Exploring Large Vacuum Systems at LIGO

A Brief Introduction to the Vacuum Challenges of the Cosmic Explorer

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AVS 69th International Symposium & Exhibition
Vacuum Technology Division - Particle Accelerators and Large Vacuum Systems
November 7th, 2023

Outline

- LIGO & Cosmic Explorer
    - Vacuum system drivers, requirements & challenges
- Studies on alternative beamtube materials
    - Mild steel manufacturing and outgassing
- Techniques for eliminating high temperature water bakeouts
    - Low temperature bake experiments
    - Ultra-high-purity dry air backfill experiments
    - Traveling induction heater experiments

Laser Interferometer Gravitational-Wave Observatory (LIGO)

- Michelson interferometer → two 4-km arms
- Detect major events in our universe → binary black hole, binary neutron star, black hole-neutron star collisions
  - Sensitivity up to 160 MPc* → ~520 million light years away!
- Stringent noise requirements
  - Ultra-high-vacuum (UHV) environment
  - Sealing and pumping
  - Contamination control
  - Material outgassing (water, hydrogen, hydrocarbons, etc.)
  - Vibration isolation/dampening
  - Stray light mitigation

LIGO: *(Top) Aerial view of Livingston, Louisiana site (LLO) and (Bottom) Ground view near mid-station of Hanford, Washington (LHO). Two sites 3000 km apart operating simultaneously for coincident detection.*

** Coalescing binary neutron stars sensitivity currently in observation run 4.*

Gravitational wave strength

Ability to detect gravitational waves relies on detector sensitivity (or strain)

$$h = \Delta L / L$$

LIGO's 4 km arms can detect a change of

$$\Delta L = h \times L \approx 10^{-22} \times 4,000\, m \approx 4 \cdot 10^{-19}\, m$$

Increased **arm length** → Increased **sensitivity**

Cosmic Explorer (CE)

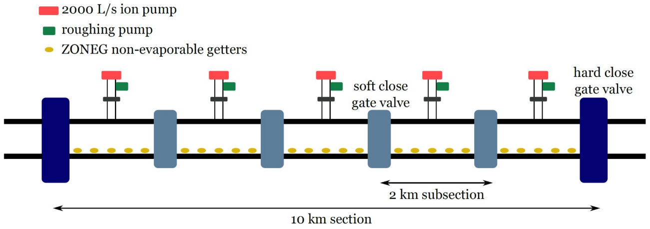
- Third generation gravitational wave detector that aims to scale LIGO detectors by a factor of 10!
    - LIGO's 4 km arms scaled to **40 km arms!**
- Vacuum size: 90-million-liter vacuum system nominally sustained at 1 x 10^{-9} Torr
- Anticipated detector sensitivity of ~ 10^{-25} $Hz^{-½}$
    - Looking back to "Cosmic noon"
- Plan for multiple detectors: 40 km and 20 km pair
- Vacuum system cost
    - $635M for CE UHV system
- Collaborations on vacuum challenges
    - US groups
        - NIST, Jefferson Lab, College of William & Mary, Dan Henkel (metallurgy expert, Material Forensics LLC), Fred Dylla (UHV materials expert, past AVS President)
    - European colleagues
        - CERN (VSC group, Paolo Chiggiato), Einstein Telescope

***Cosmic Explorer**: Artist illustration of aerial view of Cosmic Explorer.*

Vacuum System Drivers

Geometry, Pumping, Materials

- Same geometry as LIGO except for the length of vacuum arms
- Alternative beamtube material → mild steel
- Pumping configuration TBD by ultimate outgassing properties of materials
  - Non-evaporable getters (NEG, such as ZAO) & Ion Pumps along the arms - will use distributed pumping which is not the case for LIGO
  - Large cryopumps at termini
  - 2 km modules that repeat for 40 km



***CE Beamtube Sectioning**: Initial design concept for CE beamtube sectioning incorporated hard and soft close gate valves, ion pumps, and NEG's.*

Vacuum System Requirements

UHV & Outgassing

Ultra-high-vacuum required:

- $P_{Beamtubes} < 10^{-9}$ Torr
- $P_{Chambers} < 10^{-9}$ Torr

Partial pressures required):

- $P(H_2) < 10^{-9}$ Torr
- $P(H_2O) < 10^{-10}$ Torr
- $P(C_xH_y) < 10^{-14}$ Torr

	Beamtubes			Chambers	
Species	Req / torr	Goal / torr	LIGO Achvd / torr	Req / torr	Goal / torr
He	1.3×10^{-9}	3.4×10^{-10}		8.8×10^{-10}	7.9×10^{-11}
H_2	3.3×10^{-10}	8.3×10^{-11}	3.4×10^{-9}	3.1×10^{-9}	2.8×10^{-10}
Ne	1.8×10^{-10}	4.5×10^{-11}		3.9×10^{-10}	3.5×10^{-11}
H_2O	3.0×10^{-11}	7.6×10^{-12}	2.3×10^{-12}	1.0×10^{-9}	9.4×10^{-11}
O_2	2.1×10^{-11}	5.3×10^{-12}	2.0×10^{-13}	7.8×10^{-10}	7.0×10^{-11}
N_2	1.9×10^{-11}	4.7×10^{-12}	1.0×10^{-13}	8.3×10^{-10}	7.5×10^{-11}
Ar	6.7×10^{-12}	1.7×10^{-12}	9.0×10^{-14}	2.8×10^{-10}	2.5×10^{-11}
CO	5.8×10^{-12}	1.4×10^{-12}	2.0×10^{-12}	3.3×10^{-10}	3.0×10^{-11}
CH_4	4.8×10^{-12}	1.2×10^{-12}	2.2×10^{-11}	4.4×10^{-10}	4.0×10^{-11}
CO_2	2.8×10^{-12}	6.9×10^{-13}	4.0×10^{-13}	2.7×10^{-10}	2.4×10^{-11}
Xe	6.3×10^{-13}	1.6×10^{-13}		1.5×10^{-10}	1.4×10^{-11}
100 u H_nC_m	8.9×10^{-14}	2.2×10^{-14}		1.8×10^{-10}	1.6×10^{-11}
200 u H_nC_m	1.7×10^{-14}	4.2×10^{-15}		1.2×10^{-10}	1.1×10^{-11}
300 u H_nC_m	6.2×10^{-15}	1.5×10^{-15}		1.0×10^{-10}	9.2×10^{-12}
400 u H_nC_m	3.1×10^{-15}	7.6×10^{-16}		8.8×10^{-11}	7.9×10^{-12}
500 u H_nC_m	1.7×10^{-15}	4.3×10^{-16}		7.9×10^{-11}	7.1×10^{-12}
600 u H_nC_m	1.1×10^{-15}	2.8×10^{-16}		7.2×10^{-11}	6.5×10^{-12}

***CE Outgassing**: Preliminary residual gas outgassing requirements for CE.*

Vacuum System Challenges (I):
Studies on alternative beamtube material

Why not use stainless steel (SST) like the LIGO beamtubes?

Several factors considered when selecting BT material.

Besides costs associated with SST, **H_2O outgassing** is a main concern.

- Water's binding energy on SST centered around 1 eV
  → **long pump down times** and **long bake times** to remove water

Outgassing studies on **mild (low carbon) steels** proved it a viable option
→ about same H_2O outgassing as SST, but (~100x) less H_2 outgassing

LLO Beamtube: *Side view of exposed beamtube during construction at LLO.*

LIGO

Studies on alternative beamtube materials

Mild Steel - Manufacturing

Gas or petroleum pipeline:

- Cost reducer → saving $300M vs SST
- Large order size available → 80 km "small" order
- Established QA system
- Spiral welded
- No He leak testing available → need to revive leak detector
- 0.5" thick walls → stable to atm, resistant to buckling/damage, self supporting
- Epoxy coatings available for corrosion prevention
- Natural oxide layers (magnetite) → outgassing, optical scatter, corrosion

***Gas pipe mill**: Mills capable of large order sizes and established QA system in place for fuel gas pipeline safety (US DOT).*

Studies on alternative beamtube materials

Mild Steel - Outgassing

- Mild steel exhibits much lower **H_2 outgassing** vs stainless steel, mainly due to manufacturing processes (vacuum degassing during melting)
  - $q = 2 \times 10^{-16}$ Torr L/s cm^2 for A36*
  - $q = 7 \times 10^{-12}$ Torr L/s cm^2 for 304L*
- Mild steel **H_2O outgassing** levels comparable to stainless steel
  - $q_{10} \sim 10^{-10}$ Torr L/s cm^2 for A36*
  - $q_{10} \sim 10^{-10}$ Torr L/s cm^2 for 304L*
  - $q_{10} = 3.5 \times 10^{-10}$ Torr L/s cm^2 for P355N**
  - $q_{10} = 2.3 \times 10^{-10}$ Torr L/s cm^2 for 304L**
- Internal coatings to reduce water outgassing
- External coatings to prevent corrosion and provide protection

* J Fedchak *et al.*, "Outgassing studies of A36 Mild Steel," AVS 69 conference, 2023.
** I Wevers , ""Vacuum measurements of materials and coatings for GWD beampipes," Beampipes for Gravitational Wave Telescopes, CERN conference, 2023.

Vacuum System Challenges (II):

Elimination of high temperature water bakeouts

- Low temperature H_2O bake experiments (<100°C) desirable
  - High temp H_2O bakeout (~200°C) very costly (equipment, labor, time)
  - **L**ivingston **T**ube **R**ecovery **EX**periment (LTREX)
- Ultra-high-purity dry air backfill experiments
  - UHP dry air backfill to remove water in low conductance system (e.g. pulse-purging in semiconductor gas systems)
  - To be performed with LTREX
  - **V**apor **O**utgassing & **R**eexposure **T**est **EX**periment (VORTEX)
- Traveling induction heater to remove water
  - To be performed on mild steel pipe, pre-prototype of CE beamtube

***LTREX**: 7.5 m long, 1.2 m diameter, 3 mm wall thick residual section of iLIGO beamtube, matches BT surface properties, used to explore emergency venting/recovery protocols at LIGO.*

***VORTEX**: Table top experiment to investigate material outgassing.*

***RF induction heating**: Magnetic properties of mild steel make it more appealing for RF heating.*

Summary

- LIGO & Cosmic Explorer
    - Several vacuum system challenges in creating 3rd gen gravitational-wave detectors
- Studies on alternative beamtube materials
    - Manufacturing costs significantly reduced with mild steel (gas pipeline)
    - Studies on mild steel show low intrinsic hydrogen content than SST and water outgassing levels comparable to SST
- Elimination of high temp water bakeouts
    - Costs of vacuum system greatly reduced with low temp bakeouts
    - UHP dry air backfill experiments underway
    - In design process of traveling induction heater experiments

Feedback and sharing any experience that can inform us are welcome!

Reference Talks

For reference, please see the following **talks**:

- **VT-MoA-9**: “Outgassing Studies of A36 Mild Steel,” ***James Fedchak***, *E. Newsome, D. Barker, S. Eckel, J. Scherschligt*, NIST-Gaithersburg
- **INVITED VT-TuM-10**: “Exploring the Gravitational Wave Universe: Vacuum Systems for LIGO A+ and Beyond,” ***Michael Zucker***, LIGO Laboratory, Caltech and MIT

Thank you!

Thank you for your attention!

Questions?

References

[1] LIGO website: https://www.ligo.caltech.edu/

[2] CE website: https://cosmicexplorer.org/

[3] CE will consist of two 40 km arms: hard close GV's every 10 km and soft close GV's every 2 km. Same beamtube geometry as LIGO: 48" diameter, but 0.5" thick.

[4] Chongdo Park, Taekyun Ha, Boklae Cho; Thermal outgassing rates of low-carbon steels. J. Vac. Sci. Technol. A 1 March 2016; 34 (2): 021601. https://doi.org/10.1116/1.4936840

[5] Park, C., Kim, S.H., Ki, S., Ha, T., Cho, B. Measurement of Outgassing Rates of Steels. J. Vis. Exp. (118), e55017, doi:10.3791/55017 (2016). https://doi.org/10.3791/55017

[6] J. Fedchak JVST B 39 024201 (2021). https://doi.org/10.1116/6.0000657

[7] "Vacuum measurements of materials and coatings for GWD beampipes," Ivo Wevers, Beampipes for Gravitational Wave Telescopes 2023, CERN conference.

[8]