LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

LIGO Laboratory / LIGO Scientific Collaboration

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Review of the LIGO-INDIA Vacuum System Requirements Document-VSRD

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Executive Summary

The Vacuum System Requirements Document (VSRD) for the LIGO-India gravitational wave (GW) detector, as prepared by the Institute for Plasma Research (IPR), Gandhinagar, India has been reviewed and is approved. The VSRD is a compilation of the vacuum system requirements (among others) needed to successfully house and operate the GW detector. The VSRD has fulfilled its goal and the review is now closed.

The VSRD has undergone several detailed reviews by the LIGO-USA team, and is now at revision level five (7). This revision is considered final, approved and the review process complete. The document can be found in the DCC at E1700313. Since the VSRD is the first vacuum system document that IPR has published, it should be considered a requirements gathering document and not a design document.

The review charge requested eight areas be evaluated, from basic design through vendor approval also quality assurance. Some of the charge areas could only be partially answered or were beyond the scope of the VSRD although all aspects of the charge were discussed with IPR staff. IPR has indicated that out of scope details will be answered in subsequent documents as the design matures. The VSRD review trail will provide a checklist to insure all of the charge questions are addressed.

IPR is currently developing a Conceptual Design Review (CDR) document, which is substantially more detailed than the VSRD. IPR personnel visited Caltech in October 2019 and outlined the CDR, indicating this document can be expected to be ready in approximately 6 months.

IPR is actively soliciting bids for chambers (HAM, BSC) and beamtube manufacture. Their intent is to develop a prototype or first article system similar to what LIGO-USA did with Chicago Bridge and Iron (CB&I) and Process System International (PSI). Unlike LIGO-USA, IPR intends to engineer and manage the production of the vacuum system instead of biding the job (to an engineering firm) to deliver a complete system. IPR is therefore assuming most of the design risk.

The VSRD does not completely answer the global NSF question *is the LIGO-India vacuum system compatible with the existing detector*, since it does not address the interface points between the detector and the chamber, although from a vacuum perspective, the system does meet the detector requirements. Closing the NSF question will require completion of the next level of engineering documents, the QA/QC and risk assessments (FMEA), and particularly getting the RRCATs inputs for critical interface locations.

Introduction

The LIGO-India Team, specifically the Institute for Plasma Research (IPR), has developed a Vacuum System Requirements Document (VSRD) for the LIGO-India vacuum system. The VSRD is intended to serve as the template for the design, construction, and commissioning of the vacuum system for the LIGO-India Gravitational Wave Observatory.

Since the initial draft in September 2017, the VSRD has undergone several comprehensive reviews by LIGO-USA personnel. A final review was held at Caltech in October 2019, resulting in Rev. 7 of the document.

The reviewers have attempted to convey the lessons that LIGO-USA has acquired over the last two decades of observatory operation, including which design requirements for initial LIGO-USA (I-LIGO) have changed based on operational experience, increases in detector sensitivity, and enhanced physics or improvements in equipment.

Over the review period an upgrade to LIGO-USA called the "A+" enhancement project has been defined. The basic A+ layout information (i.e. floor space, additional chamber requirements and filter cavity routing, etc.) has been added to Rev. 7 of the VSRD. The LIGO-India A+ configuration will be similar (but not identical) to the USA system, taking advantage that the India site is not yet confined by existing structures or site boundaries as is LIGO-USA. Full A+ details are out of scope of the VSRD.

It is the understanding of the reviewers that some deficiencies called out during the initial review will be handled by forthcoming documents. Charge areas 3, 6, 7 and 8, partially addressed, will be covered/closed by future documents.

The review committee was charged to provide a detailed evaluation of the LIGO-India VSRD to ensure that IPR's vacuum system design will be compatible with the requirements necessary for integration and operation of the LIGO detector. This review will provide supporting evidence to the National Science Foundation (NSF) that the existing (spare) LIGO detector can be successfully integrated into the Ligo-India vacuum system and the confidence to transfer the detector from the USA.

The charge asked the reviewers to evaluate eight key areas, specifically;

1. *Determine whether the requirements provide a complete basis for the technical design of the LIGO-India vacuum system.*
2. *Determine whether the requirements and performance specifications are compatible with the installation and operation of the LIGO detectors, including both the currently operating detectors and the planned updates such as A+. If significant deviations from the LIGO-USA vacuum system are planned, comment on the risks and advantages of those deviations.*
3. *Determine whether the interfaces to the detectors and facilities are sufficiently defined, including baffles and other auxiliary systems.*
4. *Assess whether the requirements are achievable.*
5. *Analyze the practicability for control and monitoring of the vacuum system.*
6. *Consider the possible safety concerns and failure modes for this system and recommend protections that should be required.*
7. *Are the plans for quality assurance and quality control (QA/QC) and contamination control adequate, with an appropriate mixture of vendor-supplied and independent test data and certifications? Do they cover the complete process from initial fabrication through installation?*
8. *Is there an adequate implementation plan for vendor qualification?*

Review Findings by Charge

1. *Determine whether the requirements provide a complete basis for the technical design of the LIGO-India vacuum system.*

   Finding: The VSRD has fulfilled this issue.

   Recommendations:

- The VSRD is a top-level document that defines the overall approach to the vacuum system design. In this capacity the VSRD has fulfilled its requirements.
- Subsequent documents are now being prepared, particularly a Conceptual Design Review (CDR) detailing each aspect of the system. This document is expected in 2nd quarter of 2020.

- Prototype systems are being procured, which is similar to what was done during the LIGO-USA development.

2. *Determine whether the requirements and performance specifications are compatible with the installation and operation of the LIGO detectors, including both the currently operating detectors and the planned updates such as A+. If significant deviations from the LIGO-USA vacuum system are planned, comment on the risks and advantages of those deviations.*

Finding: The VSRD has fulfilled this issue.

Recommendations:

- The vacuum system design goal will support a sensitivity of 10^{-24} strain/√Hz at 100 Hz, and will provide adequate margin for future upgrades. Partial-pressures of residual gasses have been defined, so have particulate levels, being equivalent to the LIGO-USA system.
- Lessons learned by LIGO-USA have been incorporated. For example test-mass charging, shock loading, stray-light baffles, gate valve design, improved getter pump materials, hydrogen partial pressure requirements, etc., have been thoroughly discussed with IPR personnel.
- Vacuum system and facility details incorporating "A+" detector upgrades have been included. It is likely that the filter cavity (FC) will be oriented differently in India, and the HAM chambers layout will be simpler since LIGO-India will be less constrained by site boundaries or existing buildings.
- The VSRD has indicated proposed improvements or deviations from the existing design. For example the LIGO-India beamtube will likely incorporate dual gate valves at the MID position, a distinct improvement compared to the LIGO-USA layout. A mid-station cryopump may also be incorporated, reducing the (water) pressure profile in the beamtube. When appropriate, other upgrades or deviations should include analyses that detector sensitivity will not be compromised.

3. *Determine whether the interfaces to the detectors and facilities are sufficiently defined, including baffles and other auxiliary systems.*

Finding: The VSRD has partially fulfilled this issue.

Recommendations:

- The VSRD does not define all the interface requirements for the detector. The final interface will be a collaboration between IPR and the Raja Ramanna Centre for Advanced Technology (RRCAT), Indore, India, with RRCAT taking the lead role. The reviewers have not seen documentation from RRCAT therefore cannot assess this charge item. The detector interface requirements have been discussed in detail with LIGO-India personnel, and although the VSRD does define key parameters such as diameters, clear aperture, alignment, etc. no detector attachments or keep-clear areas have been defined.
- The baffle type, their dimensions, the pseudo-random edge condition, and positioning in the system have been defined. LIGO-India follows the Livingston configuration for baffle type

and position. The attachment method (expansion joint) has been discussed, any additional details can be part of the CDR.

- There have been substantial recent (2019) stray light improvements that should be passed to the India team, possibly during the systems-level review.
- The VSRD only briefly discusses the HEPI (seismic) suspension interfaces. A detailed layout with vacuum penetrations defined and all stay-clear areas internal and external to the vacuum is expected to be included in the CDR.
- The interfaces between the component parts have been adequately defined.
- The intended coordinate system should be discussed, at least briefly, rather than just mentioned (in Annex B) as RRCATs responsibility.

4. *Assess whether the requirements are achievable.*

Finding: The VSRD has fulfilled this issue.

Recommendations:

- The beamtube materials, fabrication, alignment, welding, bakeout, ultimate pressure, and leak testing have been thoroughly discussed, and are considered achievable. A separate document detailing the beamtube material approval process and engineering (particularly welding) is suggested. It is anticipated that the design of LIGO-India will be similar to LIGO Livingston, however there will be differences due to materials availability, fabrication methods particular to the Indian manufacturing sector, metric system based standards and materials, site access, etc. Potential differences have been discussed with LIGO-USA personnel. Deviations should be documented in the CDR phase of the project.
- A DCC page for archiving the beamtube steel hydrogen outgassing data should be of the first order. Details should include experimental technique, material and calibration data, air firing methods including temperature profile.
- Documentation of system engineering requirements, engineering drawings, manufacturing documents, materials and process specifications including quality assurance requirements are briefly discussed in the VSRD, indicating that a documentation system will be developed. Details of the document tree should be part of the CDR.
- The roles and responsibilities of all parties, i.e. empowered board, IPR, RRCAT, DCSEM, external contractors, vendors, etc. should be developed. The VSRD briefly mentions this, however a stand-alone document, diagram or table denoting roles and responsibilities should be developed and included in the document tree.
- Material inspection, control, suspense and release criteria should be part of the quality documentation. This is particularly critical for the steel being fabricated into the beamtube.

5. *Analyze the practicability for control and monitoring of the vacuum system.*

Finding: The VSRD has fulfilled this issue.

Recommendations:

- The Vacuum Control and Monitoring System (VCMS) system is well defined.

- The VCMS envisioned for LIGO-India provides significantly more automated control than that of LIGO-USA. During the CDR phase of the project IPR should discuss error-trapping, operator training, manual override capabilities, software development and software version control.

6. *Consider the possible safety concerns and failure modes for this system and recommend protections that should be required.*

   Finding: The VSRD has addressed this issue, noting that the FMEA will be handled by separate set of documents.

   Recommendations:

- A section in the upcoming CDR discussing IPR proposed improvements to or deviations from the existing design should be included. These upgrades should include corroborating analyses that detector sensitivity will not be compromised.
- IPR has stated that the beamtube enclosure will be constructed and placed simultaneously with the beamtube, to protect the beamtube from mechanical damage.
- The beamtube bakeout temperature proposed is 150 C, identical to LIGO-USA requirements. IPR indicated that the engineering and development of the expansion bellows has been started.
- IPR has stated that a redundant mid-station vacuum valve will be incorporated, also a mid-station cryopump may be included. Both of these design improvements are encouraged.
- Seismic and wind load conditions should be mentioned in the CDR. The extra height of the LIGO-India buildings should be analyzed for wind-induced tilt of the slab. This analysis should be part of the DCSEM review team's responsibility (F. Asira et. al).
- Deviations from LIGO-USA design are solely the responsibility of LIGO-India.
- FMEA: E960111 is referenced as a template.

7. *Are the plans for quality assurance and quality control (QA/QC) and contamination control adequate, with an appropriate mixture of vendor-supplied and independent test data and certifications? Do they cover the complete process from initial fabrication through installation?*

   Finding: The VSRD has fulfilled this issue.

   Recommendations:

- The VSRD Annex C mentions that QA/QC requirements will be handled by additional documents. A schedule indicating when these documents will be available is encouraged.
- The contamination plan is well described and includes ISO air quality requirements, flooring materials, air temperature, component cleaning, fabrications, clean rooms, etc.
- The VSRD briefly mentions materials and process control, deviation waiver authority, as-designed verification, document revision control, calibration standards, etc. The complete set of requirements should be included in the CDR or in a standalone document at the time of the CDR. The process which non-conforming materials will be reviewed, rejected or cleared is of keen interest.

- Performance requirements that must be verified or demonstrated by the vacuum system are satisfactorily listed. This includes components sourced from vendors. IPR has indicated their intent is to start with a prototype system and down-select vendors based on their bid and performance. Full scale HAM, BSC, and a section of beamtube will be assembled on site.
- Relevant drawings and specifications from LIGO-USA are included in the VSRD annex.
- A quality assurance plan, including materials and process control, deviation waiver authority, as-designed verification, document revision control, calibration standards, etc. should be included at/near the time of CDR. A dedicated meeting addressing the QA/QC plan is expected.
- Governing ASME, ISO, and India-Standard codes and specifications are included in the VSRD.
- Standardized cleanroom requirements to ISO specifications rather than obsolete FED 209 have been incorporated.

8. *Is there an adequate implementation plan for vendor qualification?*

   Finding: This requirement is out of scope of the VSRD.

   Recommendations:

- A vendor qualification plan has been described during discussions with IPR personnel however a monitoring program has not be described. Criteria for success should be clearly listed, with performance to requirements documented. An overview of this process should be part of the CDR.
- Using ISO-9001 certified vendors is encouraged.

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The review team is acknowledged for their detailed and thorough review. The team members were:

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