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## 2023 Annual Project Report:

### **Workshop on Large Ultrahigh-Vacuum Systems for Frontier Scientific Research Instrumentation, NSF PHY-1846142**

The first **Workshop on Large Ultrahigh Vacuum Systems for Frontier Scientific Research Instrumentation**, sponsored under this Award, was held at the LIGO Livingston, LA site on Jan. 28 - 31, 2019. The Workshop Proceedings ([LIGO-P1900072](#)) outlined specific programs of targeted research, now under active pursuit at Caltech, CERN, NIST, College of William and Mary, Material Forensics LLC, Cornell, MIT, Fermilab, and other institutions, and endorsed a recommendation to reconvene the group in about one year.

A second workshop was thus planned for spring of 2020, to be hosted at CERN in Geneva, Switzerland. With concurrence of the NSF Program Officer, unused Award participant costs were carried forward to support travel for US-based attendees to this follow-up workshop.

The CERN meeting was postponed due to the global Coronavirus pandemic, and was finally convened between 27 and 29 March, 2023 ([Beampipes for Gravitational Wave Telescopes 2023](#)). The Award funded travel to Geneva for three of our original US-based Workshop participants: Yulin Li (Cornell), Zuxing [Alex] Chen (Fermilab), and Stefan Ballmer (Syracuse).

Transformative progress was reported at the CERN meeting, despite the intervening pandemic. Presentations and discussions showed substantial traction on the principal objectives articulated in 2019, plus several new and promising ideas. The worldwide effort has gained significant momentum in view of the NSF funding of a CE Vacuum Study award (PI Albert Lazzarini, LIGO Lab), a substantial resource commitment by the CERN Vacuum, Materials and Coatings division, and the recent allocation of design and prototype funding to the European *Einstein Telescope* gravitational wave project.

Highlights of the second Workshop are summarized in Appendix A, prepared by Fred Dylla (LIGO Lab/AIP) in consultation with participants and organizers. A list of workshop participants is furnished in Appendix B.

Given the accelerating pace of worldwide third-generation gravitational wave observatory efforts, there is powerful consensus toward making this meeting an annual event. Three proposed venues are under investigation for next spring: LIGO Hanford, Virgo (Cascina, Italy) or CERN again. Several potential US participants had to decline at a late stage for schedule reasons. As a result, some unspent participant costs remain. We have secured an additional no-cost extension (to 31 July, 2024) in order to apply these funds to support attendance at next year's Workshop.

## Appendix A:

Comments on GWD Vacuum Workshop at CERN, March 27-29,2023

F. Dylla, 1 April 2023

### A.) Overview presentations and summaries of outgassing and surface studies:

- The CERN Vacuum Group under Paolo Chiggiato's leadership is heavily invested in a 3-year project (that started in September 2022) with design studies and a deliverable of a triplet of 15m (?) prototype vacuum vessels for ET. (The three prototype vessels will be fabricated from 304SS, mild steel, and ferritic steel.) We are familiar with most of this work scope from our bimonthly CE vacuum study group calls with the CERN group.
- The CERN ET project work scope includes the outgassing studies on mild steels, ferritic steels and Silcotek coated SS304 steels that we have been following for the last two years. There are associated outgassing modelling, TDS measurements of H-content and surface analysis (both micrographic and XPS measurements.) The outgassing measurements have progressed to a point where a complete set of outgassing measurements for both H<sub>2</sub> and H<sub>2</sub>O along with ultimate pressure measurements could be presented for the mild steel pipe alloy (P355N) that was the subject of most of their measurements. It was very helpful for the US contingent to be able to meet and interact with the CERN team in person that we have interacted with only by online communications since the 2019 workshop. The key personnel involved with the outgassing measurements are: Carlo Scarcia and Ivo Wevers along with Mauro Taborelli for surface measurements and calculations, and Antonio Ferreira for outgassing modelling.
- The US CE-LIGO contingent was well represented at this workshop with invited talks by Mike Zucker on the driving vacuum requirements for GWDs, Fred Dylla with a summary of the previous workshop in 2019 at the LLO, Jon Feicht on the status of the CE preliminary design studies, Dan Henkel on the metallurgy of mild steels, Jim Fedchak on a review of the current data on outgassing of mild steels, and an inspiring talk included in the first day's program by Rai Weiss (on Zoom) that recounted the new physics that could be done with the next generation of GWDs. Rai emphasized that the LIGO vacuum system meets the CE vacuum requirements. However, straightforward extrapolations of LIGO's vacuum system capital cost for CE exceed \$0.5B and are drivers for a significantly less costly beam pipe design (such as using mild steels). In addition, less costly H<sub>2</sub>O bakeout systems and procedures are needed to save considerable operational cost and time.
- In my overview of the recommendations from the 2019 LLO workshop, I noted that the key recommendations that remain very active for the GWD-vacuum community include: 1.) studying whether the vacuum performance of mild steels could be improved with the design and application of a magnetite-like passivation layer; 2.) studying the efficacy of localized heating with simultaneous dry gas purging to lower the cost and complexity of the in-situ vacuum bakeout necessary to lower H<sub>2</sub>O partial pressures to acceptable levels; and 3.) design and testing of soft-close and annular gate valves that will be useful for the baseline single-wall vacuum vessel or the alternative nested vessel design (that was initially presented at the LLO workshop in 2019 and updated for a presentation to the CERN-CE collaboration teleconferences in February of 2023.)
- Dan Henkel presented a remarkably complete overview of steel metallurgy in the modest 35m that was allotted to his talk. He showed from why H-content and outgassing should be significantly lower in mild steels compared to austenitic steels due to their microstructure and fabrication methodology. Henkel also emphasized in his talk and during subsequent working group discussions the savings in capital cost of the beam pipes that could be booked by taking advantage of the standard mild steel piping that is readily available for the gas and petroleum industry. His 2018 quote of ~\$50m for 80km of cleaned and externally (epoxy) coated pipe was widely referenced during the remainder of the workshop. Henkel also presented a useful comparison of the various steel specification standards (AISA, API and European ISO).

- Jim Fedchak (NIST) presented a comprehensive overview of mild steel outgassing measurements comparing the results from the four groups currently doing these studies (CERN, NIST, JLab and W&M), along with the historical data that Park et al published in 2016 along with Dylla's results from measurements at PPPL in the late 1980's (that was presented at the LLO workshop in 2019).
- As helped by Jim Fedchak's compilation, a reasonable cross-comparison of outgassing measurements from mild steels is now coalescing from four laboratories with the following conclusions:
  1. The H<sub>2</sub> outgassing from mild steels is negligible in compared to stainless steel, at least two orders of magnitude lower, perhaps lower because of the difficulty of doing background subtractions with very low H<sub>2</sub> outgassing rates. The bottom line: we can now safely say that the use of mild steel would discount the need for any high temperature pre-baking treatment to lower H<sub>2</sub> outgassing to permissible levels for GWDs.
  2. The H<sub>2</sub>O outgassing rate measurements from mild steels after pump down from atmosphere with no baking show outgassing rates that are only slightly higher than 304LSS for sample chambers that have reasonable surface topography based on data from all four recent studies, including the historical data from Park, et al and Dylla.
  3. The CERN group (I. Wevers and C.Scarcia) found by baking the mild steel chambers under vacuum at modest temperatures (40-80C), for 48 hr for each temperature step over a series of five temperature steps, with no venting to air in between steps, the H<sub>2</sub>O outgassing rate was lowered to an acceptable rate to meet both the CE and ET vacuum requirements for H<sub>2</sub>O. These results were sufficient for the CERN group to specify a 95C bakeout temperature for the initial specifications for mild steel beampipes for ET. During subsequent conversations with both Scarcia and Wevers, I encouraged further measurements of the time-temperature steps that might optimize a low temperature bakeout scenario for use with both ET and CE. For a large system such as CE and ET, it would be advantageous to trade off longer bakeout times with lower peak temperatures.
  4. Modelling of the H<sub>2</sub>O outgassing from the above experiment by the CERN group shows that over the bakeout sequence from 40-80C with subsequent air venting, the H<sub>2</sub>O partial pressure dependence could be accurately modelled if the activation energy dropped from ~1.5eV to 0.5eV and the adsorption sites dropped roughly a factor of two over whatever surface transformation occurred over this treatment. These data are a hint that beneficial surface transformation occurs with this treatment. Recall that the visual appearance of this chamber after all these bakeout test showed the inner surface oxide transforming from red-colored oxide (hematite -Fe<sub>2</sub>O<sub>3</sub>) to a grey color. We have been calling this a transformation to magnetite (Fe<sub>3</sub>O<sub>4</sub>),but we have yet to prove this supposition.
  5. The JLab data shows a similar transformation to a more beneficial surface by observation of their decreasing ultimate pressures after a series of ramped 48 hr chamber bakes followed by air exposures that affected the oxide layer.
  6. The third data point that supports a reasonable vacuum facing surface on mild steel chambers after little or no processing comes from the NIST measurement. Jim Fedchak noted that the H<sub>2</sub>O outgassing curves from their mild steel chamber were nearly identical from a first trial and a second trail almost a year later after the chamber was exposed to room air at ambient conditions in the NIST lab.
  7. The above data points from these 3 labs (CERN, JLab and NIST) showed us that mild steel is viable candidate for CE and ET-requiring: 1.) the usual reasonable care in specifying the steel grade and surface composition, pre-cleaning by any of the procedures

used by these labs, and in-situ bake at a modest temperature (that could be well below 90C) after installation.

8. Jim noted in his invited talk after carefully reviewing the original Park et al paper that their results offered an additional useful observation on the change in H<sub>2</sub>O outgassing from mild steel surfaces after a pre-bake treatment. The Park et al samples were pre-baked at a high temperature that is irrelevant for GWD application (~800C). But after exposing these pre-baked samples to air exposures the H<sub>2</sub>O outgassing was lower than our standard stainless steel measurement (Li and Dylla).
9. Everyone involved agrees that work should continue on small samples and eventually test chambers to produce and characterize a passivation layer that may mimic or improve upon the results seen in the above tests. We are currently presuming that this may be a magnetite-like structure, but there is work in progress (already initiated at CERN, W&M, JLab and NIST) to confirm this hypothesis and optimize the passivation.

Note: during the Wednesday afternoon tour of the LHC magnet fabrication facility, Dan Henkel was shown a magnetite coating that was applied by sintering hot steel samples. It has long term corrosion resistance. Henkel will be receiving samples and further information on this coating.

10. The CERN group has done surface microscopy on their various mild steel samples that shows that there are as-received rough surfaces to be avoided (cold rolled) and acceptable surface treatments for vacuum use. In addition, there are TDS measurements that confirm the low H-content of mild steel and ferritic steel. There is preliminary XPS data that show some shifts in the oxide and hydroxide peaks on the passivation layer of the chamber that achieved the best ultimate pressure. Further surface analyses will give us more data on the nature of the improved passivation layer noted in the recent CERN, JLab and NIST outgassing measurements.

## **B.) The CERN ET studies and other pan European collaborations for ET**

- As a result of the CERN-ET contract, the vacuum group has put an impressive number of collaborations together with groups across Europe who have already signed onto the 41-member umbrella collaboration working on ET design issues under the ESRI (European Scientific Research Infrastructure) initiatives. These partners come from National Labs (NIHKEF in the Netherlands, INFN in Italy and Karlsruhe (KIT) in Germany, universities and industries representing vacuum components and metal sourcing.

During the workshop we heard discussions of most of the issues related to vacuum pipe design, fabrication and installation problems geared toward the current concept for ET (Three mirror stations on a 10 km leg triangle with 4 laser beamlines per legs) including:

1. A cost estimate for the ET beampipes and associated vacuum systems -that may have relied on unreliable data from Virgo.
2. A status report on the three 15m prototype vessels being designed and fabricated by the CERN -VSC group. The three materials being used are 304SS (baseline), a Ferritic SS, type AISI 430 and type S315 MC mild steel. ( We have previously heard about the state of this project during our bimonthly CE-CERN teleconferences.) The beampipe geometry is a convoluted vessel as previously described by Cedric Garion in one of our calls. The ferritic material is having problems with successful convolution forming and with failed welds. A spare building on the CERN site has been commandeered for setting up an arrangement of these vessels that would mimic the support structure presently envisioned for the four stacked beamlines for ET. The 304L chamber is complete and the mild steel chamber is still being welded.

- Note: we toured the impressive facility where CERN cleans vacuum components up to 7m in length and 1m in diameter. They have settled on a preliminary method of cleaning mild steel chambers involving an ultrasonic isopropyl wash, followed by an ultrasonic deionized-water rinse, and then a mild air bake.
- A fairly detailed design for ET baffles was presented by Mario Martinex-Perez (Spain); it looked complete and reasonable to my untrained analysis except for a discussion on the desired specifications for the surface roughness and absorbance of the beam tube inner surface. During a subsequent off-line discussion with Mario, Mike Zucker and myself, we all agreed that specifying a reasonably black surface and surface roughness for the beamtube (as is usually received from the mill) would be advantageous for minimizing scattered light.
- Carlo Scarcia ( a very productive graduate student from Aachen University working at CERN) presented parametric analysis of a proposed scheme for locating pumps, valves and gauges in the ET beampipe vacuum system. The program he produced can be used not only to gauge the equipment needed to handle the pumping requirements, but also will be helpful to provide cost estimates as the hardware count is varied. As an example, Carlo presented bakeout simulations with three types of vessel insulation.
- One important point on the current design of the vacuum pumping arrangement that came out of the working group discussion on sector layout on Tuesday afternoon is the existing problem with location  $\sim 1\text{m}$  aperture gate valves on the current ET beam pipes. With the current tunnel diameter ( $\sim 9\text{m}$ ), there is no room for locating the gate valves either vertically or horizontally.
- Paul Cruikshank (CERN) presented an analysis of the cost and equipment needed to do the prequalification leak checking on ET vessels. He noted that with over 200k of welds in the LHC cryostats, there was a 1-5% failure rate on first leak checks after welding. These failures were due to inclusions, Cu contamination or poor welding technique.
- Andrea Moscateelo (CERN) presented an interesting study of techniques that should be employed to minimize input of dust into chamber as they are assembled. He noted that the accelerator installation work done at CERN and elsewhere employed portable ISO Class 5 clean rooms that that appear to have worked. He showed data that ion pumps generate about 30 particles when they are turned on (therefore, they should not be mounted vertically); valves generate about 2500 particles with open/close actions. Andrea estimated that the ET chamber would probably have about  $10^5$  particles in each chamber.
- Marion Purrio presented a fascinating option of chamber assembly within the tunnel that involved having a rolling mill and vacuum welder installed in the tunnel that would move as chambers were made up to 500m in length from roll stock. This obviously saves in trucking finished chambers into the tunnel. She showed a transportable laser welding machine that operates at  $\sim 1\text{mbar}$  with weld speeds of 1m/min.
- A very useful starting layout for vacuum pumping, vacuum instrumentation, and vacuum control systems for an ET sector was presented by Greg Pigney (CERN), including a cost estimate.
- A cost estimation and optimization program has been developed by the CERN group (Ferreira and Scarcia). This will obviously be useful to analyze cost trade-offs and cost drivers to refine the cost estimate of the ET vacuum systems.
- Luigi Scibile (CERN) presented an analysis of beamtube manufacturing, storage, logistics, sustainability and installation dynamics for ET, employing the Time/Cost function paradigm.

Taken with realistic underground construction constraints, extrapolation of historical Virgo and LIGO methods for fabrication, storage, installation, leak test and bakeout could potentially lead to unacceptable project duration and labor cost. The group identified strong motivation for continued studies to boost speed and parallelization of tube production, installation and commissioning. Targets may include investigations of hierarchical leak testing; alternatives to full-sector insulation and water bakeout *in situ*; subdivision of sectors with additional valves; on-site vs. off-site fabrication and processing; adaptation of existing high-volume industrial manufacturing infrastructures (e.g., petroleum pipelines); and tunnel access enhancements to support delivery and installation at multiple worksites in parallel.

### C. Working Group Summaries

During the second afternoon of the workshop, three separate working group sessions were held on the following topics:

T1. Materials and surface studies, chaired by Dan Henkel and Stefan Szoboda (CERN).

T2. Design, manufacturing, post-manufacturing treatment, QA and assembly, chaired by Cedric Garion, (CERN) Guillaume Deleglise (CNRS)

T3. Pumping system, valves, sectorization and bakeout, chaired by Antonio Pasqualetti (EGO-Virgo) and Giuseppe Bregliozzi (CERN)

Brief preliminary summaries of these working groups were presented on the third (Wednesday) morning of the workshop. Presumably, final reports from each working group will be presented to all attendees at some point following the example of the 2019 LLO workshop.

[Note: I did not have access to written versions of the preliminary summaries of these three working group reports at the time of this compilation of this workshop summary. Therefore, I expect a final workshop report will have more detail].

### D. Some final remarks

I was asked to present a ~5min summary of the workshop at the end of the morning session. I made the following points:

Mild steel was presented a possible vessel material for GWD beam pipes at the GWD workshop at LLO in January of 2019. Work performed since then and presented at this workshop confirms that mild steel is indeed a viable candidate material. There are obvious advantages in cost, manufacturability, and hydrogen content and possibly with H<sub>2</sub>O outgassing. Pending further outgassing and bakeout studies, mild steels may also offer an advantage with lower required bakeout temperatures for H<sub>2</sub>O reduction in comparison to stainless steels.

These important results on both H<sub>2</sub> and H<sub>2</sub>O outgassing have been obtained by four different laboratories since the last GWD workshop in 2019 and they confirm the earlier measurements obtained by Park, et al in 2016. Further studies are needed to characterize and optimize a useful passivation layer that may be forming on vacuum baked mild steel surfaces that may be some form of magnetite.

I noted ( as a member of the US contingent) that I and my colleagues were impressed by the collaboration that CERN has assembled for its 3-year project to support the ET design efforts and to build three prototype ET beampipe sections. In addition, we were impressed with the wider coalition attending the workshop that represented many of the national laboratories, universities and industries currently participating in the ET project across Europe.

We noted significant progress presented at this meeting on a vacuum system design for the beampipes, support structures for the beampipes, an initial study of baffles design for the beampipes, control and data acquisition systems, bakeout equipment and scenarios, leak check requirements and scenarios, a cost projection model for vacuum equipment and an overall project management structure.

Finally, on behalf of all the attendees, I offered our thanks to Paolo Chiggiato, his group's assistant, Carnita Herve, and all of his group members at CERN who helped organize this workshop.

Note: as a follow-up, I along with Mike Zucker, Albert Lazzarini ,Paolo Chiggiato and several of the attendees from Virgo thought that these workshops should be continued on an approximate annual time cycle.

## Appendix B:

### Participants in Beampipes for Gravitational Wave Telescopes 2023 CERN, 27-29 March 2023

First	Last	Affiliation
Martin	Adams	NIKHEF
Marc	Andrés Carcasona	IFAE
Stefan	Ballmer	Syracuse University / Cosmic Explorer
Marije	Barel	Nikhef
Katharina	Battes	Karlsruhe Institute of Technology (KIT)
Giuseppe	Bregliozzi	CERN
Beatrice	Busetto	SAES Getters S.p.A.
Zuxing (Alex)	Chen	Fermilab
Paolo	Chiggiato	CERN
Roberto	Cimino	INFN LNF
Livia	Conti	INFN - Padova
Mickaël	Crouvizier	CERN
Paul	Cruikshank	CERN
Manjunath	Dakshinamurthy	CERN
Krista	de Roo	Nikhef
Guillaume Julien	Deleglise	CNRS Centre National de la Recherche Scientifique (FR)
Francesco	Dinh	SAES getters
Fred	Dylla	MIT LIGO Project
James	Fedchak	National Institute of Standards and Technology (NIST)
Jon	Feicht	California Institute of Technology
Alessandro	Ferrara	SAES getters
Leonel	FERREIRA	CERN
Melina	Fuentes-Garcia	LIGO Caltech
Julien	Gargiulo	EGO (European Gravitational Observatory)
Cedric	GARION	CERN
Aniello	Grado	INAF/INFN
Steffen	Grohmann	KIT Karlsruhe Institute of Technology
Jinane	Haddad	Atlas Copco
Stefan	Hanke	KIT Karlsruhe Institute of Technology
Hana	Havlikova	CERN
Daniel	Henkel	Material Forensics LLC
Jef	Hoste	Werkhuizen Hengelhof - AGIT Aachen - POM Limburg - FEF Aachen -
Pauline	Huguenin	Aperam
jose	JIMENEZ	CERN



Alexandre	Lacroix	LAPP IN2P3
Peter	Lambertz	Leybold
Angélique	LARTAUX	IJCLab
Pierre-Emmanuel	Leger	APERAM
Yulin	Li	Cornell University
Lutz	Lilje	DESY -MVS-
Mario	Martinez-Perez	The Barcelona Institute of Science and Technology (BIST) (ES)
Andrea	Moscattello	University of Padua
Juli	Mundet	IFAE
Michele	Mura	SAES Getters S.p.A.
Christian	Pap	Ecoclean GmbH
Antonio	Pasqualetti	EGO
Ana Teresa	Perez Fontenla	CERN
Tommaso	Porcelli	SAES Getters S.p.A.
Michele	Punturo	INFN Perugia
Ellwyn	Purrio	C3DM Germany
Marion	Purrio	FEF Aachen
Purnalingam	Revathi	Rheinisch Westfaelische Tech. Hoch. (DE) RWTH Aachen University
philippe	ROSIER	CNRS IJCLAB
Carlo	Scarcia	Rheinisch Westfaelische Tech. Hoch. (DE), CERN
Ralf	Schleichert	Forschungszentrum Jülich GmbH
Daniel	Schrade	Ecoclean GmbH
Stefano	Sgobba	CERN
Achim	Stahl	Rheinisch Westfaelische Tech. Hoch. (DE)
Yasunori	Tanimoto	KEK
Martijn	van Overbeek	Nikhef
Nick	van Remortel	Universiteit Antwerpen
Audrey	Vichard	CERN
Patrick	Werneke	Nikhef
Michael	Zucker	Caltech and MIT