabilized ferritic steels show improved resistance, but systematic validation remains necessary, and it is ongoing.

The working group also identified surface condition and roughness as dominant factors for water outgassing, largely independent of bulk material grade. This underscores the importance of controlled surface finishing, cleaning, and standardized characterization methods. Chemical wet cleaning is currently the most mature and scalable solution for large tubes; laser and plasma cleaning techniques show potential but require further development to address effective removal of organic contamination, particulate generation and process implementation at large scale.

Experience from LIGO confirms that black nickel and DLC coatings are acceptable for optical baffles, with DLC exhibiting the lowest outgassing rates. Coatings on beamtubes themselves, however, remain impractical at the required scale and introduce additional risks.

Finally, system-level measurements demonstrate that, in large installations, ancillary components (valves, gauges, instrumentation) can dominate the gas load and mask the intrinsic performance of ultra-low-outgassing tubes. Integrated system testing is therefore essential.

Overall, the Working Group concludes that ferritic stainless steels represent a credible baseline option for ET, provided that industrial scalability, environmental durability, permeability, and cost validation are addressed through coordinated follow-up studies. For CE, although AISI 304 appears to be the most immediate solution, low-carbon steels remain a potential alternative that should be further investigated.

Presentation Notes

Corrosion Study of Stainless Steels for ET, A. Gervasyev, Ghent University

Corrosion resistance of welded samples made of ferritic stainless steels proposed for the ET beam tube was tested in accordance with ASTM B117 Salt Spray. The welding techniques were TIG and laser). The behaviour of welded AISI 430 ferritic (non-stabilized) and 441 ferritic (should not be susceptible to sensitization) were compared to that of welded AISI 304. The test used an atomized spray of 5% NaCl at 35°C followed by microstructural analysis mainly looking for sensitization and pitting on the welded joint and the thermally affected zone.

AISI 304L displayed pitting in 50 days. 430 revealed sensitization in 4 hours. 441 was similar to 304L with pitting observed in 50 days, although grain boundary precipitations were detected in the weld zone (chromium-free niobium-based precipitates). Lap welds between AISI 441 and AISI 304 showed minor corrosion in crevices.

Comments

- Consider performing x-ray diffraction (XRD) on the welds to determine residual stresses.
- Consider stress corrosion cracking (SCC) tests since ferritic steels are susceptible. Salt spray does not consider bending stresses on beam tube.
- Enforce no chlorides or halides in proximity of beam tube.
- Must use third generation 441 that is resistant to SCC.

Welding Novel Beamtube Materials, A. T. Perez Fontenla, CERN

The stabilized grades (AISI 441 and 444) showed no signs of martensitic transformation, a critical flaw in the older 430 grade. Welds were qualified for both materials. Laser welding proved superior to TIG, producing a finer grain structure and thus mitigating the grain coarsening issue. The combination of a stabilized FSS grade with laser welding provided the best mechanical properties and ductility for fabrication. The AISI 430 grade performed poorly in corrosion tests while the laser-welded AISI 441 sample exhibited corrosion resistance comparable to the 304L benchmark. Therefore, for mechanical and corrosion reasons, AISI 430 stainless Group 2 has been excluded. Martensite was found in grain boundaries, sensitization was observed, and grain growth was found in heat affected zones.

Thicker walls (>4 mm) require argon shielding. TIG and plasma require double pass with 317L filler, while laser weld is autogenous. The salt-spray corrosion tests will be soon completed. Impact tests will be to be performed in the next months.

Comments

Any problems with inclusions? None identified.

Ferritic stainless steels for next-generation GWT, C. Scarcia, CERN

Ferritic stainless steels have a large spectrum of applications, from domestic equipment to architectural structures. Only two applications were reported in accelerators from KEK's vacuum teams; AISI 430 was used for its magnetic characteristics. The recent studies at CERN have shown the excellent vacuum quality of this material family in terms of specific hydrogen outgassing rate. The low outgassing rate is due to the low hydrogen content, which is equivalent to that of austenitic stainless steel after high-temperature treatments (i.e., around 0.01 wt. ppm).

The tested samples underwent different finishing, including cold or hot rolling, recrystallisation and solution annealing. Bright annealing should be avoided due to the H_2 atmosphere required during the treatment. For the outgassing measurements, only detergent cleaning was applied.

The pump down curves were equivalent to that of AISI 304, with the typical pumping time inverse power low. The thermal programmed desorption showed different H_2 de-trapping peaks for different surface finishing with maximum at least 50 times lower than that for AISI 304.

The specific outgassing rate was lower than 10^{-15} mbar l $s^{-1}cm^{-2}$ after bakeout at 80° or 150°C for 48h (i.e., three orders of magnitude lower than that of non-fired AISI 304). The values for CH4, CO and CO_2 were all below $4x10^{-16}$ mbar l $s^{-1}cm^{-2}$.

Comments

The hydrogen permeability of ferritic stainless steels should be measured in laminated and deep drawn samples.

AISI 1018 Mild Steel and Black Oxide, D. Berringer, W&M

In an attempt to form a magnetite black oxide on 1018 mild steel, material was heated to 800C and quenched. This method did not try to replicate the Sun Steel method. The formed black oxide was found to be reflective at 1 micron, which may not be a problem.

To prepare for outgassing tests, sequential low temperature bakes were performed at room temperature, 40C, 60C, 80C, 100C, and 150C. High CO_2 outgassing rate was observed in samples baked at 40° C and 60° C, while for the other temperatures H_2 was the leading gas. Structural characterization was performed using several methods including SEM/EDS. Low temperature bakes showed good water reduction after bakeout. However, longer pumping time would be necessary to achieve pressure as low as those obtained with the higher temperature bakeout. The "black" oxide surfaces formed on 1018 steel has a high optical absorption at 940 nm but not enough to get rid of the optical baffles. All in all, the advantage of conversion coating on mild steels with respect to native oxide is not clear. Native oxide may be sufficient for the required vacuum.

Comments

F. Dylla requested a 4-lab comparison of partial pressures with and without bake out.

AISI 1020 Low Carbon Steel with Bare and Magnetite Surfaces, A. Al-Allaq, JLab

The work aimed at determining if a low-carbon steel has the claimed low hydrogen outgassing rate and if magnetite surface really helps reduce it even further. Two chambers were tested: one with a bare steel surface and one with a Sun Steel magnetite surface. In terms of water outgassing rates, a magnetite surface at 25C beats a bare steel surface by a factor of five. Pump down curves are well fitted by a Sips-isotherm based models.

However, after both surfaces were given an 80° C bake out, the performance flipped with the bare steel outperforming the magnetite surface.

The hydrogen outgassing rate for the bare low carbon steel is very low, ranging from $2x10^{-13}$ Torr l $s^{-1}cm^{-2}$ after bakeout at 150° to $9x10^{-16}$ after bakeout at 400°C+200°C. The values for the magnetite-coated samples were consistently higher, with a particularly large difference, up to a factor of 25, after bakeout at the highest temperatures (i.e. 400 and then 200°C). Hydrogen was more than 99% of the residual gas.

Comments

F. Dylla again requested a 4-lab comparison of partial pressures with and without bake out.

Someone questioned - what are the baseline CO and CO_2 levels?

Outgassing Measurements for Einstein Telescope beampipe, I. Wevers, CERN

A set of mild steels and ferritic stainless steels were compared to AISI 304 with respect to water and hydrogen outgassing.

Water outgassing is led more by surface roughness than the grade of the steel. While keeping the inverse power law of pumping time, the water outgassing values can differ by a factor of 10.

Temperature Programmed Desorption confirmed the low hydrogen content in ferritic steels, in the best case around a factor 80 lower than in AISI 304.

The same trend was measured for the hydrogen outgassing rate after bakeout at 80 and 150°C. The lowest values were recorded for several grades, including AISI 441 and 444, below 10-15 mbar l $s^{-1}cm^{-2}$.

The low hydrogen outgassing rates were confirmed for a 16 m long, 219 mm diameter, 6 mm thick vacuum chamber. After repeated bakeout at 80°C, the hydrogen outgassing rate attained 10^{-15} mbar l s^{-1} cm^{-2}. However, water outgassing was limited to values higher than 10^{-13} mbar l s^{-1} cm^{-2} indicating that the bakeout temperature is not sufficient to reduce the outgassing rate down to acceptable values.

When measuring the pressure of large equipment such as the test systems planned for ET-PS and CEBEX, it is important to evaluate the outgassing rate of all components of the system. Valves and instruments could be the main contributors to the total gas load hiding the tubes made of extremely low outgassing steels.

A cork-based composite is under development for thermal insulation during bake out.

Are specific coatings to potentially avoid bakeout still reasonable? The silicon alloy did gain an order of magnitude in water outgassing rate, but the CVD process left microscopic spherical particles, which is unacceptable.

Comments

F. Dylla agrees coatings are not feasible on large scale, but he still maintains that there might be something positive about having thin magnetite-like coatings on the surface, particularly if such a coating naturally develops as part of the passivation layer on mild steels. More studies are needed.

CEBEX Instrumentation and Vacuum, J. Csizmazia, LIGO

The Cosmic Explorer Beam-tube Experimental (CEBEX) facility will consist of a 120-m beam-tube from 11 sections of 10-m tubes, two end caps, and 6 spool pieces, constructed of corrugated 304 stainless steel.

The conductance of the corrugated pipe was simulated by MolFlow+. There is a 10% lower conductance with respect to the smooth pipe. In addition, the corrugation contributes to a tiny increase of the pressure close to the corrugation surfaces (around 1%). However, the main difference in terms of pressure with the corrugation is the higher surface area.

Simulation shows that to achieve the required pressure the AISI 304 components must be vacuum or air fired.

In addition, it will be necessary to measure hydrocarbon contaminations and partial pressures.

Comments

What do you mean by measuring hydrocarbons and how can you do this in the center of a long beam without physically entering the tube?

Outgassing Rates with Coatings on Baffles, A. Ananyeva, Caltech

Diamond-like coatings (DLC) are well known and well characterized for applications in optical baffles. Typical examples are some baffles installed in LIGO. This family of coatings was tested for UHV applications by RGA with excellent results.

Another coating applied on baffles is black nickel. This material is produced by Anoplate. It was successfully characterised for use in LIGO. The pump down curves showed a slope in log(P) vs. log(t) in between the polymer-like and metallic-like values.

DLC has a lower outgassing rate with respect to black nickel.

Comments

The measurement of outgassing rates of coated optical baffles is essential to evaluate the total gas load in GWT. Such measurement should be performed also in other laboratories.

Cleaning of Beamtubes, L. Ferreira, CERN

Wet cleaning processing is performed either by water-based or organic solvent-based methods. Use of water-based cleaning products has a low efficiency on salt-based contaminants and require an important investment. The latter requires a drying step, produces a significant amount of wastewater and has a higher operational cost.

Dry cleaning methods, both plasma and laser, are not yet mature for application in UHV systems for GWT. Plasma is not effective on particle removal, while laser is prone to generate particulates.

The ET beamtube sections will be 1.1-m overall diameter, 4-mm thick, and up to 20-m in length. The expected cleaning rate is 8 tubes per day. The proposed cleaning will be a two-step process with degreasing with wet alkaline solution prior to rinsing is followed by drying in a ISO6 clean room. Process will use detergent in DI water (resistivity > 1 Mohm.cm) with ultrasonic agitation at 60C, followed by first rinse with raw water and second rinse in DI water (resistivity > 5 Mohm.cm) with ultrasonic agitation.

Second step is in a clean room, drying under laminar flow wall. ISO 6 conditions are not yet refined.

The layout of the required cleaning workshop was shown, including the flow of the tube from arrival to delivery. A first cost estimate was given.

Comments

None

Alternative method for large vacuum system bakeout, F. Molkenboer, TNO (NL)

The MacBeth project for the ET vacuum tubes was introduced. One of the work packages is dedicated to plasma assisted bakeout and cleaning. It aims to develop industrial scale cleaning and its assessment for corrugate beampipes.

The challenge is to use plasma to remove water from the steel surfaces. A conceptual set-up was presented for a vacuum chamber (DN400CF, 3.6 m long) made of AISI 304 or 441. Different plasma types were considered, including RF and DC or their combinations. The project aims to provide feasibility with ET conditions.

Comments

None

Laser cleaning, D. Vlekken, Netalux (BE)

Netalux is a company that produces laser cleaning systems. First trials with laser cleaning of AISI 441 were performed with sample provided by CERN. The cleanliness was characterized at CERN by XPS and FT-IR. The former technique detected carbon concentration in the range 56 to 33 %, while the latter one showed non-compliance with respect to organic contamination. The scan speed was 36 m^2/h with an Ar flow.

An optimisation study is ongoing in collaboration with other institutes and industries.

Comments

None

Laser Scanning Microscopy of Mild Steel Surfaces, D. Henkel, Caltech

We compared advanced methods of surface roughness measurement that included laser scanning microscopy (LSM), white light profilometry (WLP) and cross-sectional metallography. LSM is the most expensive instrument but provides rapid measurement and records at least a dozen roughness parameters in seconds. Both LSM and WLP provide 3D rotatable image capabilities that enables easy visual comparisons of surfaces. We compared bead blasting to grit blasting and found bead blasting to be the cleanest and most easily controlled method of mill scale removal. Grit blasting occasionally embeds silica particles into the surface. Further study is recommended if mild steel is to be considered a viable beamtube material.

Comments

None

Deliverables of WG1

1. The group finds 441/444 ferritic stainless steels to be acceptable vacuum materials. Hydrogen outgassing is two to three orders of magnitude lower than 304. Methane and CO_2 are two orders of magnitude lower than 304.
2. The group finds mild steel outgassing to be acceptable as a vacuum material.
3. Induction heating, backfilling with gas, and alternative outgassing processes show potential at small scale for removal of adsorbed water.
4. Industrial capabilities of producing ferritic tubes with the required tolerances are not yet fully understood.
5. Long term environmental effects on ferritic stainless steel beamtubes need to be validated.
6. Epoxy-coated the outer surface of carbon steel for environmental protection brings up concerns about leak testing.
7. Based on LIGO experience, black nickel and DLC are acceptable coatings on baffles.
8. Permeability of ferritic stainless steels has not been measured; limits not defined.
9. There is an open question about the benefits of modifying the passivation layer on mild steel.
10. Chemical cleaning of tubes is mature; laser cleaning requires further study.
11. Surface characterization methods and standards need to be established for repeatable outgassing results.
12. The group recommends CERN/CEBEX collaborative studies continue to investigate potential problems (e.g., particulates).
13. Cost reductions as a function of materials and processes are outdated and need to be reevaluated.

Refined and Prioritized Future Activities

1. Ferritic Stainless Steels (AISI 441 / 444)

- Consolidate and publish inter-laboratory outgassing data, including agreed reporting standards (units, bakeout history, surface condition).
- Extend measurements to laminated and deep-drawn geometries representative of industrial production.
- Measure hydrogen permeability and define acceptable limits for GW detector applications.

2. Mild (Low-Carbon) Steels

- Establish a clearer understanding of carbon-bearing species (CO, CO_2, hydrocarbons) and their dependence on surface condition and bakeout.
- Perform systematic comparisons of bare vs. conversion-coated surfaces, including long-term stability and bakeout compatibility.
- Coordinate a multi-lab comparison of partial pressures, with and without bakeout,

3. Welding and Mechanical Integrity

- Develop a qualification matrix covering welding technique (laser, TIG, plasma), wall thickness, shielding requirements, and filler materials.
- Perform residual stress characterization (e.g. XRD) and link results to corrosion and SCC susceptibility.
- Complete impact, fatigue, and mechanical strength tests on welded sections.

4. Environmental and Corrosion Effects

- Define and execute a realistic environmental test plan addressing:
    - Stress corrosion cracking under bending and residual stress
    - Long-term exposure to humidity and contaminants
    - Crevice corrosion in dissimilar metal joints
- Enforce and document chloride/halide exclusion requirements for beam-tube environments.

5. Surface Finishing, Cleaning, and Characterization

- Establish standardized surface treatments and roughness targets for beamtubes.
- Define a reference set of surface characterization techniques (e.g. roughness metrics, XPS, FT-IR) to ensure repeatability across labs.
- Finalize and validate industrial wet-cleaning workflows, including clean-room class, drying protocols, and throughput.

6. Alternative Cleaning and Bakeout Techniques

- Continue feasibility studies on plasma-assisted bakeout for large-scale systems, with clear go/no-go criteria.
- Further evaluate laser cleaning, focusing on particulate generation, organic residue removal, and scalability.

7. Coatings for Internal Components

- Extend outgassing measurements of black nickel and DLC coatings on baffles to additional laboratories.
- Assess coating integrity, ageing, and repairability in long-term operation.

8. System-Level Vacuum Performance

- Perform integrated outgassing assessments including tubes, valves, gauges, and insulation materials.
- Develop methodologies for in-situ monitoring of hydrocarbons and partial pressures in long beamtubes.

9. Industrialization and Cost Assessment

- Identify and survey industrial capabilities for large-scale production of ferritic stainless-steel tubes.
- Update cost models reflecting current materials, processing routes, welding methods, and cleaning strategies.
- Quantify cost-performance trade-offs relative to the 304L baseline.

10. Collaboration and Coordination

- Continue CERN–CEBEX–ET–CE collaborative studies, with a focus on identifying scale-dependent effects and unexpected failure modes.
- Maintain a shared database of materials data, test results, and qualified processes.

Working Group 2: Design, Fabrication and Assembly

Co-Chairs: Marco Marrone, CERN and Dennis Coyne, LIGO

Summary Report

Working Group Charge

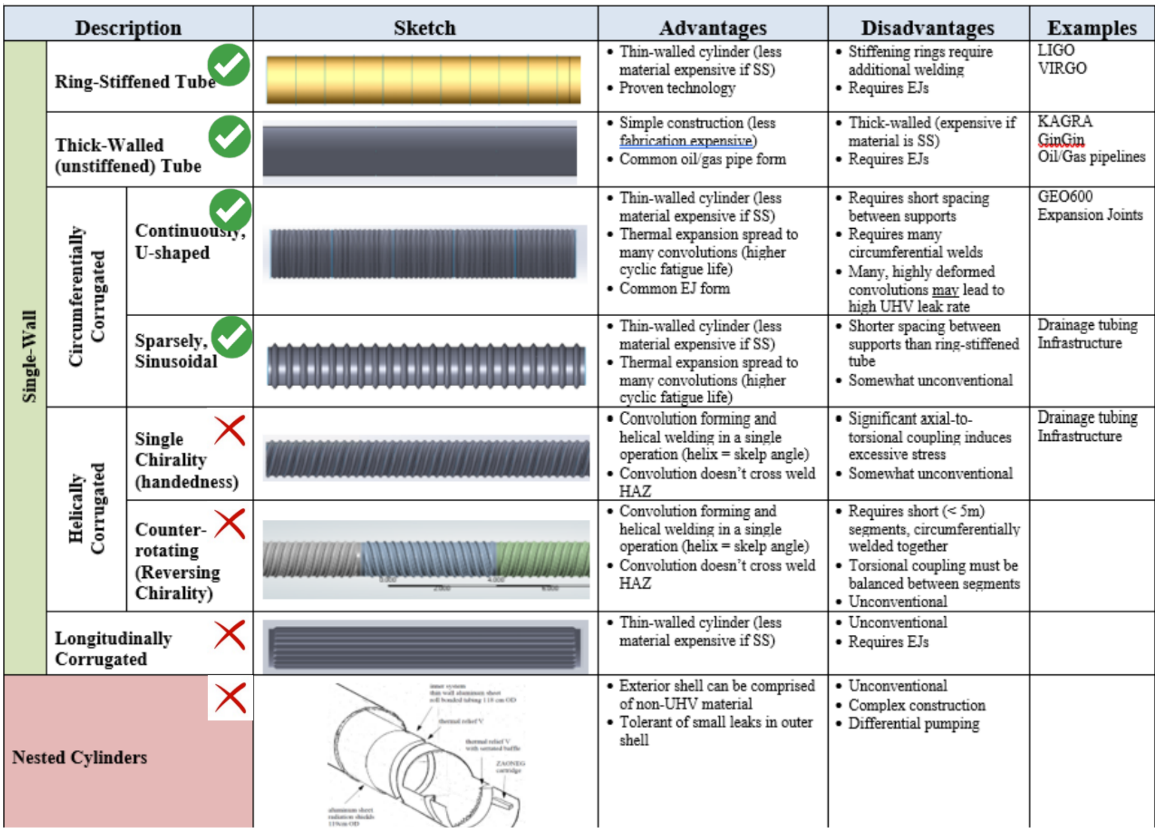
The working group is tasked with identifying the main cost drivers of conventional beamtube technology, construction, and operation, considering both stainless-steel and mild-steel concepts. The scope includes assessing opportunities in corrugated tube geometries, welding and circumferential joint design, convolution UHV leak-failure rates, tube supports, end caps, pump-port spools, bakeout strategies, insulation materials, and weld-joining approaches. The group should highlight feasible cost-saving measures and outline their potential impact on system-level design.

Discussion Highlights

Design & Fabrication Challenges for the Cosmic Explorer Beamtube

The Cosmic Explorer (CE) project represents a monumental leap in gravitational-wave astronomy, centered on the construction of an observatory with two 40 km arms. The core engineering challenge lies in the design and fabrication of its 80 km beamtube. A critical analysis reveals that simply scaling the successful design of the Laser Interferometer Gravitational-Wave Observatory (LIGO) is infeasible. Projections based on the LIGO experience indicate a fabrication and assembly timeline exceeding 10 years, with costs escalating from $76M in 1994 to an estimated $700M in 2028. This reality mandates a fundamental re-evaluation of the beamtube's design and manufacturing to meet a stringent set of performance and reliability requirements.

The CE beamtube design must adhere to a series of demanding mechanical and operational requirements. The structure must guarantee a minimum 50-year lifetime while maintaining ultra-high vacuum (UHV) integrity, with a target of no more than one significant UHV leak ($\leq 10^{-9}$ Torr-L/s) per decade. A key performance specification is the ability to withstand a 150°C bake-out procedure to achieve the required vacuum levels (though a lower bake-out temperature of ~80°C is also under consideration to reduce thermal-mechanical stresses). While cost management is a priority, the project is guided by a clear principle: "Long term reliability is far more important than minimizing cost." This mandate for long-term reliability at an unprecedented scale necessitates a fundamental departure from legacy designs, prompting an evaluation of several novel structural pathways. To address these challenges, the project is investigating main design options, see beamtube taxonomy Figure 1:



			Description	Sketch	Advantages	Disadvantages	Examples
Single-Wall	Ring-Stiffened Tube ✓				• Thin-walled cylinder (less material expensive if SS) • Proven technology	• Stiffening rings require additional welding • Requires EJs	LIGO VIRGO
Single-Wall	Thick-Walled (unstiffened) Tube ✓				• Simple construction (less fabrication expensive) • Common oil/gas pipe form	• Thick-walled (expensive if material is SS) • Requires EJs	KAGRA GinGin Oil/Gas pipelines
Single-Wall	Circumferentially Corrugated	Continuously, U-shaped ✓			• Thin-walled cylinder (less material expensive if SS) • Thermal expansion spread to many convolutions (higher cyclic fatigue life) • Common EJ form	• Requires short spacing between supports • Requires many circumferential welds • Many, highly deformed convolutions may lead to high UHV leak rate	GEO600 Expansion Joints
Single-Wall	Circumferentially Corrugated	Sparsely, Sinusoidal ✓			• Thin-walled cylinder (less material expensive if SS) • Thermal expansion spread to many convolutions (higher cyclic fatigue life)	• Shorter spacing between supports than ring-stiffened tube • Somewhat unconventional	Drainage tubing Infrastructure
Single-Wall	Helically Corrugated	Single Chirality (handedness) ✗			• Convolution forming and helical welding in a single operation (helix = skelp angle) • Convolution doesn't cross weld HAZ	• Significant axial-to-torsional coupling induces excessive stress • Somewhat unconventional	Drainage tubing Infrastructure
Single-Wall	Helically Corrugated	Counter-rotating (Reversing Chirality) ✗			• Convolution forming and helical welding in a single operation (helix = skelp angle) • Convolution doesn't cross weld HAZ	• Requires short (< 5m) segments, circumferentially welded together • Torsional coupling must be balanced between segments • Unconventional	
Single-Wall	Longitudinally Corrugated ✗				• Thin-walled cylinder (less material expensive if SS)	• Unconventional • Requires EJs	
Nested Cylinders ✗					• Exterior shell can be comprised of non-UHV material • Tolerant of small leaks in outer shell	• Unconventional • Complex construction • Differential pumping	

Figure 1:Beamtube taxonomy

It turns out that the project is investigating four principal design avenues for the beamtube structure:

- Thick-walled, unstiffened (carbon steel)
- Thin-walled, ring stiffened
- Thin-walled, continuously corrugated (U-profile)
- Thin-walled, sparsely corrugated (sine-profile)

Alongside these concepts, a range of materials is being evaluated. While austenitic stainless steel (AISI 304L) is still being considered, alternatives are under consideration. Low-carbon steel (e.g., API 5L pipe steel) is found to be UHV compatible with even lower hydrogen outgassing rates than stainless steel, offering significant cost savings. Duplex stainless steels provide superior strength and toughness with lower nickel content, while ferritic stainless steels (AISI 400 series) are also of interest. All designs are being rigorously evaluated against ASME BPVC standards for multiple failure modes, including buckling under vacuum and thermal loads, plastic collapse, and cyclic fatigue. This parallel exploration of design and materials is essential for identifying a pathway that is not only structurally sound but also inherently compatible with the automated fabrication methods required to make the project viable.

The beamtube is unequivocally a major cost and schedule driver for the Cosmic Explorer observatory. The central conclusion of the design study is that success hinges on developing innovative designs specifically optimized for rapid fabrication, efficient field assembly, and robust, integrated quality assurance. To meet the immense scope of the project, a new approach to production is required. Automation is the key enabling technology, essential for scaling up manufacturing to produce 80 kilometers of high-precision, vacuum-rated tubing within the project's practical and financial constraints [1].

Vacuum Tube Design for the Einstein Telescope

A vacuum tube design for the Einstein Telescope (ET), requiring 120 km of lightweight, optimized, and cost-effective tubing was proposed. The design philosophy balances structural and vacuum performance with manufacturability suitable for medium-series production. The system integrates two main components, the vacuum tube and its support structure, each engineered for efficiency, scalability, and operational reliability.

The tube is designed as a 15 m long, 1 m diameter section with a thin 1.5 mm Steel 441 wall, weighing about 750 kg to minimize material use. Structural rigidity is ensured by a 2 mm external spiral stiffener wound at a 150 mm pitch, preventing collapse under vacuum while keeping mass low. This geometry is advantageous for large-scale fabrication and compatible with automated, robotic manufacturing, improving on more complex processes used in earlier projects like Virgo.

A dedicated support system complements the tube. Vertical and horizontal H-beams carry two tubes each, anchored to the floor and to the tunnel wall via sliding brackets that compensate for tunnel irregularities. Adjustable jaws provide precise alignment, and the structure offers mechanical and electrical isolation for bake-outs up to 200°C. The support system is intentionally decoupled from the bellows to prevent torque transfer from tube deflection and stiffener torsion. Its sliding mechanism accommodates roughly 20 mm thermal expansion and aids bellows compression. This modular "LEGO-like" approach allows reuse and adaptation, including future integration into the CERN pilot sector.

Comprehensive simulations validated the design. Thermal expansion analysis confirmed the need for sliding supports; static and buckling analysis showed less than 7 mm deflection and a safety factor of 4.1; modal analysis identified the first 70 vibration modes, pending final validation with site-specific seismic data.

The project is advancing to fabrication. A 0.5 m prototype is being built to confirm manufacturability and leak-tightness (10^{-8} mbar). The roadmap includes prototype testing through 2025–2026, design evolution for the CERN pilot sector in 2026, and development of a new pilot sector design in 2027 [2].

Vacuum chamber design considerations for the Einstein Telescope

This design study outlines the primary considerations for the Einstein Telescope (ET) vacuum chamber, a structure with demanding specifications: a 1000 mm aperture, a total length of approximately 120 km, a target vacuum level of 10^{-9} mbar, and the ability to withstand an in-situ bake-out at 150°C. The proposed baseline concept is a thin-walled, corrugated tube fabricated from stainless steel. This design offers significant advantages, including the ability to withstand external atmospheric pressure without requiring separate bellows and a more efficient use of raw material. However, the mechanical performance of this concept is critically dependent on the type of corrugation employed.

While spiral corrugations present clear advantages for manufacturing and cleaning processes, a detailed mechanical analysis reveals significant and prohibitive drawbacks for this application. The helicoidal pattern fundamentally alters the tube's structural response, leading to the following critical issues:

• Reduced Buckling Strength: Spiral patterns cause a significant reduction of approximately 50% in buckling strength against external pressure when compared to an equivalent annular design.

• Axial-Torsional Coupling: The helicoidal geometry creates a strong coupling between axial forces and torsion. This means that tension or compression along the tube's length induces a rotational torque, leading to complex stress distributions and large reaction forces at the support points. For a structure of this scale, such behaviour would vastly complicate support design, compromise long-term alignment stability, and introduce operational risks.

• Modelling Complexity: To accurately predict this behaviour, a specialized 1D beam model had to be developed to incorporate this complex coupling effect into the structural analysis, as standard models are insufficient.

Given these severe mechanical penalties, the initial manufacturing advantages of the spiral design become secondary to ensuring structural integrity.

Based on this analysis, the final recommendation is unambiguous. Despite their manufacturing benefits, the mechanical trade-offs associated with spiral corrugations are unacceptable for this application. Therefore, the analysis concludes that vacuum chambers with annular convolutions seem required to ensure the necessary structural integrity and predictable performance. This choice avoids the reduced buckling strength and strong axial-torsion coupling effects inherent to the spiral design, which could compromise the stability and reliability of the vacuum system over its extensive length [3].

Optimized Corrugated Tube Design

This document summarizes an optimized corrugated beamtube design proposed for the next-generation Cosmic Explorer gravitational-wave observatory. The goal is to improve upon the original LIGO beamtube—which used a 3.2 mm wall thickness, welded stiffener rings, and expansion joints every 40 m—by introducing a corrugated geometry that could reduce manufacturing complexity and overall cost. Corrugations offer three key advantages: improved buckling resistance, the ability to absorb thermal expansion without external expansion joints, and the possibility of using thinner wall materials.

Because a fully corrugated tube would be too flexible over long spans, the study adopts a hybrid concept combining flat sections with corrugated modules. A sophisticated analysis workflow was developed to evaluate this design. The tube's sinusoidal corrugation profile is defined by four parameters—amplitude, period, pitch, and wall thickness—and a Python script generated 3D geometries for automated Finite Element Analysis (FEA). Simulations applied gravity, vacuum loading, and a 150°C bakeout cycle. Fourteen output parameters were monitored, with emphasis on global sag, reaction forces, buckling factor, and von Mises stresses in both flat and corrugated regions.

Using this framework, a Design Explorer optimization searched the parameter space to maximize performance while meeting constraints: buckling factor above 3, sag below 10 mm over a 20 m span, von Mises stress below 138 MPa, and minimal wall thickness (target ~2 mm). The optimization identified several viable designs. A representative verification point achieved excellent performance: sag of − 9.87 mm, tube stress of 56.9 MPa, convolution stress of 120.8 MPa, and a buckling factor of 4.4. These results show that a structurally sound corrugated beamtube is feasible and could be validated under ASME Division 2, Method B.

Before adoption, practical issues must be addressed. Optimization outputs require post-processing to match real manufacturing tolerances, and vendor input is needed to assess manufacturability; a Request for Information has already been issued. Overall, the study provides a strong foundation for developing a cost-effective corrugated beamtube for Cosmic Explorer [4].

Circumferential Joint Design

An engineering analysis of circumferential welded joint designs for the Cosmic Explorer beamtube Experiment (CEBEX), whose long-term performance depends on maintaining ultra-high vacuum (UHV) over decades, was performed. Because the beamtube will experience significant thermal and mechanical loading, the structural Integrity of the welded joints between tube sections is critical. The study evaluates a proposed welded radial lip joint to determine whether it can safely withstand operational stresses without risking crack formation or vacuum failure.

The joint was analyzed under two major sources of axial load: thermal expansion during 150°C bakeout and constant atmospheric pressure acting on the evacuated tube. A benchmark axial load of ~30 kN, taken from LIGO's fixed supports, was used as a design reference. A 2D axisymmetric linear stress analysis revealed extremely high localized stresses at the weld root. As the computational mesh was refined, the model exhibited a classic stress singularity at the sharp "crack-tip" geometry of the welded lip. This behaviour indicates that the material at the weld root would plastically yield, creating an ideal site for crack initiation, which cannot be reliably assessed through simple stress analysis. A fracture-mechanics approach is therefore required.

The resulting Stress Intensity Factor for the 20 mm lip design was $K_I = 2.47$ MPa√m, exceeding the recommended limit of 2.0 MPa√m for austenitic stainless steel, as proposed for the ASME BPVC Section XI fracture-assessment standard. A value above this threshold indicates an unacceptable risk of fatigue crack growth during the experiment's operational lifetime. While design modifications such as reducing lip height were considered, none provided adequate improvement without introducing further uncertainty.

Given that the welded radial lip joint fails to meet essential fracture-resistance criteria, it is deemed unsuitable for the CEBEX beamtube. The analysis recommends adopting an alternative geometry that removes the singular stress concentration, specifically a conical scarf joint, see Figure 2, which provides a smoother load path and eliminates the high-risk crack-tip condition. This safer joint design is essential to ensuring the long-term vacuum reliability of Cosmic Explorer [5].

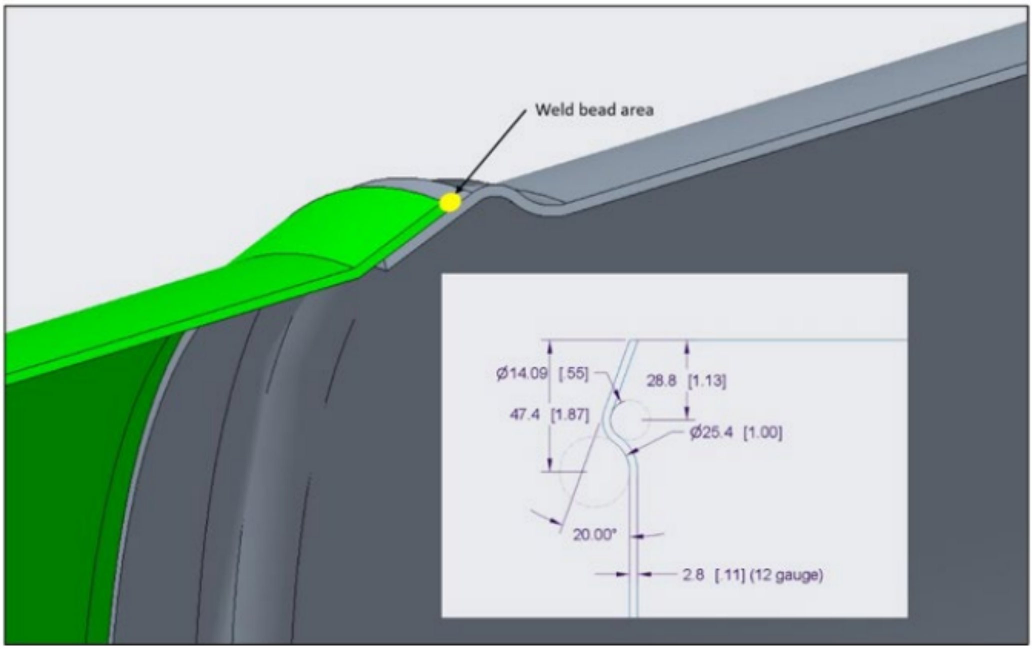


Figure 2: Conical scarf joint proposal.

Convolution UHV Leak Failure Rate Estimate

The long-term leak failure risks for the Cosmic Explorer (CE) beamtubes, whose ultra-high vacuum (UHV) requirements are far stricter than those of earlier large vacuum systems, were discussed. Gravitational-wave detectors use corrugated or bellows-based tubing to accommodate thermal expansion, but these features introduce flexing and residual stresses that can threaten UHV integrity at leak levels as low as 10^{-9} Torr-L/s.

Historical data from the Large Electron Positron (LEP) collider provide an important warning. During its operational period LEP experienced only 3 small leaks at a much looser threshold ($\approx 75\times10^{-9}$ Torr-L/s) than for CE and ET. Assuming that the leak location is associated with (scales with) the convolution number (and using the 5% lower bound statistical estimate) gives a leak failure rate of 2e-9 per convolution-hour. When scaled to CE's total number of convolutions (for a convoluted tube design), LEP-equivalent performance would imply roughly seven leaks per year—completely unacceptable for CE given the difficulty and cost associated with finding and repairing leaks on a multi-kilometer tube. Notably, LEP bellows were lightly stressed yet still failed, underscoring the need to understand the root cause.

Three main failure mechanisms are examined. Cyclic fatigue, driven by daily thermal cycles, can be analyzed using EJMA and ASME methods, though predictions vary widely. Fully corrugated tubes experience very low stress amplitudes, suggesting effectively infinite fatigue life. Stress Corrosion Cracking (SCC) remains a credible long-term risk due to residual manufacturing stresses and potential corrosive species; estimated crack-growth timelines (≈32 years) match the leak-free history of LIGO bellows. Microbial Induced Corrosion (MIC) is deemed unlikely for CE's likely dry deployment sites.

The study concludes that cyclic fatigue is the most immediate design concern, favouring fully corrugated tubing. However, the unexplained high leak rate observed in LEP bellows represents a critical unresolved risk. Before finalizing the CE design, a focused R&D campaign is essential to reproduce and diagnose the LEP-like failure mechanism to ensure long-term UHV reliability [6].

Leak Detection Strategy for the ET Pilot Sector

The leak detection strategy for the ET Pilot Sector beamtubes as well as the ET vacuum system was presented [7]. The welds and components of the pilot sector will be 100% leak tested using conventional He bagging and mass spectrometry. For the ET production system, component (ex-situ), sub-sector (in-situ), and sector level (in-situ) leak testing was outlined for three test strategies: "max" test strategy (classic, preventative approach), "mid" test strategy and "min" test strategy (corrective approach). The plan is to adopt the "mid" test strategy but dynamically change test frequency as the fabrication and installation evolves. Based on LIGO experience, the ET team were encouraged to consider the long time constants and cycle times for sub-sector & sector testing (for clearing out He after testing) as well as the unacceptability of more than 1 leak per volume. The team were also encouraged to consider robotic testing.

Design Proposal for CEBEX Beamtube Components

The preliminary design strategy for several key components of the CEBEX hardware was discussed. CEBEX is a 110-meter ultra-high-vacuum demonstrator to be built at LIGO Hanford to validate technologies for the much larger 80-km Cosmic Explorer (CE) gravitational-wave observatory. Its purpose is to test new manufacturing approaches and design concepts that could reduce cost and complexity in the full-scale facility.

A central theme of the proposal is the use of parametric design, which enables rapid iteration by allowing engineers to modify geometric parameters without rebuilding entire CAD models. Three component categories were highlighted: end caps, pump port spools, and supports. For the end caps, the major innovation is the transition from LIGO's flat septum plate to a tori spherical geometry. This curved profile reduces membrane stresses and allows for thinner walls, which in turn lowers thermal mass and shortens hydrogen diffusion paths, critical factors for efficient H_2 degassing during bakeout. The material choice, still under evaluation, will depend on permitted residual hydrogen levels, with candidates including 304L stainless steel and A36 carbon steel.

Pump port spools share similar material concerns but are mainly driven by the need for precise port placement to meet the vacuum instrumentation layout. The support system features the most substantial redesign: CEBEX adopts a corrugated beamtube whose geometry accommodates thermal expansion. This eliminates the need for LIGO-style guided supports, enabling the use of simple fixed supports placed every 10 meters.

Next steps include finalizing materials, integrating bakeout cable features into the supports, optimizing steel profiles for weight reduction, and performing mechanical analyses in ANSYS [8].

Beam tube principal cost drivers

The major cost drivers for the Cosmic Explorer (CE) beamtube hinge on an analysis based on historical cost data from the original LIGO beamtube project, using it as a template to evaluate how different design and manufacturing choices affect total project cost for a future 80-km gravitational-wave observatory.

The cost model is intentionally limited in scope to components directly tied to the beamtube structure and its manufacturing. Included cost items encompass beamtube materials, stiffeners, pump ports, supports, cleaning and bakeout, leak testing, and transportation. Broader infrastructure and vacuum-system hardware, such as foundations, baffles, enclosures, pumps, and project management, are excluded. This focused approach allows a clear assessment of how core engineering decisions shape cost outcomes.

The methodology relies on detailed 1994 cost data from Chicago Bridge & Iron (CB&I) for LIGO, preserved in document LIGO-T2400377 [8]. Though outdated in absolute terms, these data remain valuable for relative comparisons. Using this foundation, Rai Weiss previously projected the cost for a 40-km interferometer (escalated to 2028 USD), yielding an estimate of roughly $635 million for a full 80-km CE facility. Building on this, Coyne's presentation addresses how cost responds to two critical design variables: tube segment length and stiffener spacing.

The first key finding concerns tube segment length. Costs increase sharply for segments exceeding about 20 meters, primarily due to freight and installation constraints. Oversized loads incur disproportionately high transport fees, making very long segments economically impractical given CE's continental-scale logistics. This establishes an effective upper bound on segment length.

The second major cost driver is stiffener spacing. A wider spacing between stiffening rings necessitates a thicker steel shell to prevent vacuum collapse, raising material costs. Conversely, closer stiffener spacing introduces additional fabrication expense. Since several cost categories—supports, bellows, pump ports, installation, leak testing, and freight—remain unaffected by stiffener spacing, the optimization reduces to balancing stiffener fabrication cost against shell thickness. Analysis shows that LIGO's historical design, with 758 mm stiffener spacing in 304L stainless steel, remains near-optimal for a ring-stiffened geometry.

A promising alternative emerged from the study: adoption of a corrugated tube. This design could reduce total beamtube cost by roughly 34% by removing the need for stiffeners and bellows and enabling thinner walls. As a result, while the LIGO design serves as a validated baseline, the corrugated approach stands out as the most compelling avenue for future cost-saving R&D [9].

Welding Design and Strategy for Chamber Assembly for ET pilot sector.

The development and validation of a welding strategy for assembling large ultra-high-vacuum (UHV) chambers was discussed. The main objective is to achieve reliable mechanical strength and leak-tightness while closely controlling dust contamination.

A phased mock-up program qualified a manual TIG fillet-welding process using 317L filler.

- The first mock-up (Ø 850 mm, open sleeve) validated the forming process and contamination monitoring.

- The second mock-up (Ø 1008 mm, closed 4 mm sleeve) demonstrated improved structural integrity and leak-tightness.
- The methodology is now being applied to a 40 m pilot sector, using a 2 mm closed sleeve (1 mm gap).

For production, the strategy is two-tiered:

- First line: manual welding at CERN using the validated 4 mm closed-sleeve design, chosen for robustness, reparability, and low contamination risk.
- Second line (future): exploration of automated welding using a double-collar joint, offering better tolerance to component geometry and eliminating tube-end machining.

Automation faces equipment constraints. CERN's existing orbital TIG welder (650 mm track) cannot accommodate the 1008 mm chambers, preventing trials of both the 45° fillet weld and the double-collar lip weld. A larger custom track (>1008 mm) could be purchased (≈15 kCHF, 3-month lead time), enabling vertical welding tests for the lip weld but not angled fillet welding [10] [11].

Thermal Insulation Strategy for the Einstein Telescope Beam Pipe System

The Einstein Telescope (ET) requires an effective thermal insulation strategy to manage the high-temperature bakeout of its extensive beam pipe system. This process, which utilizes direct Joule heating to bring the pipes to a maximum temperature of 150°C, is essential for achieving the required vacuum conditions. Thermal insulation is critical for this operation as it limits heat loss to the surrounding environment, which in turn reduces the required electrical current and significantly lowers operational costs. Given that this bakeout procedure is anticipated to occur only once or twice over the facility's 50-year lifespan, the choice of insulation carries long-term financial and logistical implications.

Standard industry solutions have been deemed unsuitable for the immense scale of the ET project. The approach used by LIGO and VIRGO—installing a permanent 15 cm layer of mineral wool—would be prohibitively expensive for the ET's 120 km of piping, with a projected total insulation cost of €18-23 million. The financial model of a permanent mineral wool installation is fundamentally incompatible with a system designed for only one or two uses over a 50-year operational lifespan. Furthermore, a permanent installation raises significant concerns regarding depreciation costs, long-term storage, sustainability, cleanliness (dust generation), and overall safety, including fire risks. Other common materials like aerogel, while offering excellent thermal properties, are expensive and brittle, while polyurethane foam is inadequate due to its lower maximum operating temperature.

To address these challenges, a dedicated development project has been initiated through a collaboration between CERN and PIEP (PT) to engineer a novel thermal insulation system tailored to the ET's requirements. The new solution is designed to be sustainable, cost-effective, and reusable, taking the form of castable shells that can be installed for the bakeout and removed afterward. The development is exploring two primary material bases: a cork and bio-phenolic foam composite, and a fire-retardant modified polyisocyanurate (PIR). A primary objective is to develop a material with exceptional fire safety characteristics, targeting a Euroclass A1/A2 rating, which represents the highest classifications for non-combustibility and limited contribution to fire. The project is also aiming for a maximum operating temperature of 400°C, providing a significant performance and safety margin well above the required 150°C bakeout temperature. This innovative material is scheduled for its first installation in the ET-PS in the third quarter of 2026. This targeted development is therefore crucial for enabling the ET's commissioning in a manner that is both cost-effective and operationally sustainable [12]

Induction Bakeout Experiment (IBEX) at LIGO Caltech

The Induction Bakeout Experiment (IBEX) was developed to evaluate induction heating as a practical method for vacuum bakeout in the next generation of gravitational-wave observatories, particularly Cosmic Explorer (CE). CE's unprecedented scale demands a vacuum system constructed from materials that balance technical performance with manufacturability. Mild steel has emerged as a strong candidate due to its low cost and intrinsically low hydrogen outgassing. However, its low electrical resistivity makes conventional ohmic (I^2R) bakeout impractical, as mild steel does not heat efficiently through resistive methods. Induction heating, which exploits the material's magnetic and eddy-current losses, offers a promising alternative and motivated the creation of IBEX.

The experiment focused on validating a "zone bakeout" strategy in which the beamtube is heated in sequential segments rather than uniformly along its entire length. Although thermal modelling predicted that zonal heating would effectively remove water from the steel surface, experimental verification was essential. To test the concept, researchers constructed a 6-meter mild steel vacuum tube equipped with a mobile, clamshell induction coil powered by a 25 kW RF generator. This traveling heater was engineered to raise the tube from ambient temperature to 150–250 °C within roughly five seconds, enabling rapid and localized bakeout. By repositioning the induction unit along the tube, each zone could be independently heated and pumped.

The results confirm that induction-based zone bakeout is both efficient and highly effective. The system achieved post-bakeout vacuum pressures in the 10^{-9} to 10^{-10} mbar range, indicating strong removal of surface-bound volatiles. Residual gas analysis showed that the bakeout primarily removed water, and measurements yielded a water outgassing rate of 3.5×10^{-13} mbar L/s cm^2, fully consistent with expectations for well-conditioned mild steel. A hydrogen outgassing rate of 1×10^{-12} mbar L/s cm^2 further validated the material's excellent low-hydrogen behaviour. Critically, the data demonstrated that outgassed water from unbaked sections does not significantly diffuse back into previously baked areas when adequate pumping is maintained, eliminating the principal risk associated with the zonal approach.

With IBEX, the feasibility of induction heating for long mild steel beamtubes has been decisively demonstrated. The experiment removes a major technical barrier to adopting mild steel for Cosmic Explorer, supporting its potential to dramatically reduce vacuum-system cost while maintaining ultra-high-vacuum performance. Future work will focus on engineering challenges such as designing a kilometre-scale heater carriage, optimizing the pumping scheme, and evaluating the use of circulating dry gas to maintain cleanliness during extended installation campaigns [13].

Plasma Alternative for large vacuum system bake-out

The baseline method for baking out the adsorbed water in the beamtube is Joule heating. Plasmas have been demonstrated to degas vacuum surfaces. A "high risk, high gain" demonstration project [14] has been initiated (as part of MACBATH) to experiment with DC and RF plasmas on a small-scale system (3.6 m long, 0.3 m diameter). The hope is that plasma-generating antennas can be placed behind optical baffles and be capable of degassing significant lengths of the adjacent tube.

Overview of Potential Manufacturing Techniques for Corrugated beamtube

The goal of the MACBETH (Manufacturing and Cleanliness of Beampipe for Einstein Telescope in High vacuum) project is the industrialization of the (arm) vacuum system and in particular a cost-efficient design of the production facility and the installation scenario [15], including:

- Industrialization for manufacturing and cleaning of the 120km corrugated vacuum beampipe
- Measurement and quality control of the cleanliness
- Industrialization of the packaging and logistics (production, installation and maintenance)
- Plasma assisted bake-out and cleaning

The work will start with a prototype beampipe section (minimum of 3m length), including a supply chain study, fabrication of prototype machines/tooling to produce beampipe sections and measurement/validation of requirements. The project is currently considering the various options for rolling a coil into a circumferentially corrugated tube [16]:

- Rolling short sheet lengths into tubes, forming longitudinal welds, rolling the corrugations, and then circumferentially welding 2m length tubes together to form a 20 m beam pipe
- Forming a circular pipe with 2 longitudinal seam welds, then rolling the corrugations
- Spiral welding a circular tube, then rolling the corrugations

Welding techniques under consideration include orbital TIG welding, K-TIG welding and laser welding.

The next phase of the work will develop a proof of concept for measurement and quality control of the cleanliness with a robotic system. The third project phase will consider industrialization of the handling, packaging, transportation, storage, installation, alignment and logistics and include packaging and transport to the CERN test facilities. The fourth phase of the project entails a feasibility study and proof of concept test of the alternative plasma bake-out and cleaning approach (see paragraph above). The ambitious project schedule started in the 3^{rd} quarter of 2025 and is planned to finish by the 3^{rd} quarter of 2027.

Key Open Issues

There are of course many issues which remain open, but here is a short list of a few key issues that were discussed at the workshop (in no particular order):

1) More complete and firmer requirements definition for CE:
    a. We have assumed that the beamtube diameter is the same as for LIGO (1.2 m). The diameter is a very significant cost driver. Scattered light modelling presented at the workshop indicates that the diameter can't likely be reduced.
    b. Vibrational requirements need to be defined from systems-level considerations. Currently the assumption is that seismic isolation is not required and there have been no imposed modal frequency or damping requirements. However, Matt Evans expressed the opinion that the first modal frequency should be > 10 Hz and that passive damping be included at least in the form of an elastomeric interface at the beamtube supports.
2) Better definition of allowable surface particulate density levels is required in order to evaluate cleaning and welding methods. Particulate transport (e.g. convection during pump down) and deposition onto the baffle surfaces is apparently not a problem. However, the rate of particulates falling through the beam can be a problem.
3) Understanding of the long term, UHV leak failure mechanisms of corrugated tubes (whether formed as long tubes or as short bellows segments) is essential for determining the viability of corrugated tubes relative to stiffened or unstiffened (thick-walled) beamtubes.
4) Viable techniques for cost-effective manufacture of UHV-compatible, corrugated beamtubes are still to be developed.

References:

[1] Coyne, D. (2025). G2502099-v1 Design specifications: Tube design overview for CE. Caltech. Presented at the Beamtube Workshop #3, September 30 – October 2, 2025.

[2] Lacroix, A. (2025). G2502117-v1. Vacuum Tube Design for the Einstein Telescope. LAPP. Presented at the CE-ET Beamtube Workshop #3, September 30 – October 2, 2025.

[3] Morrone, M., & Garion, C. (2025). G2502154-v1. Design inputs and concept for the Einstein Telescope. CERN. Presented at the CE-ET Beamtube Workshop #3, September 30 – October 2, 2025.

[4] Franco-Ordovas, A. (2025). G2502143-v1 Design specifications: Tube design overview for CE. Caltech. Presented at the Beamtube Workshop #3, September 30 – October 2, 2025.

[5] Coyne, D., Feicht, J., & Zucker, M. (2025). G2502097-v1 Circumferential Joint Design_5.pdf: Cosmic Explorer Beamtube Experiment (CE-BEX). Presented at the Beamtube Workshop #3, September 30 – October 2, 2025.

[6] Coyne, D. (2025). G2502098-v1 Convolution UHV Leak Failure Rate Estimate. Presented at the Beamtube Workshop #3, September 30 – October 2, 2025.

[7] Revathi, P. & Hansen, J. (2025). G2502167-v1 Leak Detection of the ET Pilot Sector beamtubes. Presented at the Beamtube Workshop #3, September 30 – October 2, 2025.

[8] Iudintseva, A. (2025). G2502110-v1 Design Proposal for CEBEX beamtube Components. Presented at the Beamtube Workshop #3, September 30 – October 2, 2025.

[9] Coyne, D. (2025). G2502114-v2beamtube principal cost drivers.pdf. Presented at the Beamtube Workshop #3, September 30 – October 2, 2025.

[10] Misler, R., & Favre, G. G2502115-v1 Weld design join chambers - LIGO Workshop_10.pdf. Presented at the Beamtube Workshop #3, September 30 – October 2, 2025.

[11] Misler, R., & Favre, G. G2502116-v1 Welding techniques - LIGO Workshop.pdf. Presented at thebeamtube Workshop #3, September 30 – October 2, 2025.

[12] Thermal insulation for GWDs beam pipe vacuum systems (G2502127-v1) Authors: Carlo Scarcia, Karl Owens Date: 2025/10/01. Presented at the Beamtube Workshop #3, September 30 – October 2, 2025.

[13] Fuentes-Garcia, M., Lazzarini, A., Feicht, J. (2025, October 2). Induction Bakeout EXperiment (IBEX) at LIGO Caltech. LIGO-G2502145-v1. Presented at the Beamtube Workshop #3, September 30 – October 2, 2025.

[14] Molkenboer, F., et. al., G2502095-v1 Alternative Method for Large Vacuum Systems Bake-out. Presented at the Beamtube Workshop #3, September 30 – October 2, 2025. Presented at the Beamtube Workshop #3, September 30 – October 2, 2025.

[15] Quinten, F., G2502109-v1, MACBETH: Manufacturing and Cleanliness of Beampipe for Einstein Telescope in High-vacuum. Presented at the Beamtube Workshop #3, September 30 – October 2, 2025.

[16] van der Heijden, P., G2502139v-v2, Overview of Potential Manufacturing Techniques for Corrugated Beamtube, Presented at the Beamtube Workshop #3, September 30 – October 2, 2025.

Working Group 3: Scattered Light Isolation and Baffles

Co-chairs: Mario Martinez, IFAE, Barcelona and Matt Evans, MIT

Charge

The working group is tasked with identifying the key aspects of stray-light control elements within the vacuum pipes of the Cosmic Explorer (CE) main arms, in alignment with the solutions being explored for the Einstein Telescope (ET) and considering the approaches implemented in LIGO, Virgo, and KAGRA. The objective is to identify viable and cost-effective solutions that ensure stray-light–induced noise in the main arms remains negligible relative to the anticipated CE sensitivity.

Executive summary

The working group concluded that a viable technical solution exists, capable of keeping the induced noise at negligible levels—at least two orders of magnitude below the anticipated sensitivity, based on existing simulation estimates.

Although the simulations are believed to include the dominant contributions, the current uncertainties in the predictions justify maintaining a conservative safety margin in the design of the stray-light control system. The group also recognizes the need to sustain a strong effort to improve these simulations and to validate them with experimental data whenever possible.

The identified solution is inspired by those already implemented in LIGO and Virgo. In the bulk of the vacuum tube, it consists of strategically spaced conical baffles installed along the tube. The baffles would be mirror-polished and coated with black-nickel–based coatings.

The placement of baffles along the tube away from the mirrors is primarily driven by geometrical considerations to ensure that the bare tube surface remains fully shielded. This leads to baffle-to-baffle separations that increase with distance from the mirrors and eventually reach an asymptotic spacing, which will most likely be determined by the distribution of the vacuum pumping stations.

In the first few hundred meters from the mirrors in the main cavities, slightly different solutions may be employed, including additional dampers or suspended baffles to reduce vibrations, as well as the application of enhanced optical coatings where necessary.

In all cases, appropriately large inner apertures will prevent excessive clipping losses while ensuring sufficient flexibility to accommodate future interferometer operation with significant laser-beam offsets. For a given baffle height (i.e., outer radius - inner radius), this will also determine the minimum vacuum-tube diameter that can be adopted.

A dedicated optimization program aimed at further improving performance and reducing costs is still required. Several action items have been identified as prospective activities that must be completed before the design of the stray-light control system in the arms can be considered final.

Baffle layout and apertures

The baffle layout in the bulk of the main vacuum tube within the arm optical cavities is guided by the following principles: preventing any direct line of sight from the mirrors to the bare vacuum tube structures, thereby avoiding backscattering—this requires installing a minimum number of baffles in the tube, including sufficient geometrical overlap between consecutive baffles to compensate for possible misalignments; and shielding the vacuum pump stations and any other internal structures with appropriate baffle placement. From the standpoint of scattered-light noise, mechanical misalignments of a few centimeters along the vacuum tube or in the transverse plane perpendicular to the beam axis remain acceptable. This indicates that typical mechanical tolerances of a few millimeters in the tube construction do not pose a limitation.

The total number of baffles installed in the cavity will depend on several factors, including the total cavity length, the length of the individual vacuum sections, the anticipated baffle apertures, and the distribution of vacuum pumping stations along the tube, which are expected to be placed approximately every 200–250 meters. A detailed integration with the vacuum pipe design is still required to finalise this distribution.

The placement of baffles along the tube near the mirrors (first few 100 meters) is primarily driven by geometrical considerations to ensure that the bare tube surface remains fully shielded. This leads to baffle-to-baffle separations that increase with distance from the mirrors and eventually reach a spacing greater than 1km, at which point wave effects (i.e., diffraction) dominate and regular baffle spacing is required. The baffle separation in this region (which is most of the tube) will most likely be determined by the distribution of the vacuum pumping stations and other considerations that facilitate off-site assembly of integrated ready-to-install components that include both baffles and vacuum-related hardware.

Within the framework of ET [1,2], initial estimates for the number of baffles per arm have been provided based on a 10 km arm length, indicating that the total number of baffles is expected to range between 120 and 240, depending on the baffle-to-baffle separation. In these studies, baffle apertures have been set to limit beam clipping losses to values below 10^{-8}, while accounting for potential laser beam offsets of up to 5 cm. Consequently, the baffles have a clear aperture of 0.84 m (for a total tube diameter of 1 m) and are installed at an inclination angle of 55° relative to the pipe normal. As discussed in Ref. [1], large offsets of the laser beam may lead to a significant increase in the total induced stray-light noise, thereby motivating the use of large apertures.

Similar studies are being conducted within the framework of CE [3,4] for an arm 40 km in length and a tube diameter of 1.2 m, which is expected to require a few hundred baffles per arm.

Baffle installation inside the tube

The team concluded that baffle installation would be equally feasible in both corrugated and non-corrugated vacuum tubes. Therefore, this aspect does not constitute a limitation in deciding whether a corrugated or non-corrugated solution should be adopted. By following the principle that baffles are strategically placed to shield the bare tube surface from the mirrors' line of sight, constraints on the vacuum tube surface finish are greatly reduced, and the presence of corrugation does not contribute to backscattering noise.

Different installation methods were discussed, including those used in the LIGO main arms (baffles attached to the inner walls of the tube by pressure), in the Virgo main arms (baffles welded to pre-existing rings inside the vacuum tube sections), mounted in frames attached to the inner walls using springs as used by both LIGO and Virgo, or mechanically fixed with screws to pre-existing holed rings, as in the case for example of Virgo filter cavities. In all cases, special precautions should be taken to ensure that baffle edges or fixation structures are not exposed to scattered light from the mirrors, as this could generate backscattering noise. Additionally, measures should be implemented to ensure the robustness and longevity of the chosen installation method. In this regard, a slight preference was expressed for stronger fixation structures, based on observations that enhanced vibrations have occurred in baffles fixed by pressure to the tubes. Different solutions will likely be required for the bulk of the vacuum tube compared to regions near the mirrors.

At present, the ET prototype at CERN is considering the fabrication of separate tube sections to house the baffles [5], which would then be integrated into the bulk of the main tube. This approach facilitates the installation of the baffles, simplifies their cleaning, and helps preserve their optical properties during integration. In the framework of CE and ET, the production of a set of short vacuum sections—including baffles both with and without vacuum ports—will be necessary to finalize and validate the solutions adopted for baffle integration and for ensuring complete shielding of the vacuum ports inside the vacuum tube.

Finally, a large number of suspended baffles is not foreseen in the bulk of the vacuum tube, as the total stray-light noise is already small. However, a limited number may still be considered for other purposes (e.g., higher-order mode attenuation, initial alignment, stray-light measurement, glitch detection, etc.). Current ideas involve just 2 suspended baffles, one near each mirror (i.e., between a few 100 meters and a few km from each end). These may facilitate the transition from the near-the-mirror logarithmic-spacing region to the far-from-the-mirror regular spacing region.

Stray light noise calculations

Detailed calculations have been performed to estimate the stray-light–induced noise in the bulk of the vacuum tubes. These calculations incorporate state-of-the-art mirror maps and account for contributions from both diffraction-induced noise (arising from the limited baffle apertures) and backscattering-induced noise (caused by photons scattering from the baffles back toward the main mirrors and recoupling into the cavity laser modes).

The calculations do not include contributions from scattering off the tube itself, which is relatively unknown and poorly modelled. This further reinforces the principle of implementing baffles to shield the bare tube surface from the mirrors' line of sight. Dedicated laboratory measurements of the BRDF of the tube surface at large incident angles would improve understanding of potential backscattering contributions from the bare tube.

Currently, baffles are assumed to vibrate with the same spectrum as the ground floor (corresponding to a mechanical transfer factor of 1), representing a no-isolation and no-amplification assumption. Initial mechanical simulations for baffles tightly fixed to the vacuum tube surface indicate no amplification of tube vibrations below 130 Hz [6], though LIGO data suggests that current beamtube supports may cause amplification around 10 Hz. At frequencies near 130 Hz, an amplification factor of approximately 20 is observed; however, this does not pose a risk, as it occurs in a frequency range where the total stray-light–induced noise remains many orders of magnitude below the anticipated sensitivity. Nevertheless, a systematic laboratory campaign is required to experimentally determine the actual vibration of baffles in each location for given fixation methods under controlled conditions before adopting an installation method. Such measurements will also be instrumental in assessing the potential need for additional elements to damp the resulting vibrations.

In the current configuration, the total induced noise computed in the simulations remains at least two orders of magnitude below the nominal anticipated sensitivity and is dominated by diffraction noise, which approximately scales with the square root of the number of baffles. To reduce the diffraction noise contribution, the baffle inner edges are serrated. The baffle surfaces are designed to meet a BRDF requirement below 10^{-4} /sr at the back-reflection angle (i.e., –55°), which governs the level of backscattering noise, together with the effects of vibrations and light exposure on the baffles.

Given the existing uncertainties [4] in the various factors influencing the calculation of stray-light–induced noise—such as mirror maps, modelled cavity fields and interactions, diffraction patterns, backscattering contributions, vibrations, and mechanical transfer factors—it is recommended to adopt a conservative approach. The baffle system design should ensure that the total noise remains at least two orders of magnitude below the nominal interferometer sensitivity across the entire frequency range of interest. This approach also calls for a further optimization program in the final design, potentially allowing a reduction in the total number of baffles through slightly smaller baffle apertures, improved BRDF of the baffle surfaces, and/or attenuated vibrations for those baffles contributing most significantly to the total induced noise.

Finally, the results discussed above do not account for the baffle layout in the first tens to hundreds of meters from the mirrors. This region includes baffles located at the mirror payloads, vacuum tower walls, and cryotrap areas, for which a dedicated study is still in progress and will require special attention. Preliminary studies performed in the ET framework [7] highlight the importance of a valid baffling design to preserve sensitivity at relatively low frequencies.

Material and coatings

A comprehensive review of the materials and coatings implemented in LIGO and Virgo was carried out [8,9] based on intense work performed by LIGO. Motivated by the requirement to achieve a BRDF smaller than 10^{-4}/sr, a cost-effective solution was identified for the baffles in the bulk of the vacuum tube: mirror-polished stainless steel (304L or 316LN) with back-nickel coatings, a configuration extensively used in the current interferometers. Higher-quality optical coatings, such as diamond-like carbon (DLC), should be explored for regions of the interferometer closer to the core optical elements. A second review of the adequacy of materials and coating in view of the large power expected in the CE cavities will serve to revalidate the design.

As part of the R&D activities at CERN and motivated by the use of stainless steel with reduced hydrogen content in the tube (to mitigate the impact of bakeout requirements and to limit outgassing), a 441 stainless steel solution from CERN has also been explored for the baffles. Initial attempts to mirror-polish the 441-material yielded unsatisfactory quality. Currently, the baffles installed in CERN's prototype are based on polished 316LN materials and require a bakeout campaign prior to installation. Although baffles are not expected to contribute to outgassing, special attention should be paid to coatings and materials used for damping of vibrations.

Effect of dust on the baffles

The group discussed the impact of dust contamination on the baffle surfaces and its effect on stray-light noise levels. In principle, the accumulation of dust particles on the baffle surfaces could increase their BRDF, thereby enhancing the backscattering component of the induced noise. Such contamination would occur during the installation of the baffles inside the vacuum tube.

Existing calculations [10,11] indicate that the expected accumulation of dust particles would not lead to a significant change in the resulting backscattering noise. This finding could have an important impact on the interferometer's construction cost and on the baffle installation procedure, as the cleanliness requirements could be relaxed, substantially reducing both cost and operational complexity for baffle installation. Nevertheless, given the uncertainties in the current estimates, the group agreed to pursue an experimental approach. An activity will be launched to measure, using test samples, the contamination levels on the baffles and the corresponding change in BRDF during their installation in the ET and CE vacuum prototypes, in order to validate these assumptions.

Active stray light monitoring in the main cavity

We explored the incorporation of instrumented baffles [12,13,14] in the main arms, equipped with optical sensors, as well as the installation of infrared cameras in viewports monitoring the light incident on the baffles. Instrumented baffles have already been installed in the Advanced Virgo experiment and are being considered an integral part of the ET design. LIGO implemented a limited number of photosensors in suspended baffles, providing restricted information [15]. In Virgo, the instrumented baffles are currently equipped with approximately 100 Si-based, optically coated photo-sensors (with a reflectivity of about 2%) distributed across up to five concentric rings around the beam axis, with readout at 1 kHz.

A number of strategically placed instrumented baffles along the vacuum tube can provide continuous monitoring of stray light within the cavity, facilitate pre-alignment of the cavities during commissioning and operation, supply data to validate optical models of stray-light distribution, and help identify potential noise sources when correlated with glitches in the interferometer output and control signals. These instrumented baffles could be the realization of the suspended baffles discussed earlier (i.e., one a few 100 m from each end), and/or large aperture baffles in the region even closer to the mirrors (like the current Virgo and LIGO instrumented baffles).

Although a working solution already exists, an R&D campaign aimed at further improving the optical performance of the sensors—including reduced reflectivity and BRDF, enhanced readout speed, and remote powering—would be beneficial for future applications in the interferometers.

Action items

The following action items were identified during the workshop:

– Continue the development of optical simulations in the cavities, including those leading contributions to the total stray-light–induced noise, to build confidence in the robustness of the predictions.

– Utilize data from instrumented baffles and driven vibration tests in Virgo and LIGO to validate, as far as possible, the current optical simulations in the cavities.

– Conduct laboratory measurements to determine the optical performance of vacuum tube materials at large incident angles, to inform simulations of stray-light noise originating from the tube itself.

– Converge on a working design for the baffles in the CE and ET arms.

– Implement a program to optimize the baffle system layout and design.

– Collaborate with the optical divisions of ET and CE to define requirements for baffle apertures, ensuring sufficient flexibility for future interferometer operations.

– Determine the necessity of suspended baffles in the CE and ET arms.

– Finalize a working design for baffle installation in the CE and ET arms. Initiate a program to produce short vacuum sections incorporating baffles and vacuum ports in order to finalize and validate a solution for baffle integration.

– Conduct a comprehensive measurement campaign to determine the expected vibration spectrum of baffles in different locations.

– Extend current simulations to include regions close to the main mirrors.

– Validate with experimental data that the materials and coatings used for baffles in LIGO remain suitable under CE and ET conditions.

– Investigate, through simulations and experiments, the effect of dust on the optical performance of baffles.

– Initiate R&D on enabling technologies for active monitoring of stray light in the main arms, exploring different solutions.

References

[1] M. Andrés Carcasona et al., "New modeling of the stray light noise in the main arms of the Einstein Telescope", Class.Quant.Grav. 42 (2025) 21, 215021.

[2] M. Andrés Carcasona et al., "Study of scattered light in the main arms of the Einstein Telescope gravitational wave detector", Phys.Rev.D 108 (2023) 10, 102001.

[3] A. Kontos, https://dcc.ligo.org/LIGO-G2502148

[4] A. Kontos, https://dcc.ligo.org/LIGO-G2502142

[5] C. Scarcia, https://dcc.ligo.org/LIGO-G2502132

[6] M. Andrés Carcasona, https://dcc.ligo.org/LIGO-G2502118

[7] E. Vallejo, https://dcc.ligo.org/LIGO-G2502140

[8] A. Ananyeva, https://dcc.ligo.org/LIGO-G2502166

[9] A. Ananyeva, LIGO-T1800001.

[10] A. Moscatello et al., "Scattered light noise due to dust particles contamination in the vacuum pipes of the Einstein Telescope", arXiv: 2510.26919 (2025).

[11] V. Frolov, LIGO-T2500041-v1

[12] M. Andrés Carcasona et al., "Stray light noise simulations for the Einstein Telescope and Virgo and the use of instrumented baffles", *PoS* EPS-HEP2023 (2024) 551.

[13] M. Andrés Carcasona et al., "Instrumented baffle for the Advanced Virgo input mode cleaner end mirror", *Phys.Rev.D* 107 (2023) 6, 062001.

[14] M. Andrés Carcasona et al.,"Performance of an instrumented baffle placed at the entrance of Virgo's end mirror vacuum tower during O5", Phys.Rev.D 111 (2025) 4, 042001

[15] https://dcc.ligo.org/LIGO-D1200657

Appendix A: BTW3 Program

Cosmic Explorer (CE)-Einstein Telescope (ET) Beamtube Workshop III (BTW3)

LIGO Hanford Observatory, Hanford, Washington, USA, September 30-October 2,2025

Workshop Schedule

Day 1: Tuesday, September 30, 2025

1.Welcome, Introduction and Purpose 8:30-9:45

Session Chair : F. Dylla, Caltech/MIT

- Welcome and Workshop Overview : M. Zucker, LIGO 8:30-8:40
- Remembrance of Ranier Weiss, F. Dylla 8:40-8:50
- Summary of Workshop II at CERN (2023): F. Dylla 8:50-9:00
- Cosmic Explorer: Project Update and Vacuum Requirements 9:00-9:30

Matt Evans, MIT

Einstein Telescope: Project Update and Vacuum Requirements 9:30-10:00

Thomas Bulik, University of Warsaw

2. LHO Site Tour: LSB Lobby (departure & return) 10:15 - 12:30

Guides: LHO Staff

3.Design Space Trade-Offs : Vacuum Materials and Fabrication (LSB Auditorium)

Session Chair: Paolo Chiggiato, CERN 13:30-15:00

- Candidate Beamtube Materials Vacuum Properties

Carlo Scarcia, CERN

- Fabrication and Assembly Trade-offs with Candidate Beamtube Materials

Michael Zucker, LIGO

Day 1 Wrap Up and Working Group Organization 15:15-15:45

Session Chair: F.Dylla

- Summary Discussion of Day 1

- Working Group Organization

Kick-Off Working Group Meetings: Session 1 15:45-17:00

- **Working Group 1: Materials, surface treatments and outgassing**

  Co-chairs: Paolo Chiggiato, CERN and Dan Henkel, LIGO

- **Working Group 2: Design Fabrication and Assembly**

  Co-chairs: Denis Coyne, LIGO and Marco Marrone, CERN

- **Working Group 3: Scattered Light Isolation and Baffles** (OSB Multi)

  Co-chairs: Matt Evans, MIT and Mario Martinez, IFAE, Barcelona

Day 2: Wednesday 1 October 2025

4. Design Space Trade Offs: Fabrication, Assembly & Stray Light

Session Chair: Mario Martinez, IFAE
8:30-10:15

- Design drivers for scattered light baffles

  Antonio Kontos, Bard College (TBC)

- Mechanical/Optical Design Options for baffles

  Marc Andres, MIT

5. Experimental Program Reports (LSB Auditorium) 10:30-12:00

Session Chair: TBC

- CE Prototype Beamtube Test Stand
  M. Zucker, LIGO
- ET Prototype Beamtube Test Stand
  Ana Teresa Fontenia, CERN and Alexander LaCroix, CNRS

Working Group Breakout Session 2 13:00-16:30

1. **Materials, surface treatments and outgassing**
2. **Design, Fabrication & Assembly**
3. **Scattered Light, Isolation and Baffles**

Day 2 Wrap Up & Day 3 Plan 16:30-17:00

Session Chair: F. Dylla

Day 3: Thursday, 2 October 2025

Working Group Breakout Session II 8:30- 10:15

1. **Materials, surface treatments and outgassing**
2. **Design, Fabrication & Assembly**
3. **Scattered Light, Isolation and Baffles**

Working Group Breakout Session III 10:30-12:30

1. **Materials, surface treatments and outgassing**
2. **Design, Fabrication & Assembly**
3. **Scattered Light, Isolation and Baffles**

Working Group Reports 13:30-15:00

Session Chair: F.Dylla

Workshop Wrap Up & Plan for Next Meeting (CERN,2027) 15:15-16:30

Session Chairs: M. Zucker ,F. Dylla and P. Chiggiato

Adjourn 16:30

Appendix B: Workshop Attendees

Achim Stahl	Rheinisch Westfaelische Tech. Hoch.
Adrian Helming-Cornell	
Aiman Al-Allaq	JLab
Alberto Franco-Ordovas	CIT
Alena Ananyeva	CIT
Alessandro Ferrara	SAES
Alexander Richardson	
Alexandre Lacroix	LAPP IN2P3
Alexey Gervasyev	Ghent University
Ana Teresa Perez Fontenla	CERN
Anamaria Effler	LLO
Andrea Mostcatello	University of Padua
Aniello Grado	INAF/INFN
Anna Iudintseva	LHO
Antonino Chiummo	INFN
Antonios Kontos	Bard College
Ashvini Bhardwaj	IPR
Atul Kumar Prajapati	
Bob Cottingham	LLO
Bram Slagmolen	The Australian National University
Carlo Scarcia	CERN
Cedric Garion	CERN
Daniel Henkel	Contractor, Caltech
David Reitze	CIT
Dennis Coyne	CIT
Douglas Beringer	William and Mary
Elisabet Vallejo	

Enrico Maccallini	**SAES**
Fabian Robert Quinten	**Nikhef**
Frank Rathmann	
Fred Dylla	**Consultant, Caltech**
Freek Moikenboer	
Geepo Cagnoli	
Gerardo Moreno	**LHO**
Gilles Favre	**CERN**
Hannah Hansen	**LHO**
Hans d'Achard van Enschut	**Settels Savenije**
Hiroaki Yamamoto	**Institute of Science Tokyo**
Ivo Wevers	**CERN**
Jan Hansen	**CERN**
JanCarlo (JC) Sanchez	**LLO**
Janos Csizmazia	**LHO**
Johannes Stefanski	**Edwards Vacuum**
Jordan Vanosky	**LHO**
Leo Kestens	**Ghent University**
Livia Conti	**INFN - Padova**
Lutz Lilje	**DESY -MVS**
Manjunath Dakshinamurthy	**CERN**
Marc Andrés Carcasona	**MIT**
Marco Morrone	**CERN**
Margaret Brashear	**Leybold**
Marije Barel	
Mario Martinez-Perez	**The Barcelona Institute of Science and Technology (BIST)**
Matt Evans	**MIT**
Matt Poelker	**JLab**
Melina Fuentes-Garcia	**CIT**

Michael Landry	**LHO**
Mike Zucker	**CIT / MIT**
Mohamed Elbashbishy	
Paolo Chiggiato	**CERN**
Pedram Sabouri	**Leybold**
Pijm van der Heijden	**VDL Enabling Technologies Group**
Rakesh Kumar	**IPR**
Robert Schofield	**LHO**
Roxane Misler	**CERN**
Shima Samandari	
Stefano Sgobba	**CERN**
Tim Kuhlbusch	
Todd TeVogt	**Edwards Vacuum**
Tomasz Bulik	**University of Warsaw**
Will Parker	**LLO**
Yuliya Hoika	