Vacuum System Requirement for a 5 km Baseline of Gravitational-Wave Detector

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Abstract. Gravitational wave laser interferometer detectors use a pair of cylindrical vacuum tubes, placed perpendicular to each other, in which the partial pressure of hydrogen is required to be ~10⁻⁹ mbar to obtain residual gas-phase noise of ~10⁻²⁵ Hz⁻¹². It is advantageous to use longer arm-length interferometers, as the total strain sensitivity decreases proportionally to arm length. The tube diameter of the interferometer is set by the light scattering requirements, and also by the possible need for additional optical cavities within the tube. Vacuum performance depends critically on the stainless-steel outgassing rate as well as the conductance of the tube. A novel method of low temperature vacuum baking using solar bakeout technique is also mentioned in this paper.

1. Introduction

The Australian Consortium for Interferometer Gravitational Astronomy (ACIGA) is developing a proposal to install a 5-Km gravitational wave interferometer at Australian International Gravitational Observatory (AIGO) site at Gingin, Western Australia. Presently three multikilometer scale gravitational wave detectors have been constructed in the northern hemisphere. Two detectors in the USA (LIGO) [1] are functioning with a strain sensitivity of ~3x10⁻²³ Hz⁻¹², whereas the VIRGO [2] detector in Italy is expected to have similar sensitivity. There are two smaller gravitational wave detectors in Germany (GEO) [3] and Japan (TAMA) [4] which are functioning at lower sensitivity. By the middle of the next decade, the northern hemisphere detectors will have their sensitivities improved, through the use of high optical power and other advanced technique, to a gravitational wave strain sensitivity of ~2x10⁻²⁴ Hz⁻¹². If the present long-baseline detectors in the northern hemisphere were combined with a single detector in the south west part of Australia, the average angular resolution [5] would be improved by a factor of 4, thereby reducing the area of uncertainty in the sky by more than one order of magnitude. The AIGO interferometer will be designed to achieve [6] strain sensitivity similar to that of the proposed advanced detectors in the northern hemisphere.

To attain such sensitivity the detector requires to be in ultra high vacuum with the partial pressure of different species like hydrogen, water, nitrogen, carbon monoxide, carbon dioxide and...
methane controlled to a permissible limit. Of all the species, hydrogen and hydrocarbons play a very important role in controlling the vacuum. Among this hydrogen is the critical species as it is continually outgassed from stainless steel even at room temperature [7]. Moore has analyzed the variation in time required to achieve low outgassing rate from the vacuum chamber. According to him, at high bake temperatures, the hydrogen concentration becomes uniform, so the time to degas to a specific level is linear with the thickness of the vacuum chamber. Reducing the wall thickness by a factor of 10 will reduce the bake out time by a factor of about 10.

The proposed AIGO interferometer will have a pair of vacuum tube made of stainless steel 304L (SS304L), 5 km long and will have an optimal internal diameter which will regulate the partial pressure of hydrogen to < 10⁻⁹ mbar. The consideration of tube diameter and the vacuum calculations has been reported in our earlier paper [8]. For clarity a brief summary of the content is reported here. The schematic setup of the AIGO gravitational-wave detector is shown in figure 1.

![Schematic setup of gravitational-wave detector](image)

Fig. 1 Schematic setup of gravitational-wave detector

Vacuum tubes connect the end stations, which contain pairs of mirrors forming Fabry-Perot cavities. These mirrors at the end stations are suspended from multistage low-frequency vibration isolators, which attenuate the seismic noise. Baffles, designed to minimize the scattering of light will be placed inside the tube during the fabrication of the tube. It is proposed to fabricate the tube in long lengths on site from rolls that have been pretreated at high temperature. For the interferometer baseline, three different tube diameters are considered. They are 70, 100 and 120 cm respectively. The number of vacuum pumps required to evacuate the baseline will depend mainly on the tube diameter and the outgassing of the material. Table I shows the variation in calculated value of vacuum obtained in the three different tube diameters when an outgassing of 1.5x10⁻¹⁵ mbar l cm⁻² s⁻¹ is achieved.
Table 1. Vacuum obtained for three different diameter tubes.

| Diameter (cm) | 70  | 100 | 120 |
|---------------|-----|-----|-----|
| Length (km)   | 1.00| 1.25| 1.67|
| Average Pressure (mbar) | $8.8 \times 10^{-10}$ | $7.2 \times 10^{-10}$ | $9.3 \times 10^{-10}$ |
| Time taken (days) | 5 | 5 | 7 |
| Number of TMP | 5 | 4 | 3 |

We have assumed that the vacuum tubes will be evacuated using turbo molecular pumps (TMP) backed by suitable backing pumps. Provisions to integrate getter pumps in future will be made in order to improve the partial pressure requirement for hydrogen.

The SS304L before being formed into a tube will undergo air bake procedure at about 450°C in a low humidity atmosphere to reduce the hydrogen outgassing rate. Later, after fabrication and installation it will undergo a low temperature bake of about 150°C in vacuum to remove species such as H₂O, CO and CO₂. The air baking procedure should ensure a hydrogen-outgassing rate of $1.5 \times 10^{-15}$ mbar l cm⁻² s⁻¹. The low temperature vacuum bakeout will be performed using a solar bakeout technique [9], wherein the tube will be housed in a solar bake out enclosure that has already been tested on a prototype system.

2. Low temperature solar vacuum bakeout

Solar bakeout procedure will be used for the vacuum baking of the long baseline tube. This will maintain the partial pressure within the vacuum tube to a permissible level. The bakeout technique as shown in the figure 2 will consist of fibre glass insulation box structure, double-glazed with polyester film on the roof. This double glazed polyester roof will prevent convective energy loss and will retain the long wave radiation within the enclosure. After the baking process is completed, a hinged insulated cover installed across the tube will prevent a further rise of temperature. The bakeout procedure will be done over a summer season allowing an integrated heating time of about 30-50 days. Data obtained from the prototype experiment gives strong evidence that an average maximum temperature of 140°C can be obtained by this technique. Proper ventilation and air circulation will ensure uniform heat distribution on the tube as well as regulate the temperature within the enclosure to a desired level, as it is known that a solar collector of this type will contain strong vertical temperature gradients.

This novel technique used for baking the proposed 5 km vacuum tube will be a cost saving factor compared with the electrical heating systems. The results obtained are in par with the electrical heating procedure performed for outgassing.
3. Tube design and vacuum monitoring

The interferometer vacuum baseline is constructed using SS304L material. The tube will be fabricated at site in long lengths from the rolls that are pretreated to reduce hydrogen outgassing. The rolls will be spiral welded to form the beam tube. Baffles will be welded spirally within the tube and will follow the spiral weld of the tube. Extreme care will be taken of during welding so that the tube is devoid of any leaks or air pockets. Gaskets used at joints or blanks meant for the interface with the vacuum pumps will be made of copper. SS304L bellows will be located at 200 m intervals along the tube to compensate for the thermal expansion during the baking process. Stiffening rings will be used at regular intervals to prevent the collapse of the tube under atmospheric pressure. The tube will be supported on concrete footings along the length and will be surveyed to ensure linearity within 5 mm.

Vacuum monitoring and control will be performed by a general-purpose automation controller system that will have the facility to remotely monitor and control the vacuum components through a computer network, as well as via the internet.

4. Vacuum pump down procedure

The tube will be roughed with a dry pump to $\sim 10^{-3}$ mbar pressure. To evacuate hydrogen, TMPs with good compression ratio for hydrogen and lighter species will be used. This will ensure partial pressure requirement for hydrogen within the tube to a great extent. Provision will be made on the vacuum tube to integrate getter pumps to further improve the partial pressure requirement. These getter pumps will be switched ON once the tube reaches a high vacuum regime with the help of TMP. A combination of getter pumps along with TMP could help to improve the vacuum within the tube to a greater extent. Although we prefer to use TMP alone for evacuation, ports will be provided to integrate getter pumps in future.
The vacuum pumps will be distributed equally on the both arms as shown in the figure 3. We have assumed that the end-station tanks, which are used to install the vibration isolators and the related optics, will be evacuated separately and that they do not contribute to the additional load. To improve the vacuum within the tube, the pump-to-pump spacing needs to be reduced to a reasonable limit. The presence of optical baffles within the tube deteriorates the vacuum by a factor of 3.2. The calculation performed is for the worst-case baffle design, wherein the baffles run along the tube with a separation of 1 meter among them. But a more realistic baffle design which will be less in number, shows that the degradation in the vacuum is negligible. The pumping speed of TMP is not a critical parameter in our calculation. There is only 7% degradation in pressure when the pumping speed is reduced from 2500 to 1000 l/s as shown in table 2.

### Table 2. Variations in vacuum parameters when TMPs with different pumping speeds are used for three different diameter tubes.

| Diameter (cm) | 70          | 100          | 120          |
|---------------|-------------|--------------|--------------|
| Average Pressure (mbar): 1000 l/s Without baffles | 2.9x10^{-10} | 2.6x10^{-10} | 3.4x10^{-10} |
| Average Pressure (mbar): 1000 l/s With baffles   | 9.4x10^{-10} | 8.3x10^{-10} | 1.0x10^{-9}  |
| Average Pressure (mbar): 2500 l/s Without baffles | 2.7x10^{-10} | 2.2x10^{-10} | 2.9x10^{-10} |
| Average Pressure (mbar): 2500 l/s With baffles   | 8.8x10^{-10} | 7.2x10^{-10} | 9.3x10^{-10} |
5. Conclusion

For the air baked SS304L outgassing rate of $1.5 \times 10^{-15}$ mbar l cm$^{-2}$ s$^{-1}$, the partial pressure requirement for the smallest diameter tube is easily met. The requirement for number of TMPs will be more for smaller diameter tube compared to the larger tube diameters. The pumping speed of the TMP is not a critical parameter, as the degradation in pressure will be only 7% when a TMP of lesser pumping speed is used. Optical baffles designed for the worst case helps to degrade the vacuum by a factor of 3.2 only. The low temperature solar bakeout technique will prove to be an energy saving factor compared to the electrical bakeout procedure.

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