New Folder Name Vacuum Technology Challenges

CALIFORNIA INSTITUTE OF TECHNOLOGY

102-33 E. BRIDGE LABORATORY
PASADENA, CALIFORNIA 91125

LIGO PROJECT
Telephone (818) 356-2129
Fax (818) 304-9834

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Heather Messenger, Editor
Laser Focus World
One Technology Park Drive
Westford, MA 01886

Dear Ms. Messenger;

Enclosed is the short paper on LIGO vacuum technology which Donna Bakale suggested I submit for the November issue of *Laser Focus World.* I am also submitting an illustrated figure which will give the readers some idea of what the LIGO vacuum system will look like. I do not have access to a photograph of the figure, just the enclosed four-color print. I am enclosing several copies in case you need them.

I hope that this manuscript is in time for your consideration. If you have any questions or additional needs, please feel free to contact me at (818) 356–2131.

Sincerely,

Stan

Stanley W. Whitcomb
Deputy Director

SEW/bb

Enclosures

cc: Donna Bakale

bcc: B. Moore
R. Vogt
S. Whitcomb
File

The Laser Interferometer Gravitational-Wave Observatory (LIGO) Project: Vacuum Technology Challenges

by

Stanley E. Whitcomb

LIGO Project

California Institute of Technology

Gravitational waves are ripples in the fabric of space-time which are produced by violent events in the distant universe. Einstein first predicted their existence in 1916 as a consequence of his theory of general relativity, but only in the past decade has technology advanced to the point where their direct detection and study has become possible. The LIGO project, a collaboration between the California Institute of Technology and the Massachusetts Institute of Technology sponsored by the National Science Foundation, is a new initiative to detect gravitational waves and to harness them for a wide range of investigations in physics and astronomy.

A LIGO detector compares the separation of test masses at the ends and corner of an "L", where each arm is 4 km long. A gravitational wave striking the detector will cause the test masses on one arm to move toward each other while causing the masses on the other arm to move apart. A laser interferometer is used to sense these motions, which are expected to be on the order of $10^{-17} - 10^{-18}$m. The project proposes to build detectors at two sites separated by more than 1500 miles. Comparisons of the signals measured at the two site will be used to eliminate local disturbances, such as micro-seisms, acoustic noise, or laser fluctuations. The two sites at large separations also serve to determine the position of the gravitational wave source in the sky by arrival time delays; ultimately, in coordination with interferometers in Europe and Asia, the LIGO will become part of a worldwide gravitational wave observatory network as the science matures.

An ultra-high vacuum system encloses the test masses and the optical beams used to sense their motion, to minimize disturbances on the detector. This vacuum system will have multiple end chambers to accommodate the test masses and their auxilliary control systems and a 1.2 m diameter beam tube spanning the full length of the "L", making it among the world's largest vacuum systems. Because it is the most expensive single component in LIGO, innovative and cost-effective designs for the vacuum system are particularly important.

The Vacuum System Requirements

The vacuum requirements for the system arise in two ways: from the effects of residual gas on the test masses, and from its effect on the optical beams. Collision with residual gas molecules produce Brownian motion of the test masses, which could mask a gravitational wave signal. This sets a vacuum requirement for the end chambers where the test masses are located. This requirement is a relatively easy one, around 10^{-6} torr.

The more stringent requirement applies to the 4-km long tubes which contain the optical beams in each arm. Statistical fluctuations in the number of molecules in the beam change the index of refraction of the residual gas. These changes cause phase shifts in the light which add noise to the measured separation. The vacuum level required to reduce this noise to a level below the ultimate sensitivity of the LIGO detectors depends on the species of gas present. Hydrogen and water are expected to dominate the residual gas. Their pressures must ultimately be reduced below 10^{-9} and 10^{-10} torr, respectively, although 1000 times higher pressures will meet the sensitivity goals of the initial LIGO interferometers.

Meeting the Vacuum Challenge

LIGO's unique requirements and the high cost of conventional approaches have driven us to develop and adopt new vacuum techniques. The most important of these are the development of stainless steel with reduced hydrogen outgassing and of lower temperature bakeout procedures.

Low Hydrogen Stainless Steel — Hydrogen is usually a major component of the residual gas in UHV systems made from stainless steel. Hydrogen diffuses through stainless steel and can be released when it reaches the surface. Starting with the hypothesis that the principal source of hydrogen is gas which is dissolved in the bulk material when the steel is fabricated, the LIGO team worked with a major stainless steel manufacturer (J&L Specialty Products Corporation, Pittsburgh, Pennsylvania) to modify the usual manufacturing process to reduce the amount of embedded hydrogen. Samples produced by J&L have been tested by the LIGO project and preliminary results show that the initial hydrogen outgassing rate for this material is 100-1000 times lower than the values which are normally quoted in the literature.

Special Bakeout Procedures - Ultra-high vacuum systems are traditionally baked to remove adsorbed gases, especially water, typically using heating tapes or ovens to raise the temperature to 400 C or more for a period of several hours. We must also eliminate residual water vapor, but the costs of traditional baking techniques are prohibitive for the LIGO beam tubes. Instead, we have been experimenting with lower temperature (around 100 C) bakeout cycles of long duration (up to 30 days). The long duration of the bake is feasible for the LIGO beam tubes, because they will be kept under vacuum indefinitely after their initial pump-down. The lower temperatures allow the use of inexpensive commercial building insulation, and a 2 km section of tube can be baked to 100C with less than 500 kW input power.

A second innovation in the beam tube bakeout is the elimination of the heater tapes; the beam tube itself will act as the heater element. Calculations have shown that a current of about 2000 amps passing through the tube will heat it to the required temperature. The voltage required to heat a 2 km length of tube is only a few hundred volts. Bellows sections in the tube (required to allow for thermal expansion) can be held to the same temperature by tailoring their insulation, even though their thinner walls (and therefore higher electrical resistance) causes greater heat deposition.

To test these ideas on a realistic scale we have built a 40 m long section of 60 cm diameter tube (half the diameter of the LIGO beam tubes) using the low hydrogen stainless steel. This tube is being used to test the outgassing rate for both hydrogen and water with different bakeout cycles. The tube is heated by passing the current directly through the tube wall. Different insulation schemes have been evaluated, and we have confirmed that we can achieve the required uniformity in the temperature.

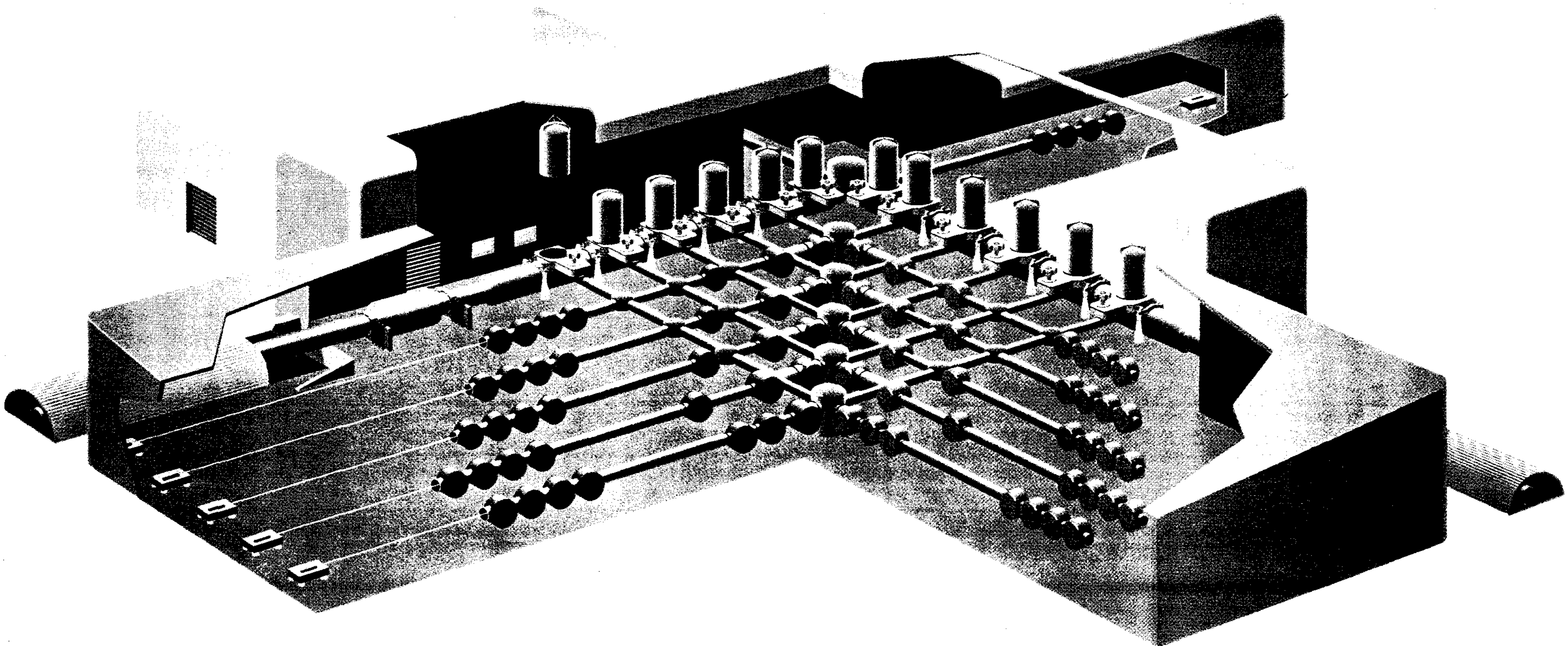
The Next Step

When it is successful, probably sometime late in this decade, LIGO will open new fields of study on the boundaries between physics and astronomy. The sources of gravitational waves which we can predict for LIGO include some of the most interesting objects in the universe - black holes, neutron stars, even the Big Bang. LIGO will offer the opportunity to test our theoretical understanding of these objects against new experimental tests, by providing information which can be obtained in no other way.

In the meantime, the development of the required technology produces its own excitement, often in ways which were unforeseen a few years earlier. By pushing the limits of precision measurements, LIGO is contributing to the development of stabilized lasers, high performance optics, and vibration isolation systems. Along with the vacuum techniques described here, these technological advancements can find applications in areas far removed from the science of gravitational waves.

Figure Caption

Cut-away view of the corner building of one of the LIGO L's showing the network of vacuum chambers which will house the test masses and auxilliary optics. The beam tubes which span the 4 km arms are visible in the semi-cylindrical structures at the left and right of the figure. The configuration shown is an advanced one, capable of simultaneously accommodating six interferometers, either in different states of development or optimized to detect different types of gravitational waves. The initial vacuum system will have fewer chambers and interconnecting tubes.



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