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Revision 2.
August 18, 1995

CALIFORNIA INSTITUTE OF TECHNOLOGY
Laser Interferometer Gravitational Wave Observatory Project
LIGO

Specification for the LIGO Vacuum Equipment

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Document Control Page

Revision	Date	By	Description of change
1.	3/27/95	JW	Dimension changes to Figures 4,5,6,7
2.	8/11/95	JW	Changes at contract award: -Delete TMC references and drawings. -Change aperture of 80K pumps to 130cm from 105cm; change aperture of associated gate valves to 112cm from 120cm. -Delete requirement for metal seals on large flanges. -Remove 6 large rough pumps from end and mid stations. Delete associated performance requirement for 4 hour roughdown. -Allow fixed pump stations for backing purposes. -Exempt turbo pump from acoustic specs. -Change ultimate pressure requirement to a total pressure requirement. -Change sequence of purge testing. -Change bakeout temperature tolerances to -20 and +20 C. -Change EMI requirements. -Include purge piping in cleaning process. -Include requirement for floor anchors. -Added main ion pump valves. -Changed requirement for auxiliary ports. -Delete requirement for rack mounted gauge controllers. -Added system test to purge systems.

Vacuum Equipment Specification

1.0 SCOPE

This specification defines the technical requirements for the design, procurement, delivery, qualification, installation, and acceptance testing of the LIGO (Laser Interferometer Gravitational-Wave Observatory) vacuum equipment. The LIGO includes two installations at widely separated sites, near Hanford, WA and Livingston, LA. Each installation includes laser interferometers in an L shape with 4-km long arms, a vacuum system for the sensitive interferometer components and optical beams, and other support facilities. The vacuum equipment consists of interconnected vacuum vessels, pumping systems, valves and a monitoring and control system for each site. The vacuum equipment will be located in structures called stations, located at the corners, mid points, and ends of the L-shaped pattern. See Figure 1.

The vacuum tube joining the vacuum equipment in the stations is provided under separate contract, and is described by LIGO 1100004, Beam Tubes Specification. Cleaning, alignment and leak checking are critical processes. Vacuum levels during operation may range from a nominal 10^{-6} torr at the chambers to 10^{-9} torr in the beamtube.

2.0 APPLICABLE DOCUMENTS

If more than one document applies to a technical requirement, the more stringent standard shall have precedence. Requirements set forth in this specification shall have final precedence.

2.1 Industry Documents

2.1.1 American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code

Pressure Vessels, Section VIII, Division I.

Welding and Brazing Qualifications, Section IX.

2.1.2 American Society for Testing and Materials

ASTM E498 Standard Test Methods for Leaks Using the Mass Spectrometer Leak Detector.

2.1.3 Handbook of Acoustical Measurements and Noise Control

Chapter 43, Noise Criteria for Heating, Ventilating, and Air Conditioning Systems.

2.1.4 International Standards Organization

ISO Standard 2861 Flange standards.

2.1.5 American Society of Civil Engineers

Minimum Design Loads for Buildings and Other Structures, ASCE 788.

2.1.6 Expansion Joint Manufacturer's Association (EJMA)

Standards of Expansion Joint Manufacturer's Association.

2.1.7 National Fire Protection Association (NFPA) Standards

No. 70-National Electrical Code.

2.2 Government Standards

Building and safety codes: local, state, and federal, including OSHA.

Federal Standard 209 for clean rooms.

2.3 LIGO Documents

2.3.1 LIGO Drawings

LIGO Drawing 1101100, Vacuum Equipment, Corner Station, Washington Site, Phase A, attached.

LIGO Drawing 1101101, Vacuum Equipment, Corner Station, Louisiana Site, Phase A, attached.

LIGO Drawing 1101102, Vacuum Equipment, End Stations, Phase A, attached.

LIGO Drawing 1101103, Vacuum Equipment, Mid Stations, Washington Site, Phase A, attached.

LIGO Drawing 1101009, Beam Splitter Chamber (BSC).

LIGO Drawing 1101010, Horizontal Access Module (HAM).

LIGO Drawing 1101051, Attachment Brackets.

2.3.2 LIGO Specifications

LIGO 1100004, Beam Tubes Specification.

2.4 Interface Control Documents

2.4.1 Provided by LIGO

LIGO document TBD, LIGO Interferometer to the Vacuum Equipment.

LIGO document TBD, Vacuum Equipment to the Beam Tube.

2.4.2 Provided by the Vacuum Equipment Contractor

Contractor document TBD, Vacuum Equipment to the Buildings and Utilities.

Contractor document TBD, Vacuum Equipment to the LIGO CDS.

3.0 SYSTEM DESCRIPTION

The LIGO vacuum system is divided into two parts: the beam tube modules and the vacuum equipment. The beam tube modules are two kilometers long and are addressed in a separate contract. The vacuum equipment is housed in buildings located at the intersection (corner) and ends of the beam tube modules. These buildings are the corner station, mid stations, and end stations. The vacuum equipment consists of the following subsystems:

- Vacuum enclosure subsystem
- Pumping subsystem
- Valve subsystem
- Vent and purge subsystem
- Bakeout subsystem
- Monitor and control subsystem

Together these subsystems, along with the beam tube modules, make up the vacuum system. The Washington site schematic is shown in Figure 2 and the Louisiana site schematic is shown in Figure 3. A description of the vacuum equipment according to station is given below.

3.1 Corner Station Washington Site

The vacuum enclosure for the corner station of the Washington Site is shown in Figure 4 and is divided into four vacuum sections as shown in Figure 2. The Vertex Section includes three beam splitter chambers (BSC), six horizontal access modules (HAM), and the two 76 cm diameter mode cleaner tubes. Two 122 cm gate valves isolate this section from the Beam Manifold Sections. All gate valves at the 80K pump locations shall provide 112 cm of clear aperture. Each Beam Manifold Section includes one BSC, a section of 183 cm diameter beam manifold, and one 80K pump. The beam manifolds provide for the addition of more chambers in future expansions. The Diagonal Section includes one BSC chamber, six HAM chambers, and two 122 cm gate valves. All major optical components are housed in the two chamber types (BSC, HAM). Removal of access covers from the chambers will allow for servicing the optical components during normal operations; the seals on these covers shall be designed as double O-rings with a pumped annulus for economical reuse during operations. A clean air vent and purge system shall be provided to break vacuum and maintain cleanliness of the optical components whenever a chamber is open.

The corner station pumping system shall include two 80K pumps (liquid nitrogen, continuous flow, or refrigerated) near the beam tube interfaces, and main ion pumps as shown in Figure 2. Ion pumps shall also be used to pump the annuli of double O-ring seals except as noted herein. Rough pumping from atmosphere shall be done with portable and stationary pump stations.

3.2 Corner Station Louisiana Site

The vacuum equipment for the corner station at the Louisiana site is similar to that at the Washington site, except that only one of the BSC/HAM groupings shall be installed. See Figures 3 and 5 for details.

3.3 End Stations Both Sites

The vacuum equipment for the end stations is shown in Figure 6. Vacuum enclosures shall include one BSC. The pumping system shall include one 80K pump with 112cm isolation valves, and ion pumps for both the enclosure and the annuli. Rough pumping from atmosphere shall be done with portable and stationary turbo molecular pump stations.

3.4 Mid Station Washington Site

The vacuum equipment for the mid stations is shown in Figure 7. The pumping system shall include two 80K pumps with 112 cm isolation valves, and ion pumps for both the enclosure and the annuli. Rough pumping from atmosphere shall be done with portable and stationary turbo molecular pump stations.

3.5 Midpoint Pumping Station Louisiana Site

No equipment or utilities are to be installed here. One electrically operated 122 cm diameter gate valve shall be supplied for others to install. Refer to Figure 7.

4.0 SYSTEM REQUIREMENTS

4.1 Leak Rate

All leaks greater than 1 x 10^{-9} torr liters/sec of helium shall be repaired according to LIGO approved procedures. Leak checking procedures shall conform to ASTM E498 Standard Test Methods for Leaks Using the Mass Spectrometer Leak Detector.

4.2 Pump Down Time

Each vacuum section (an isolatable volume) of each corner station, without interferometer components, shall pump down from atmosphere to 1 x 10^{-6} torr in less than 24 hours. Of this time, acoustic noise and vibration may exceed the limits described below in Section 4.6 for no more than the initial 4 hours. Turbo pumps are exempt from the acoustic noise criteria at all times. In the case of the vertex and offset vacuum sections, two pump stations may be connected at once. Otherwise, only a single pump station shall be connected at one time.

4.3 Ultimate Pressures

Each vacuum section shall attain a total pressure of 2×10^{-8} torr, measured with an RGA at an ion pump pumpout port, after 100 hours of pumping. If the hydrogen content of the steel prevents the attainment of this value, then the total pressure of all gases, other than H_2 and H_2O, shall not exceed 6×10^{-9} torr. The partial pressure goals below will be adjusted, as mutually agreed upon by LIGO and the contractor, so that they are consistent with the prototype chamber results and the design margins required for reliable implementation, but in any case not less than

Table 1: Partial Pressures Goals

Gas Species	Partial Pressure - torr
H_2O	5×10^{-9}
H_2	5×10^{-9}
N_2	5×10^{-10}
CO	5×10^{-10}
CO_2	2×10^{-10}
CH_4	2×10^{-10}
All Others	5×10^{-10}

shown in Table 1.

This ultimate pressure test shall be performed after a 48 hour, 150 C bakeout and subsequent cool-down period. The section under test shall be exposed to the operating 80K pumps. The only other pumps allowed are the installed main ion pumps, the annulus ion pumps and the pumps required for temporary pumping of the gate valve annuli.

4.4 System Control and Protection

Each vacuum section shall have sufficient instrumentation and hardware to allow safe and reliable operation of valves, pumps and gauges under all conditions. LIGO will supply process control functions (hardware and software programming) needed for safe acceptance testing as well as normal operations.

4.5 Bakeout/Degassing Capability

A means shall be provided to heat all vacuum surfaces in a given section to any desired temperature, ranging from ambient to 150 C, with a maximum variation of -20 C to + 20 C. No vacuum seals shall be damaged by non-uniform temperatures or by overheating. Ramping of temperatures shall be controllable. Power density shall be limited in order to provide fail safe protection. The rate of temperature rise during warmup shall not exceed 1.8C/hour. Particulate generation or shedding caused by placement or removal of the insulation shall be minimized. The surfaces may be blanketed or entire vacuum sections may be insulated by rigid or flexible partitions.

4.6 Special Environmental Requirements

The LIGO vacuum equipment and laser areas house instrumentation which is potentially highly sensitive to vibration and acoustic noise, shock-induced damage or misalignment, electromagnetic interference, and contamination.

4.6.1 Shock

Valve actuation or other intermittent device operation shall induce no more than 0.01 g peak-to-peak acceleration at any point within 1 meter of any HAM or BSC chamber.

4.6.2 Acoustic Noise

Acoustic noise from all simultaneously operating equipment in normal operation shall not exceed NC-20 (Noise Criterion 20) at any location within LIGO vacuum equipment and laser areas. Limited narrowband exemptions may be permitted subject to LIGO approval. Rough pumping equipment, used intermittently to initiate pumpdowns, may be exempted for limited periods as provided in Section 4.2.

4.6.3 Vibration

The Vacuum Equipment shall be designed in such a way that vibration from all simultaneously operating vacuum equipment, in the absence of vibration from other sources, shall not induce motion of the walls of any vacuum chamber or of the facility floor within 1 meter of any chamber which exceeds the following spectral density limits (Table 2). Limited narrowband exemptions may be permitted subject to LIGO approval. Rough pumping equipment, used intermittently to initiate pumpdowns, may be exempted for limited periods as provided in Section 4.2. Compliance with this specification may be demonstrated by any combination of measurements and analysis, subject to LIGO approval.

Table 2: Maximum allowable spectral density of chamber or floor vibration induced by operation of LIGO vacuum equipment.

Frequency Band (Hz)	Vibration Limit ($m/\sqrt{Hz}$)
0.1 - 10	3×10^{-11}
10 - 1000	$3 \times 10^{-9} \times (1\ Hz/f)^2$
1000 - 10000	3×10^{-15}

4.6.4 Electromagnetic Emissions

All electrical equipment shall meet commercial standards for EMI.

4.6.5 Particulates and other contaminants

No installed equipment shall emit or harbor particulates at a level inconsistent with maintenance of a clean environment conforming to Federal Standard 209 Class 50,000. Bakeout insulation may be exempted from this if it can be shown that reasonable cleaning procedures and a reasonable time period will restore the environment.

4.7 Interfaces

The following interfaces shall be provided for and fully documented:

- LIGO Interferometers to the vacuum equipment.*
- Vacuum equipment to the beam tube.**
- Vacuum equipment to the buildings and utilities.***
- Vacuum equipment to process control system.***

* ICD to be provided by LIGO.

** ICD to be provided by Beam Tube Installer.

*** ICDs to be provided by the Vacuum Equipment Contractor.

4.8 Design Life

The contractor shall design the vacuum equipment for a minimum serviceable life of 20 years assuming equipment is maintained and operated in accordance with vendors' recommendations.

4.9 Environmental

Under normal operations, the vacuum equipment will be operated in a temperature and humidity controlled environment. In case of power or control failure, and during the construction phase, conditions will be dictated by diurnal and seasonal ranges. Exposure to these conditions shall not damage the vacuum equipment provided that equipment is maintained, stored and operated in accordance with vendors' recommendations.

5.0 SUBSYSTEMS

5.1 Vacuum Enclosure Subsystem

The vacuum enclosure includes all components such as chambers, tubes, flanges, elbows, tees, blank-offs, and other fittings, which form the barrier between atmosphere and vacuum. These components are required to be compatible with use at 1×10^{-9} torr. Specific requirements are below.

5.1.1 Materials

All fabricated components exposed to vacuum shall be made from type 304L or 316L stainless steel, using low carbon weld filler wire, or aluminum alloys where required. Standard catalogue items of 304 or 316 stainless steel are acceptable if not available in 304L or 316L. Copper, aluminum, and prebaked Viton may be used for seals. Vacuum feedthroughs may utilize UHV compatible glass or ceramic. All other materials are subject to LIGO approval. Copies of mill test reports of chamber, tube and flange materials shall be furnished. Internal surface finish is subject to LIGO approval.

5.1.2 Cleaning

All surfaces exposed to vacuum or purge gas shall be cleaned in accordance with procedures approved by LIGO prior to fabrication and installation; surface recontamination shall be prevented during all subsequent processes.

All items shall be wrapped or sealed after cleaning to maintain cleanliness through handling, transportation, and storage. Care shall be taken to minimize exposure to corrosive environments, such as those containing chloride compounds. No visible contaminant (viewed with the naked eye, under both natural and ultraviolet light) of any form shall be left within the vacuum enclosures or purge system piping when installed (for example: water, dust, sand, hydrocarbon film, etc.).

5.1.3 Welding

All welding exposed to vacuum shall be done by the tungsten-arc inert-gas (TIG) process. Exceptions may be allowed subject to LIGO approval. Welding techniques shall deviate from the ASME Code in accordance with the best ultra high vacuum practice to eliminate any virtual leaks in the welds; i.e., all vacuum welds shall be, wherever possible, internal and continuous; all external welds added to these for structural purposes shall be intermittent to eliminate trapped volumes. Defective welds shall be repaired by removal to sound metal and rewelding. All vacuum weld procedures shall include steps to avoid contamination of the heat affected zone with air, hydrogen, or water. This requires that inert purge gas, such as argon, be used to flood the vacuum side of heated portions.

5.1.4 Alignment and Dimensions

All chambers shall be aligned to within 2mm of the design optical axis in both transverse directions and to within 25mm of the design position in the axial direction. Unless noted otherwise, dimensions of chambers (including interconnecting tubes) refer to nominal internal dimensions. All other dimensions shall be +/- 3mm, +/- 1 degree, and +/- 3mm per 3 meter section of tube.

5.1.5 Mechanical Loads

All vacuum components shall be anchored to the floor or to each other so as to restrict all motion to bellows units. The floor anchors shall be supplied and installed by the contractor. The design of the vacuum enclosure shall allow for strains and stresses due to the following: normal cycling of the station HVAC (heating, ventilating, and air conditioning) system (expected to maintain temperature within a range of +/- 2 C); variations in atmospheric pressure; vacuum cycling of other sections of the vacuum enclosure; bakeout of any vacuum section; failure or non-operation of the HVAC.

5.1.6 Design

Each vacuum element with a diameter greater than 12 inches shall be designed according to the latest edition of ASME Boiler and Pressure Vessel Code, Section VIII, Division 1 and its subsequent addenda (except as noted in 5.1.3), even though vacuum chambers lie outside of the scope of that document. Alternate design methods may be employed subject to LIGO approval. Code certification and stamping are not required. All separable parts shall be fully interchangeable between assemblies. Adequate clearance shall be provided for assembly of mating flanges, and for handles. External access shall be provided to all vacuum seams for leak checking. All vacuum elements heavier than 50 lbs shall have lift lugs installed and each chamber assembly shall have an electrical ground connection (removable for diagnostic purposes). Calculations shall be made to determine design features, including the need for and the size of any reinforcements due to openings. Chambers shall be designed to withstand the loadings exerted by all applicable loads in accordance with the provisions of all applicable codes and standards. All chambers shall be designed to be free standing to allow blanked-off leak checking. To determine the probability of earthquakes and seismic coefficients in various areas of the United States, Standard ANSI A58.1 (ASCE Minimum Design Loads for Buildings and Other Structures) shall be applied.

5.1.7 Chambers

All optics are housed in two types of chambers. These chambers contain the seismic isolators and alignment mechanisms which support the optical elements. The two chambers are designated BSC and HAM.

5.1.7.1 Beam Splitter Chamber (BSC)

The Beam Splitter Chamber (BSC) configuration is shown in Figure 8.

5.1.7.2 Horizontal Axis Module (HAM)

The Horizontal Axis Module (HAM) configuration is shown in Figure 9. One spare HAM is required at the Washington site.

5.1.8 Attachment Brackets

Both chamber types shall have internal attachment brackets as shown in Figure 10. These brackets will be used to support lightweight optical components.

5.1.9 Flanges and Ports

Dual O-ring flanges shall be designed for convenient, quick and easy disassembly and assembly, consistent with reliable sealing. O-rings shall be vacuum quality Viton, free of lubricant, and baked to remove contaminants. O-ring grooves shall retain the O-ring during assembly/disassembly. Flange centering pins shall be tapered, rounded, and replaceable; centering pins for flange sets in the vertical plane shall support the weight of the mating cover. Except for the case of chamber to chamber connections, flange centering pins shall be included in the chamber flange of flange sets in the vertical plane, and the lower flange of flange sets in the horizontal plane. Port designs shall provide for maximum aperture and minimum neck length. Where applicable designs shall conform to ISO Standard 2861.

5.1.10 Access Connectors

The 152 cm diameter short tube sections located at BSC 2 and BSC 4 are defined as access connectors, and shall be designed for convenient removal and installation. As a minimum the total axial space required at these locations is 90 cm. The bellows portion shall be as short as practical to allow addition of side access ports in the future. A similar access connector is required at BSCs 7and 8.

5.1.11 Optical Baffles

All connecting tubes shall be designed to allow for installation of optical baffles at a later date. This requirement can be met by allowing access to all internal surfaces.

5.1.12 Annular Spaces

The annuli of each chamber shall be connected to a single flange. Pumping speed between this flange and any point of the pumped annulus is to be greater than 0.3 liters/sec for air, in molecular flow. Interconnecting tubing shall be routed close to the chamber wall, with all connections to be welded or CF flanges.

5.1.13 Fasteners

Flange fasteners shall be of high quality, appropriate for efficient assembly and disassembly. All fasteners shall be plated or made of alloys which allow use without lubricants. Floor anchors need not be plated. Where possible plate nuts shall be used.

5.1.14 Component Leak Rate

The contractor shall ensure that all leaks greater than 1 x 10^{-9} torr liter/second of helium on each chamber or tube section are repaired at the site of manufacture according to LIGO approved procedures. Leak checking procedures shall conform to ASTM E498 Standard Test Methods for Leaks Using the Mass Spectrometer Leak Detector.

5.1.15 Workmanship, Finish, and Appearance

The finished product shall be free of weld spatter, cutoff spatter, free iron, weld oxidation and defects. There shall be no grinding or abrasion of completed welds or internal vacuum surfaces.

5.1.16 Marking

Each separable part (except fasteners, seals, and interchangeable, standard blank flanges) shall be permanently marked with a unique identification number in a location readily viewed.

5.2 Pumping Subsystem

Vacuum pumps include portable roughing pumps, stationary backing pumps, annulus pumps, main ion pumps, and 80K pumps. The roughing pumps are used to pump the systems down from atmosphere to 10^{-6} torr. The ion pumps, and 80K pumps are used for vibration-free pumping during normal operation.

The main pumping phases include:

- Initial Pumpdown (from 760 torr to less than 1 torr): Roots roughing pump sets are to be used. Smaller volumes may only require roughing with the turbo backing pumps. The duration of this phase is limited to 4 hours per vacuum section for all sections in the corner stations. See Section 4.2.
- Intermediate Pumpdown (from 1 torr to less than 10^{-6} torr): Turbo molecular pump sets are to be used. The duration of this phase is expected to be of order 24 hours. Low noise and vibration are required.
- Final Pumpdown and normal operation (below 10^{-6} torr): No mechanical pumps may be used. Ion pumps and cryogenic pumps are to provide continuous pumping without vibration.

5.2.1 Roughing Pumps

The roughing pumps shall consist of two types of portable pump stations and stationary backing pumps, the main roughing pump set and the turbo molecular pump sets. The main roughing pump set shall be used for pumping from atmosphere to less than 1 torr while the turbo molecular pump set shall be used for pumping from 1 torr to less than 10^{-6} torr. The main roughing pump sets are exempt from the vibration and acoustic noise limits. The turbo molecular pump sets, however, shall be designed to operate for extended periods of time without contributing to vibration and noise levels beyond those described in Section 4.6. The design of the roughing pumps shall preclude contaminating the beam tubes and chambers during the life of the equipment, even with equipment failures and operator mistakes.

5.2.1.1 Main Roughing Pump Sets

Each main roughing pump set shall consist of a roots blower backed by one or more backing pumps. Four sets are required in total. The minimum pumping speed at 1 torr at the pump inlet shall be 500 CFM and at 0.1 torr, 1000 CFM. There shall be no oil in the pumping path. The pump set shall be self contained so that under power failure or pump failure, interlocks shall prevent the pumped chambers from being vented. The pump set shall be capable of roughing volumes as large as the 2 km beam tube module (volume 2000 m^3) without overheating. Provisions for connection to the control system shall be provided. Provision for sealed connection to a ducted facility exhaust system shall be provided. There shall be vacuum gauges located at each pump inlet (both the roots pump and the backing pump) and there shall be auxiliary valved (manual) ports to allow connection of a leak detector. All unused connections shall be fitted with blankoff flanges.

5.2.1.2 Turbo Molecular Pump Sets

Each turbo molecular pump set shall consist of a wide range magnetically levitated turbo molecular pump backed by an oil free pump (diaphragm, piston, or scroll pump). Ten sets are required in total. The minimum pumping speed at the roughing port shall be 1400 liters/sec for nitrogen at 10^{-3} torr. Throughput at a backing pressure of 1 torr shall be at least 5 torr liters/second. The pump set shall be capable of pumping large volumes (2000 m3) without overheating. The pump set shall be self contained so that under power failure or pump failure, interlocks shall prevent the pumped chambers from being vented or exposed to pump lubricants. Provisions for connection to the control system shall be provided. There shall be vacuum gauges located at each pump inlet (both the turbo pump and the backing pump) and there shall be auxiliary valved (manual) ports to allow connection of a leak detector or auxiliary backing turbo. All unused connections shall be fitted with blankoff flanges.

5.2.2 Main Ion Pumps

The main ion pumps, positioned as shown in Figures 2 and 3, have nominal pumping speeds of 2500 liter/sec minimum for nitrogen. Each main ion pump shall have a manual isolation valve as well as a manual pump out valve. The minimum life of the pumps shall be 40,000 hours or more at an operating pressure of 10^{-6} torr. Noble gas diode-type ion pumps shall be used. If required for starting purposes, or to avoid the use of custom power supplies, multiple power supplies and feedthroughs may be employed to operate each pump. The ion pump design shall allow starting at pressures of 1×10^{-5} torr. However, the power supplies need only be capable of providing starting current for 1×10^{-6} torr. Ion pump power supplies shall be mountable in standard 19 inch racks. All ion pump power supplies shall have remote control capability with both current and voltage signals remotely readable.

5.2.3 80K Pumps

There are two types of 80K pumps: long and short. The long 80K pumps shall have a cylindrical cold surface 3.7 m long and the short 80K pumps shall have a cold surface 1.2 m long. All other features of the 80K pumps shall be identical. The pumping surface shall be coaxial with the beam tube axis, and provide a clear aperture of at least 1.30 m, warm or cold. The aperture at the pump flanges and necks shall be that of the adjacent gate valves. The 80K pumps may be of the liquid nitrogen, continuous flow, or refrigerated design. In any case the vibration requirements of section 4.6 shall be met.

Certain parts of the 80K pumps may have large thermal gradients which may give rise to local, intermittent release of gas. The design shall preclude the sudden and direct release of this gas into the optical path. Each 80K pump shall have a removable beam tube section at one end to allow insertion of optics components. The minimum length required for this section is 60 cm.

5.2.4 Annulus Pumps

Auxiliary turbo molecular pump sets (auxiliary turbo carts) shall be provided for roughing of the annular spaces. Ten pump sets are required. The pump sets shall be self contained so that under power failure or pump failure, interlocks shall prevent the pumped volumes from being vented. Provisions for connection to the control system shall be provided. These pump sets shall use an oil free backing pump to minimize the risk of contamination of the annuli. Each chamber shall have a 200l/s (maximum) ion pump to maintain the annular vacuum. The ion pump shall be isolatable from the annuli with a hand valve. Noble gas diode pumps shall be used. The minimum annulus ion pump used anywhere shall be at least 20l/s. All ion pump power supplies shall have remote control capability with a remotely readable current signal.

5.3 Valve Subsystem

5.3.1 Gate Valves

All gate valves shall be stainless steel with metal sealed flanges or weld fittings where appropriate, and metal bellows stem feedthroughs. O-ring seals are allowed on the beam line flanges. Only non-contaminating and non-migratory lubrication shall be used on the internal mechanisms. Valve body and flange leakage shall be measured to be less than 10^{-10} torr liter/sec of helium before installation. 112 cm and larger gate valves shall have double viton gate seals. Annular spaces between gate valve seals shall be isolatable. This space shall be provided with a blanked-off port. All gate seals shall be leak free to a level of 10^{-9} torr liter/sec of helium. Valves of the same size and type shall be identical to minimize the number of required spare parts. All valves shall be rated for 10000 cycles before service is required. All valves, regardless of operation (electric, pneumatic, or manual), shall be protected from accidental operation. Such protection may be provided by mechanical, electrical, or procedural means. In instances where accidental venting is possible, redundant means shall be employed.

5.3.2 Small Valves

Small valves (less than 15cm aperture), such as right angle manual valves, shall be all metal and bakeable to 150C. Exceptions are those valves which are used on the o-ring annuli and those which are mounted on the portable pump stations. These may be viton sealed. All metal sealed valves shall be rated for 10000 cycles before service is required.

5.4 Vent and Purge Subsystem

Components inside each of the chambers shall be protected against particulate and hydrocarbon contamination at all times: when chambers are open, while venting to air, during opening and closing, and when closed, including pumpdown. This protection against particulates shall be equivalent to exposure within a Fed. Std. 209 Class 100 clean room. The vacuum enclosure area of each station will be constructed with materials consistent with a Fed. Std. 209 Class 50,000 clean room. Vent and purge systems shall be provided with valved and pressure limited, Class 100 air with a water vapor dew point of less than -60 degrees Celsius. The vent and purge system shall not introduce hydrocarbons into the purge air stream. There shall be one 200 CFM system available in the corner stations and 50 CFM systems elsewhere. No systems are required at the LA mid stations.The air compressors shall be mounted in the designated mechanical room areas. The purge system shall allow for the connection of air shower manifolds in the chambers, used to distribute purge gas over the optical components inside the chambers. Additionally, portable soft-wall cleanrooms shall be provided to allow coverage of open chamber ports. The cleanrooms shall be designed per Federal std. 209 (Methods at rest approach). Air flow shall be designed to optimize particulate removal. Unidirectional air flow is not required. A total of 13 portable units are required (8 for the Washington site).

5.5 Bakeout Subsystem

Insulation and heating equipment shall be modular so as to allow efficient removal and placement. There need only be enough equipment to bake the largest contiguous vacuum section at one time; however, the equipment shall be capable of baking any of the vacuum sections. Bakeout controls shall be sufficient to ensure that the performance requirements are met.

5.6 Monitor and Control Subsystem

Vacuum monitoring and control equipment includes Pirani gauges, ion gauges (cold cathode), process controllers for the large valves, and process controllers for the 80K pumps. Gauge tubes shall be mounted on 2 3/4 inch metal seal CF flanges at the locations shown in Figures 2 and 3. There shall be two auxiliary ports (one 2 3/4 and one 4 1/2 inch CF) complete with all metal valves and blankoffs for each BSC chamber. The 4 1/2 inch CF port is reserved for RGA sensors (to be provided by LIGO). There shall be sufficient controls logic (including hardware and software) to safely operate and commission each vacuum section. Site wide functions such as data logging and control room operations will be provided by the LIGO control system. The interfaces to this system shall consist of discrete digital and analog signals. Signal types, cabling and connectors are subject to LIGO approval. The suggested signal levels are listed below:

- Analog Input 0 to 10 VDC, input impedance greater than 1 Kohm.
- Analog Input 4-20 mA, input impedance 600 ohms nominal.
- Analog Output 0 to 10 VDC, output current drive 10 mA minimum.
- Analog Output 4-20 mA, voltage compliance 15 VDC maximum.
- Discrete Input 24 VDC, input impedance greater than 1 Kohm, or contact closure with contacts rated at 24VDC, 500mA.
- Discrete Output 24 VDC, 100 mA maximum.
- Discrete Contact Output 24 VDC, 1 A maximum.
- RTD Temperature Measurement ISO 385 curve platinum RTDs, 100 or 1 Kohm.
- Thermocouple Measurement Types B, R, S, E, T, J, K.

Input is defined as an input to LIGO controls from the Vacuum Equipment. Output is defined as output from LIGO controls to the Vacuum Equipment. All Vacuum Equipment electronics shall be supplied complete with standard 19" racks, however, vacuum gages are allowed to be of the "smart gage" type and do not require rack mounting.

5.6.1 Vacuum Gauges

Vacuum instrumentation shall be provided for pressures from atmospheric down to 1×10^{-9} torr (N_2 equivalent). Each chamber and beam tube section which can be isolated shall have installed one Pirani gauge, and one cold cathode gauge. Vacuum gages may be self contained "smart gage" type. Connectors for all vacuum gauges shall have locking, positive contact to the mating vacuum feedthrough, properly shield the high voltage and signal connectors, and provide proper strain relief.

5.6.1.1 Pirani Gauges

Pirani gauges shall operate from atmosphere to 10^{-4}torr. The controller shall have at least one setable process control contact or setpoint if commercially available. The gauges shall be installed on CF flanges and be bakeable to 200 degrees Celsius.

5.6.1.2 Cold Cathode Gauges

Cold cathode gauges shall operate from 10^{-3} torr to 1x10-9 torr. The controller shall have at least one setable process control contact or setpoint if commercially available. The gauges shall be installed on CF flanges and be bakeable to 250 degrees Celsius.

6.0 QUALITY ASSURANCE

6.1 Test Plans

Detailed plans including descriptions of the test equipment and procedures for the qualification, screening, and acceptance tests shall be approved by LIGO prior to use. Of particular interest are the qualification requirements for large gate valves.

6.1.1 Control of Contamination

Detailed plans to ensure control of cleanliness shall be approved by LIGO.

6.1.2 Component Acceptance Tests

6.1.2.1 Chamber and Tube Leak Tests

The contractor shall document helium leak rates on each vacuum chamber or tube section as part of the fabrication process. No vacuum chamber or fabricated tube section shall be field installed without first demonstrating acceptable leakage.

6.1.2.2 Pumps

Each electrically powered vacuum pump shall be tested (or certified) for speed, ultimate pressure, leakage, noise and vibration, and operation of protective features, before shipment from the manufacturer.

6.1.2.3 Valve Tests

Each vacuum valve shall be tested for leakage prior to shipment from the manufacturer. For dual gate seals, each seal shall be individually tested. As well, each vacuum valve (including each individual gate seal) shall be tested for leakage after installation on the LIGO vacuum system. Operation of each valve shall also be demonstrated.

6.1.3 System Acceptance Tests

6.1.3.1 Leakage

All vacuum leaks greater than the limit set by the system requirements section shall be measured, repaired and documented.

6.1.3.2 Pumpdown

Pumpdown from atmosphere to ultimate pressure (100 hours pumping) shall be performed on all vacuum sections and documented.

6.1.3.3 Noise and Vibration

Acoustic noise shall be measured and documented at the vacuum chamber walls with vacuum equipment operating in each of the 3 modes described in Section 5.2. Additionally, background levels shall be measured and documented as well. Vibration levels at the floor near the chambers shall be measured and documented, both with and without simultaneous operation of all of the vacuum equipment. All tests shall be conducted per the statement of work.

6.1.3.4 Purge System

A test shall be developed to ensure the cleanliness of the purge air supply system.

6.1.3.5 Control and Monitoring

Operation of each vacuum gauge shall be demonstrated after installation. Operation of each vacuum pump and each valve shall be demonstrated after installation. Operation, temperature uniformity, and temperature stability of the bakeout system shall be demonstrated.

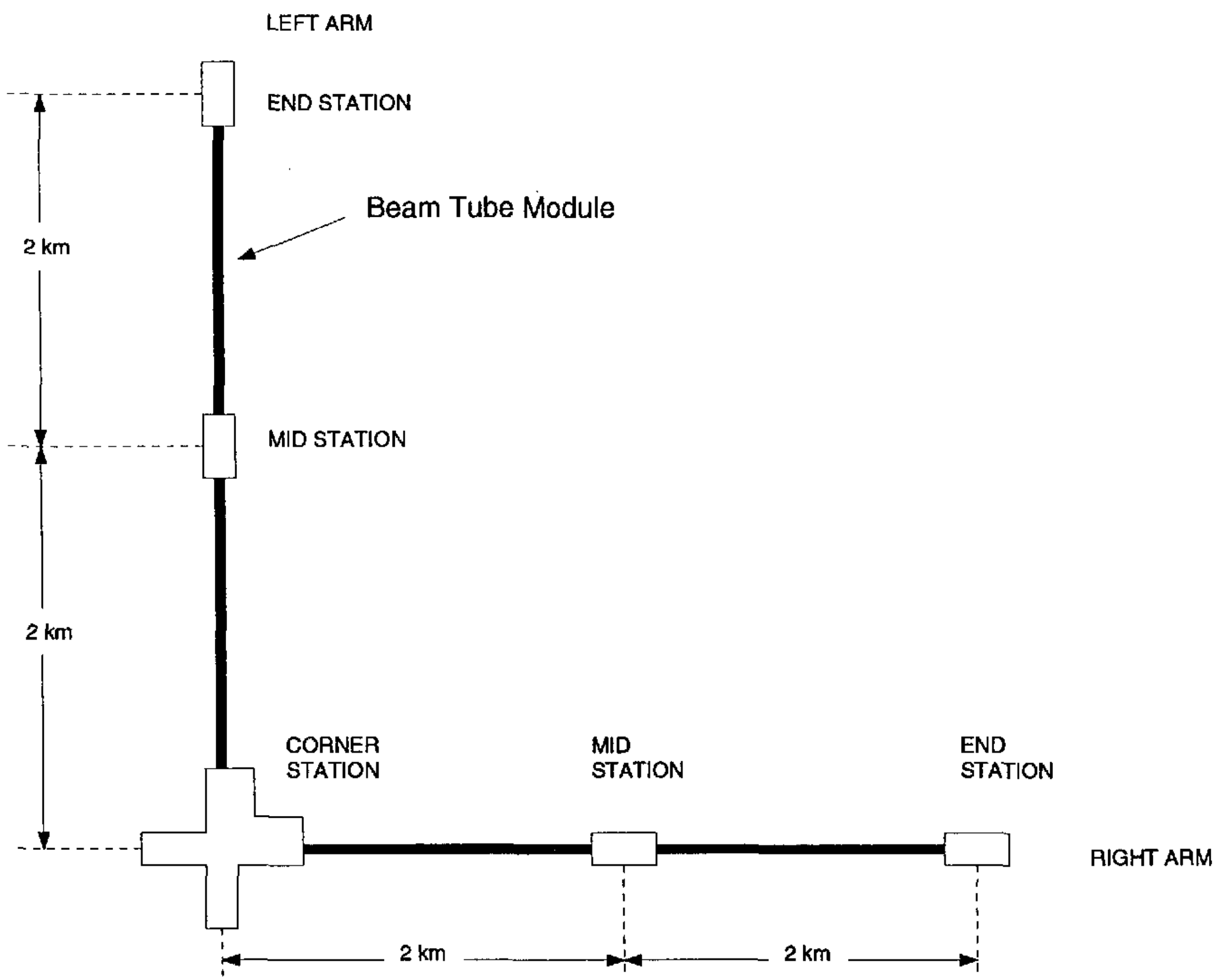
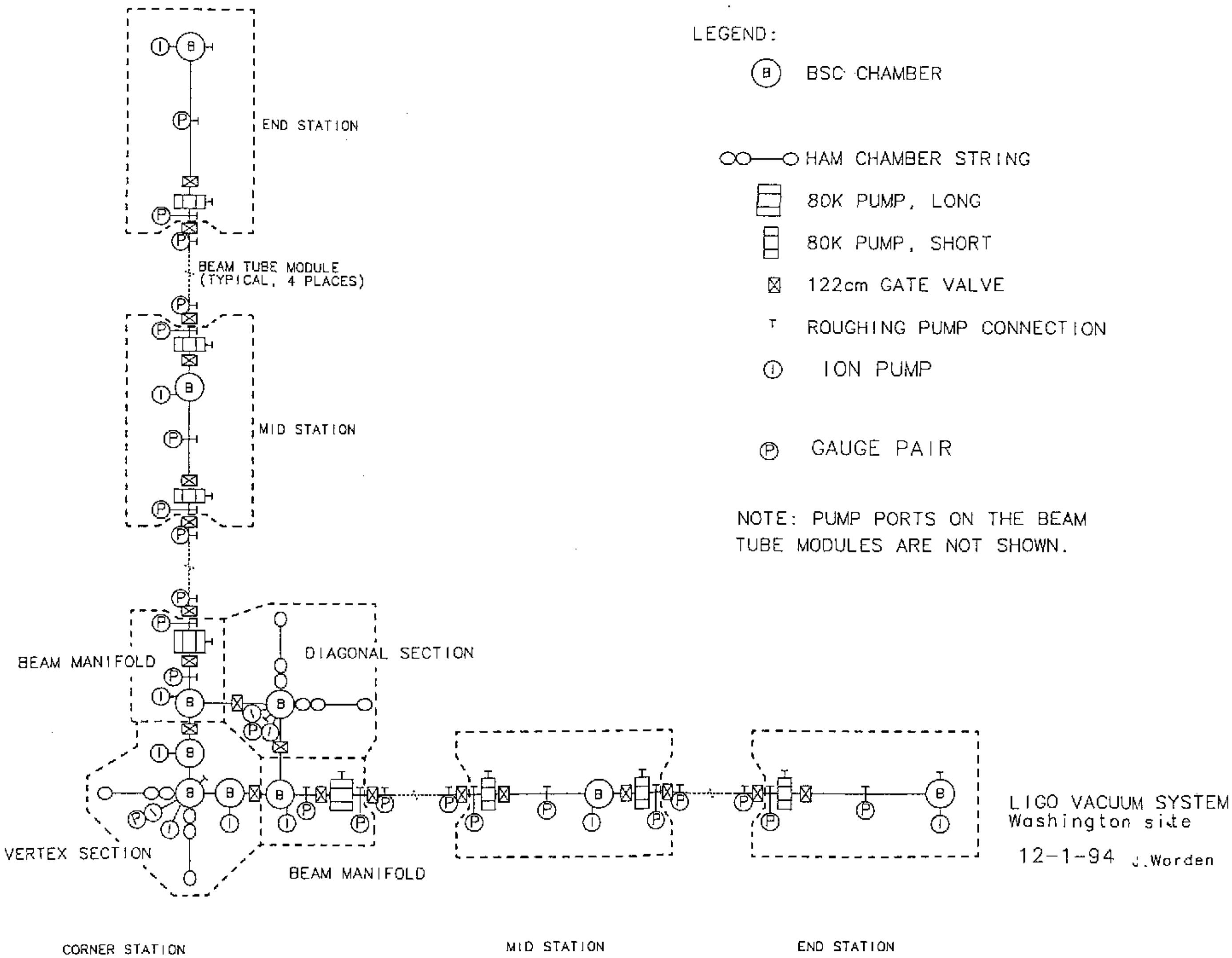
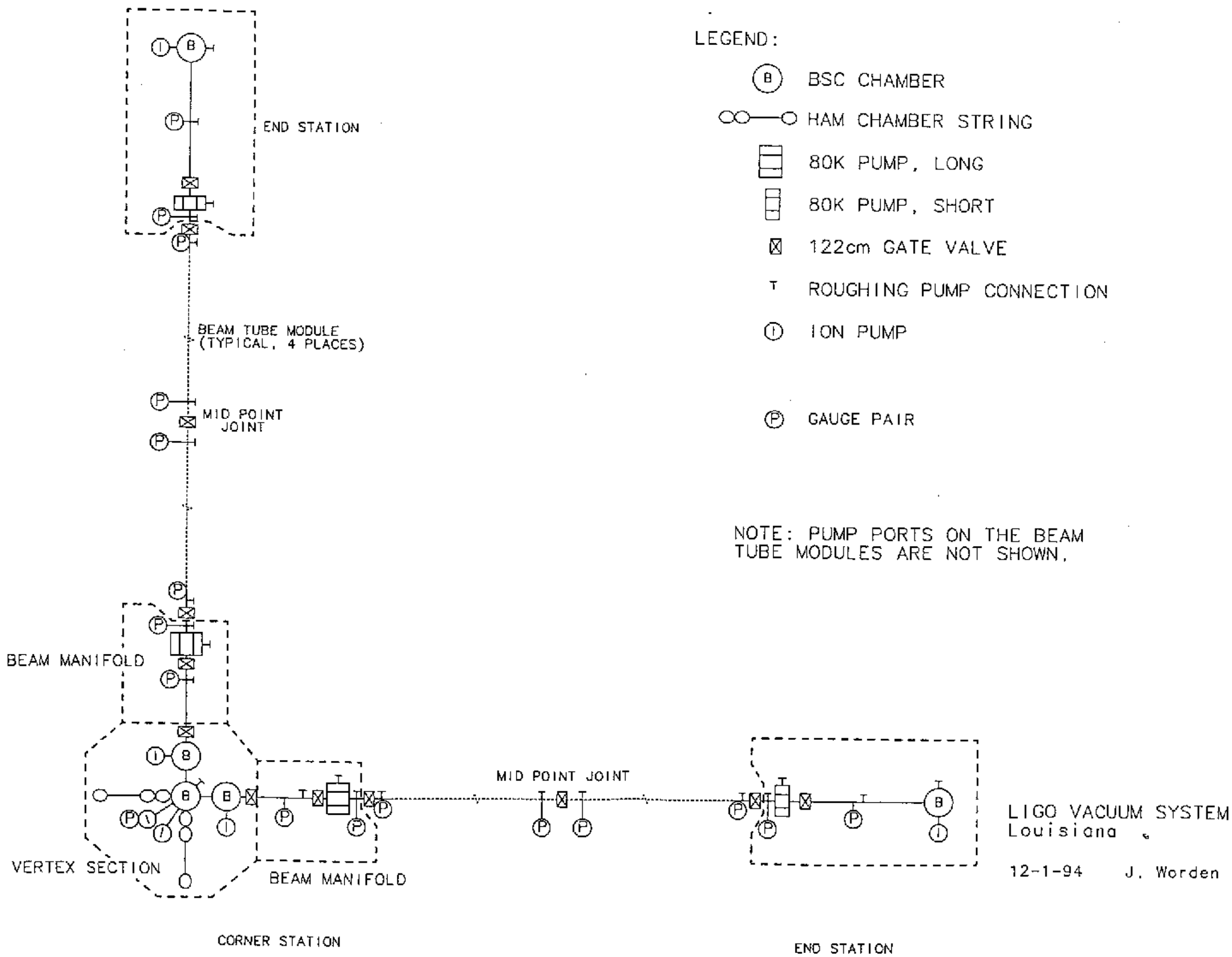


Figure 1. LIGO Geometry



SEP 13 1995

Figure 2.



END STATION
BEAM TUBE MODULE
(TYPICAL, 4 PLACES)
MID POINT
JOINT
BEAM MANIFOLD
VERTEX SECTION
BEAM MANIFOLD
CORNER STATION
MID POINT JOINT
END STATION
LEGEND:
BSC CHAMBER
HAM CHAMBER STRING
80K PUMP, LONG
80K PUMP, SHORT
122cm GATE VALVE
ROUGHING PUMP CONNECTION
ION PUMP
GAUGE PAIR
NOTE: PUMP PORTS ON THE BEAM
TUBE MODULES ARE NOT SHOWN.
LIGO VACUUM SYSTEM
Louisiana
12-1-94 J. Worden

Figure 3.

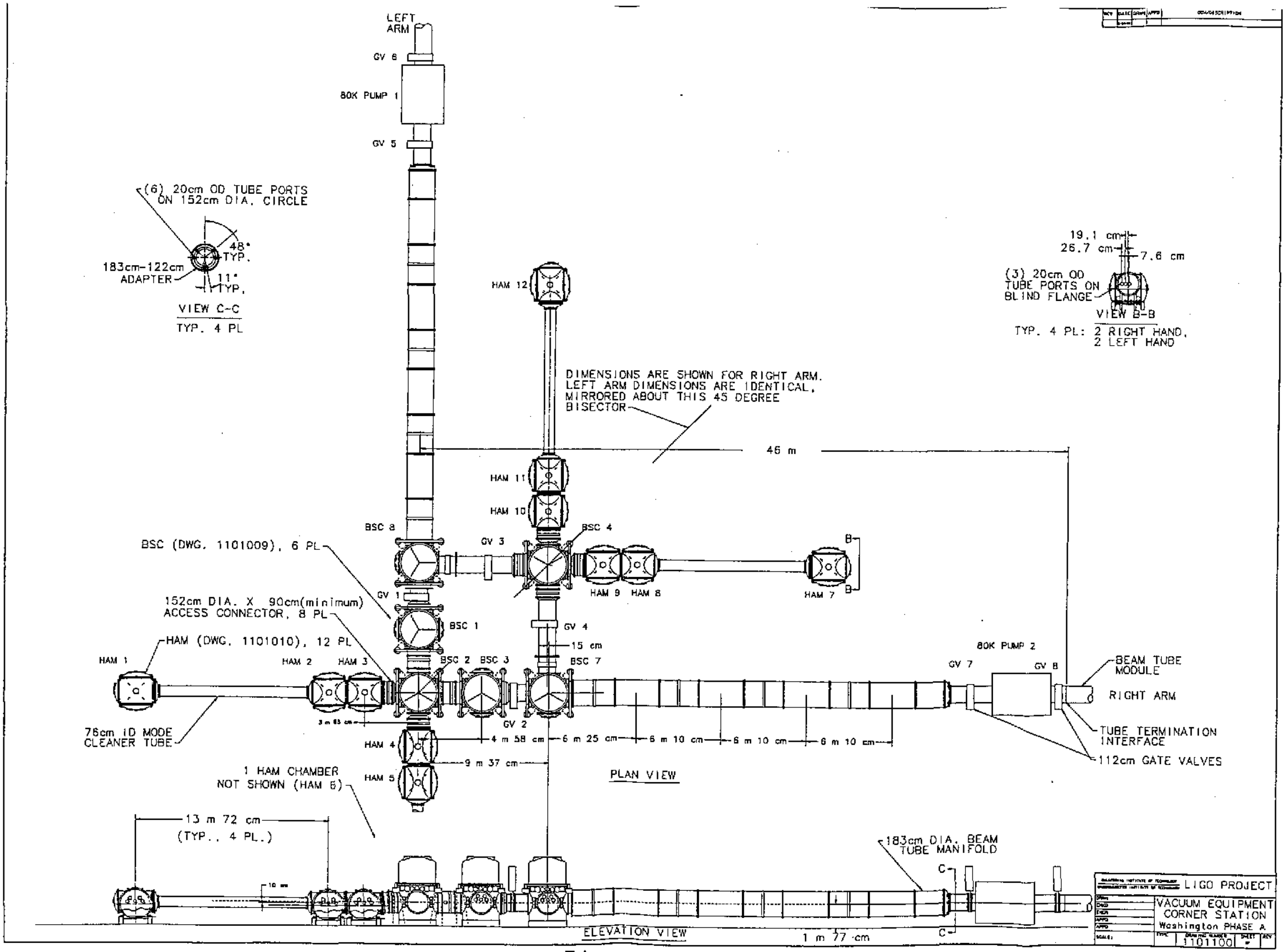


Figure 4.

SEP 13 1995

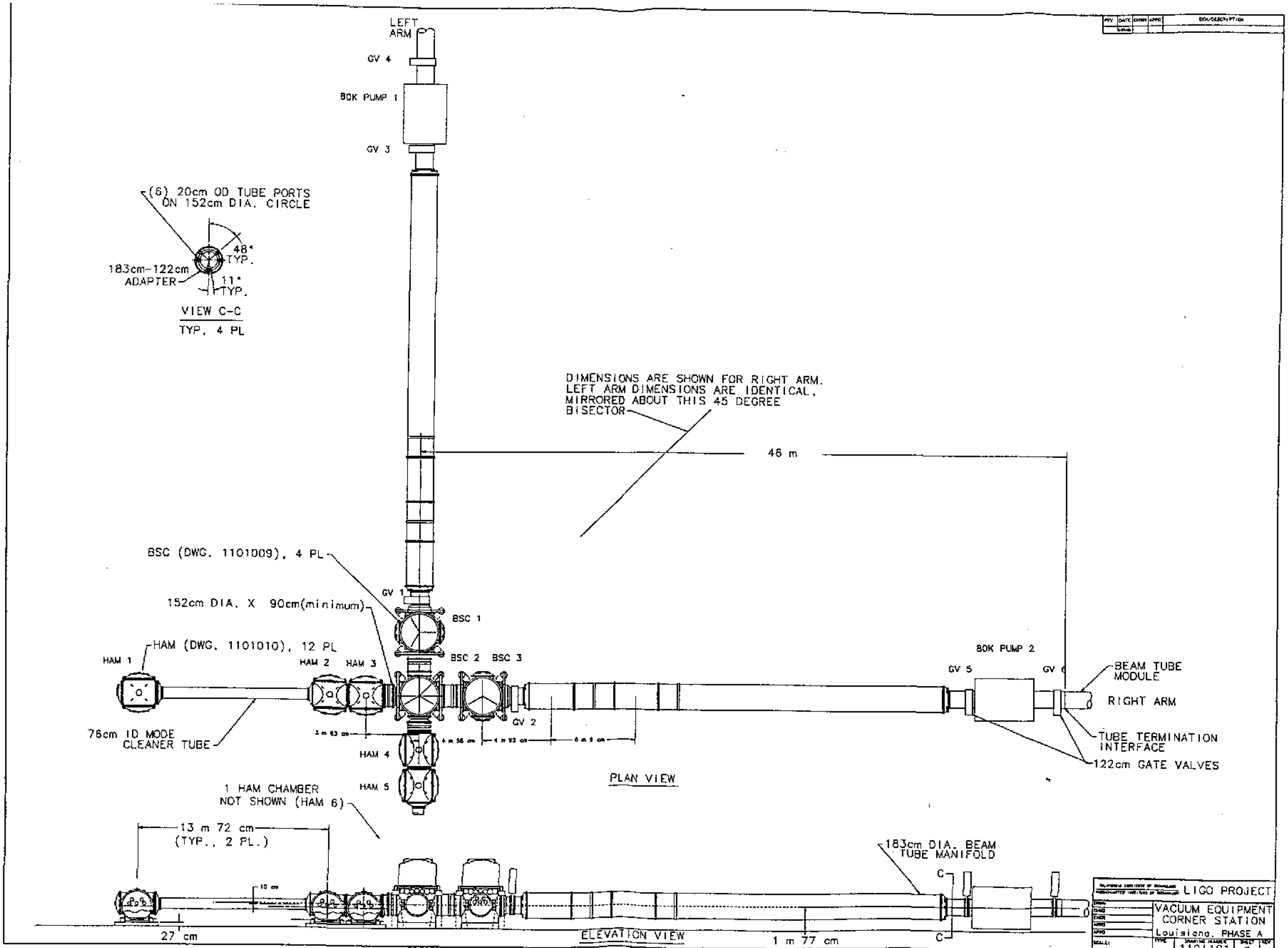


Figure 5.

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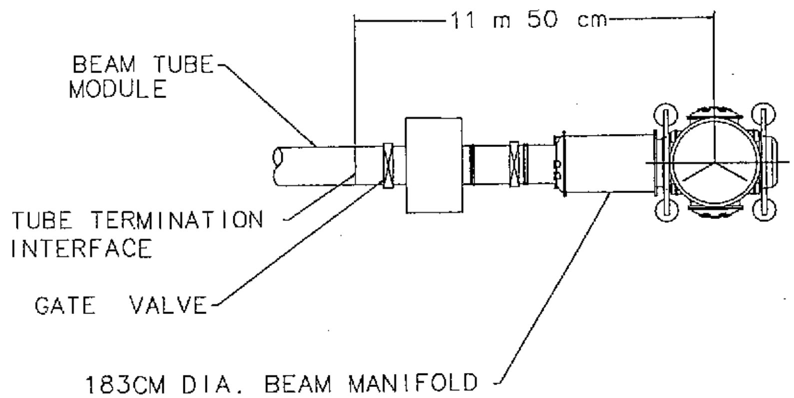

END STATION

BOTH SITES WA and LA

Figure 6.

LIGO PROJECT

VACUUM EQUIPMENT
END STATIONS

1101102

SEP 13 1995

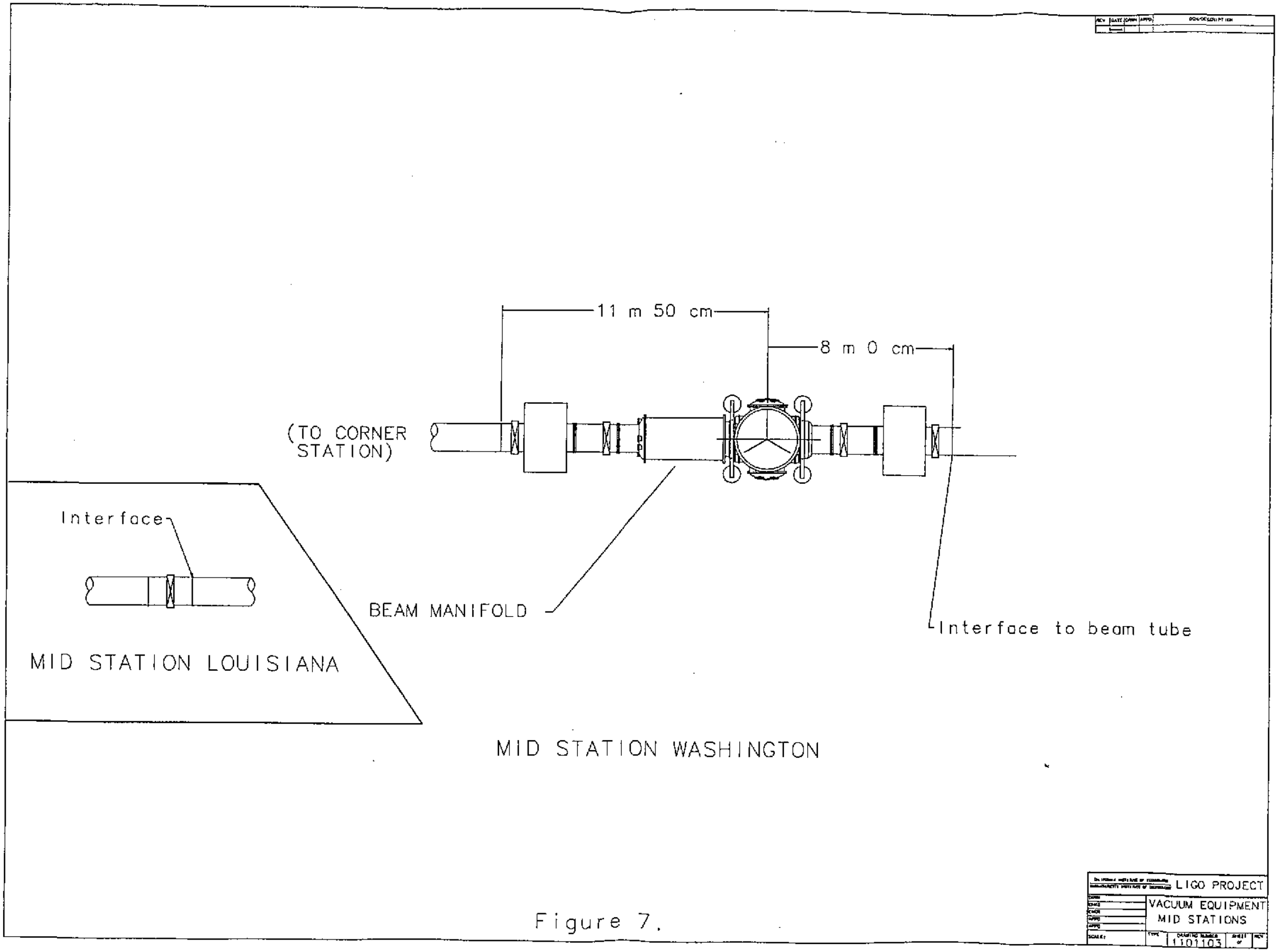

Figure 7.

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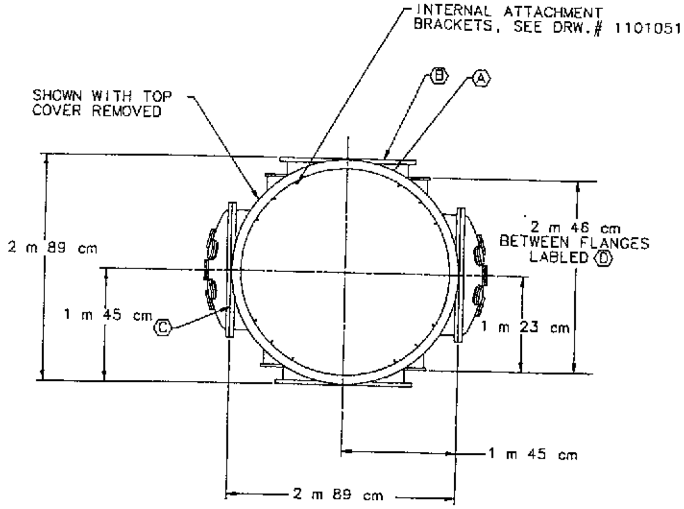
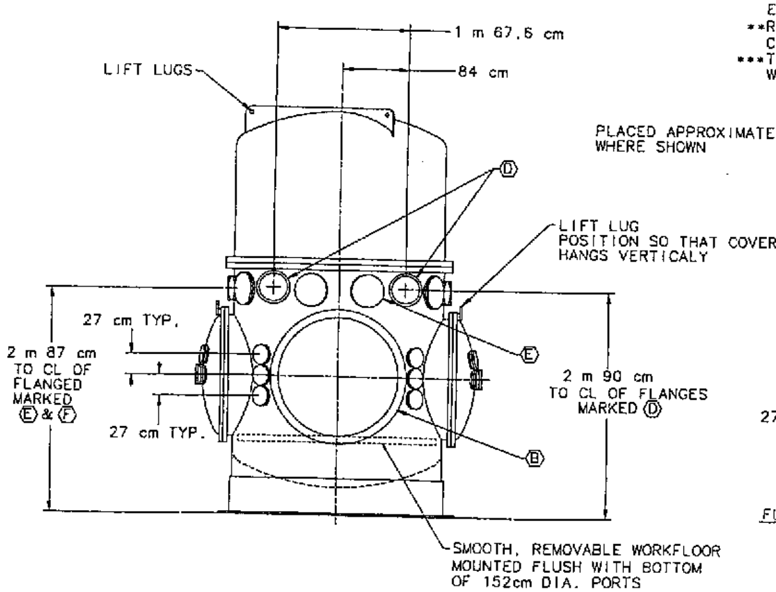


NOTES:
1. HEADS ARE ASME F&D.
2. INCLUDE CENTERING PINS ON NOZZLE FLANGES WHERE APPROPRIATE.
3. VIEWPORT (ITEM Ⓖ) MEASUREMENTS REFER TO INTERSECTION OF VIEWPORT AXIS WITH OUTER SURFACE OF VACUUM WALL.
4. TOLERANCES, UNLESS OTHERWISE SPECIFIED: LINEAR, ±0.25 CM
   ANGULAR, ± 1 DEGREE
5. NOZZLE SCHEDULE PER TABLE BELOW:

ITEM	SIZE	QUANTITY	FLANGE TYPE	PURPOSE
Ⓐ	264cm ID TUBE	1	O/O-O/METAL*	MAJOR ACCESS
Ⓑ	152cm ID TUBE	2	O/O-O/METAL*	LASER BEAM, ACCESS (MINIMIZE NECK LENGTH)
Ⓒ	152cm ID TUBE	2	O/O-O/METAL*, WITH BLIND FLANGE	ACCESS (MINIMIZE NECK LENGTH)
Ⓓ	35cm OD TUBE	4	CONFLAT**	SUPPORT BEAMS REFERENCE ICD # TBD
Ⓔ	35cm OD TUBE***	8	CONFLAT**, WITH BLIND FLANGE	AIR SHWR, BACK-TO-AIR PURGE ROUGHING & ION PUMPS, UTILITY
Ⓕ	25cm OD TUBE***	6	CONFLAT**, WITH BLIND FLANGE	ELECTRICAL FEEDTHROUGHS
Ⓖ	20cm OD TUBE***	22	CONFLAT**, WITH BLIND FLANGE	OBSERVATION, BEAM PICK-OFFS
Ⓗ	3.8cm OD TUBE	1	CONFLAT**, WITH BLIND FLANGE	ANNULUS PUMPOUT (NOT SHOWN)

*DUAL O-RING DESIGN.
THESE FLANGES EACH INCLUDE AN ANNULAR CHANNEL BETWEEN O-RINGS, MANIFOLDED TO A SINGLE PUMPOUT PORT ON EACH CHAMBER, WITH CONFLAT** SEAL.
**REGISTERED TRADEMARK, VARIAN VACUUM PRODUCTS; COMPATIBLE ALTERNATES ARE ACCEPTABLE.
***THESE FLANGES ARE TANGENT TO LOCAL VACUUM WALL, WITH MINIMUM NECK LENGTH.



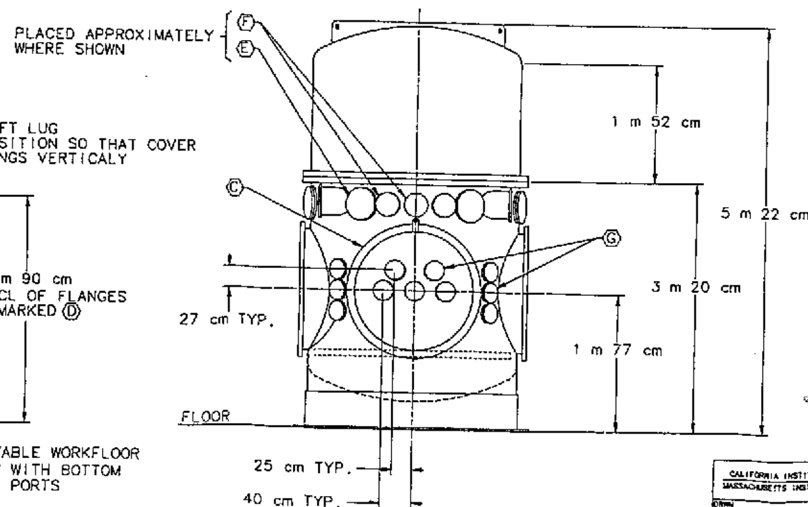


Figure 8.

CALIFORNIA INSTITUTE OF TECHNOLOGY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LIGO PROJECT

DRWN J. JODELE
CHK

BEAM SPLITTER CHAMBER (BSC)

SCALE: | DRAWING NUMBER 1101009 | SHEET 1 of 1 | REV.

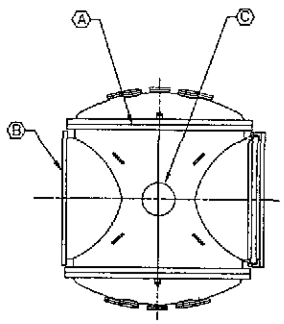
SEP 1 3 1995

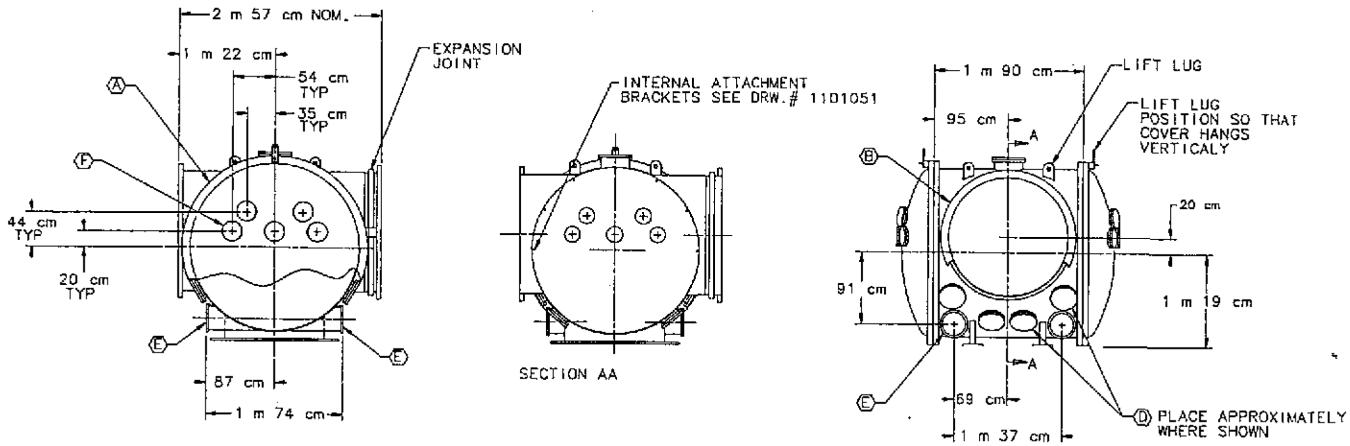
REV	DATE	DRWN	APPD	DCN/DESCRIPTION

NOTES:
1. HEADS ARE ASME F&D.
2. INCLUDE CENTERING PINS ON NOZZLE FLANGES WHERE APPROPRIATE.
3. VIEWPORT (ITEM Ⓕ) MEASUREMENTS REFER TO INTERSECTION OF VIEWPORT AXIS WITH OUTER SURFACE OF VACUUM WALL.
4. TOLERANCES, UNLESS OTHERWISE SPECIFIED: LINEAR, ±0.25 CM
   ANGULAR, ± 1 DEGREE
5. NOZZLE SCHEDULE PER TABLE BELOW:

ITEM	SIZE	QUANTITY	FLANGE TYPE	PURPOSE
Ⓐ	213cm ID TUBE	2	O/O-O/METAL*	MAJOR ACCESS
Ⓑ	152cm ID TUBE	2	O/O-O/METAL*	LASER BEAM
Ⓒ	35cm TUBE ***	1	CONFLAT**, WITH BLIND FLANGE	ION PUMP/AIR SHOWERS, BACK-TO-AIR PURGE
Ⓓ	25cm OD TUBE***	8	CONFLAT**, WITH BLIND FLANGE	ELECTRICAL FEEDTHROUGHS, UTILITY
Ⓔ	30cm OD TUBE	4	CONFLAT**	SUPPORT BEAMS REFERENCE ICD # TBD
Ⓕ	20cm OD TUBE***	10	CONFLAT**, WITH BLIND FLANGE	OBSERVATION, PICKOFFS
Ⓖ	3.8cm TUBE	1	CONFLAT**, WITH BLIND FLANGE	ANNULUS PUMPOUT (NOT SHOWN)

* DUAL O-RING DESIGN,
THESE FLANGES EACH INCLUDE AN ANNULAR CHANNEL BETWEEN O-RINGS, MANIFOLDED TO A SINGLE PUMPOUT PORT ON EACH CHAMBER, WITH CONFLAT** SEAL.
** REGISTERED TRADEMARK, VARIAN VACUUM PRODUCTS; COMPATIBLE ALTERNATIVES ARE ACCEPTIBLE
*** THESE FLANGES ARE TANGENT TO LOCAL VACUUM WALL, WITH MINIMUM NECK LENGTH





CALIFORNIA INSTITUTE OF TECHNOLOGY / MASSACHUSETTS INSTITUTE OF TECHNOLOGY		LIGO PROJECT
DRWN J. JOOELE		HORIZONTAL ACCESS MODULE (HAM)
CHK		
SCALE:	DRAWING NUMBER 1101010	SHEET 1 of 1 REV.

Figure 9.

SEP 1 8 1995

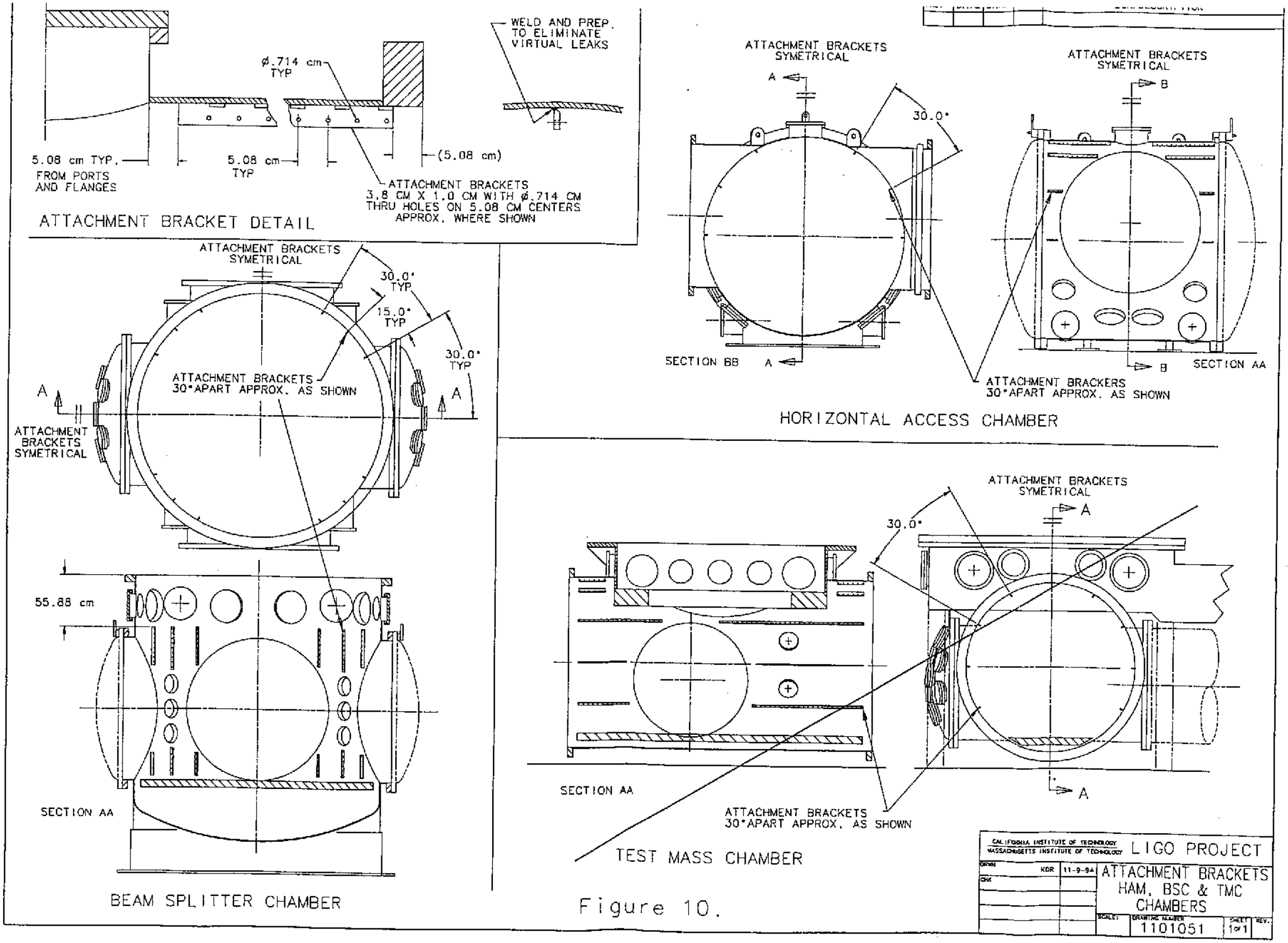


Figure 10.

SEP 13 1995

VACUUM EQUIPMENT SPECIFICATION
LIGO FACILITY

LIGO-E940002-01-V

PREPARED BY: John Worden John Worden

REVIEWED BY: Gerry Stapfer

REVIEWED BY: Mike Zucker M. E. Zucker

REVIEWED BY: A. Lazzarini

APPROVED BY: Gary Sanders

EFFECTIVE DATE: March 28, 1995

CALIFORNIA INSTITUTE OF TECHNOLOGY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

LIGO PROJECT

DOCUMENT CONTROL PAGE

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REVISION	DATE	BY	DESCRIPTION OR DCN	APPROVED
1.	3/27/95	J. W.	Dimension changes to Figures 4,5,6,7	

Contents

LIGO

1. SCOPE

This specification defines the technical requirements for the design, procurement, delivery, qualification, installation, and acceptance testing of the LIGO (Laser Interferometer Gravitational-Wave Observatory) vacuum equipment.

The LIGO includes two installations at widely separated sites, near Hanford, WA and Livingston, LA. Each installation includes laser interferometers in an L shape with 4-km long arms, a vacuum system for the sensitive interferometer components and optical beams, and other support facilities. The vacuum equipment consists of interconnected vacuum vessels, pumping systems, valves and a monitoring and control system for each site. The vacuum equipment will be located in structures called stations, located at the corners, mid points, and ends of the L-shaped pattern. See Figure 1.

The vacuum tube joining the vacuum equipment in the stations is provided under separate contract, and is described by LIGO 1100004, Beam Tubes Specification.

Cleaning, alignment and leak checking are critical processes. Vacuum levels during operation may range from a nominal 10^{-6} torr at the chambers to 10^{-9} torr in the beamtube.

2. APPLICABLE DOCUMENTS

If more than one document applies to a technical requirement, the more stringent standard shall have precedence. Requirements set forth in this specification shall have final precedence.

2.1 Industry Documents

2.1.1 American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code

- Pressure Vessels, Section VIII, Division I.
- Welding and Brazing Qualifications, Section IX.

2.1.2 American Society for Testing and Materials

- ASTM E498–Standard Test Methods for Leaks Using the Mass Spectrometer Leak Detector.

2.1.3 Handbook of *Acoustical* Measurements and Noise Control

- Chapter 43, Noise Criteria for Heating, Ventilating, and Air Conditioning Systems.

2.1.4 International Standards Organization

- ISO Standard 2861–Flange standards.

2.1.5 American Society of Civil Engineers

- Minimum Design Loads for Buildings and Other Structures, ASCE 7–88.

2.1.6 Expansion Joint Manufacturer's Association (EJMA)

- Standards of Expansion Joint Manufacturer's Association.

2.1.7 National Fire Protection Association (NFPA) Standards

- No. 70—National Electrical Code.

2.2 Government Standards

- Building and safety codes: local, state, and federal, including OSHA.
- Federal Standard 209 for clean rooms.

2.3 Other Standards

- VDE 0871–Standards for Electro Magnetic Interference.

2.4 LIGO Documents

2.4.1 LIGO Drawings

- LIGO Drawing 1101100, Vacuum Equipment, Corner Station, Washington Site, Phase A, attached.
- LIGO Drawing 1101101, Vacuum Equipment, Corner Station, Louisiana Site, Phase A, attached.
- LIGO Drawing 1101102, Vacuum Equipment, End Stations, Phase A, attached.
- LIGO Drawing 1101103, Vacuum Equipment, Mid Stations, Washington Site, Phase A, attached.
- LIGO Drawing 1101009, Beam Splitter Chamber (BSC).

LIGO

- LIGO Drawing 1101010, Horizontal Access Module (HAM).
- LIGO Drawing 1101013, Test Mass Chamber (TMC).
- LIGO Drawing 1101051, Attachment Brackets.

2.4.2 LIGO Specifications

- LIGO 1100004, Beam Tubes Specification .

2.5 Interface Control Documents

2.5.1 Provided by LIGO

- LIGO document TBD, LIGO Interferometer to the Vacuum Equipment.
- LIGO document TBD, Vacuum Equipment to the Beam Tube.

2.5.2 Provided by the Vacuum Equipment Contractor

- Contractor document TBD, Vacuum Equipment to the Buildings and Utilities.
- Contractor document TBD, Vacuum Equipment to the LIGO Process Control System.

3. SYSTEM DESCRIPTION

The LIGO vacuum system is divided into two parts: the beam tube modules and the vacuum equipment. The beam tube modules are two kilometers long and are addressed in a separate contract. The vacuum equipment is housed in buildings located at the intersection (corner) and ends of the beam tube modules. These buildings are the corner station, mid stations, and end stations. The vacuum equipment consists of the following subsystems:

1. Vacuum enclosure subsystem
2. Pumping subsystem
3. Valve subsystem
4. Vent and purge subsystem
5. Bakeout subsystem
6. Monitor and control subsystem

Together these subsystems, along with the beam tube modules, make up the vacuum system. The Washington site schematic is shown in Figure 2 and the Louisiana site schematic is shown in Figure 3. A description of the vacuum equipment according to station is given below.

3.1 Corner Station Washington Site The vacuum enclosure for the corner station of the Washington Site is shown in Figure 4 and is divided into four vacuum sections as shown in Figure 2. The Vertex Section includes three beam splitter chambers (BSC), six horizontal access modules (HAM), and the two 76 cm diameter mode cleaner tubes. Two 122 cm gate valves isolate this section from the Beam Manifold Sections. Each Beam Manifold Section includes one test mass chamber (TMC), a section of 183 cm diameter beam manifold, and one 80K pump. The beam manifolds provide for the addition of TMCs in future expansions. The Diagonal Section includes one BSC chamber, six HAM chambers, and two 122 cm gate valves. All major optical components are housed in the three chamber types (BSC, HAM, TMC). The corner station building will be built with enough room for the future addition of up to four TMC/BSC/HAM groupings. Removal of access covers from the chambers will allow for servicing the optical components during normal operations; the seals on these covers shall be designed as double O-rings with a pumped annulus for economical reuse during the early period of operation when access is more frequent; later, the inboard O-ring may be replaced with a metal seal. A clean air vent and purge system shall be provided to break vacuum and maintain cleanliness of the optical components whenever a chamber is open.

The corner station pumping system shall include two 80K pumps (liquid nitrogen, continuous flow, or refrigerated) near the beam tube interfaces, and main ion pumps as shown in Figure 2. Ion pumps shall also be used to pump the annuli of all double O-ring seals. Rough pumping from atmosphere shall be done with portable pump stations.

3.2 Corner Station Louisiana Site The vacuum equipment for the corner station at the Louisiana site is similar to that at the Washington site, except that initially there shall be no TMCs, and only one of the BSC/HAM groupings shall be installed. See Figures 3 and 5 for details.

3.3 End Stations Both Sites The vacuum equipment for the end stations is shown in Figure 6. Vacuum enclosures shall include one BSC initially.

The pumping system shall include one 80K pump with isolation valves, and ion pumps for both the enclosure and the annuli. Rough pumping from atmosphere shall be done with portable pump stations.

3.4 Mid Station Washington Site The vacuum equipment for the mid stations is shown in Figure 7. Vacuum enclosures shall include one TMC initially.

The pumping system shall include two 80K pumps with isolation valves, and ion pumps for both the enclosure and the annuli. Rough pumping from atmosphere shall be done with portable pump stations.

3.5 Midpoint Pumping Station Louisiana Site No chambers are to be housed here. A 122 cm diameter gate valve allows isolation of the adjoining beam tube modules. A valved and instrumented roughing port shall be located on each side of this gate valve. Refer to Figure 7.

4. SYSTEM REQUIREMENTS

4.1 Leak Rate All leaks greater than 1 x 10^{-9} torr•liters/sec of helium shall be repaired according to LIGO approved procedures. Leak checking procedures shall conform to ASTM E498 "Standard Test Methods for Leaks Using the Mass Spectrometer Leak Detector".

4.2 Pump Down Time Each vacuum section (an isolatable volume), without interferometer components, shall pump down from atmosphere to 1 x 10^{-6} torr in less than 24 hours. Of this time, acoustic noise and vibration may exceed the limits described below in Section 4.6 for no more than the initial 4 hours. In the case of the vertex and offset vacuum sections, two pump stations may be connected at once. Otherwise, only a single pump station shall be connected at one time.

4.3 Ultimate Pressures Each vacuum section (empty) shall attain the following partial pressures (Table 1), measured at the ion pumps, after 100 hours of pumping:

Table 1 Maximum allowable residual gas partial pressures for each section, after conditioning procedures described in text. Measurements are to be taken with ion pumps operating, and with the section under test exposed to operating 80 K pump.

Gas Species	Partial Pressure - torr
H_2O	5×10^{-9}
H_2	5×10^{-9}
N_2	5×10^{-10}
CO	5×10^{-10}
CO_2	2×10^{-10}
CH_4	2×10^{-10}
All others	5×10^{-10}

For the purposes of the ultimate pressure test the TMC dome section shall be considered to be part of the 183 cm beam manifold. Each vacuum section shall undergo a prior conditioning consisting of a 48 hour bakeout followed by a vent and purge for 24 hours.

4.4 System Control and Protection Each vacuum section shall have sufficient instrumentation and hardware to allow safe and reliable operation of valves, pumps and gauges under all conditions. Sufficient controls shall be provided to ensure safe operation during acceptance testing. Site wide functions such as data logging and control room operations will be provided by the LIGO control system.

4.5 Bakeout/Degassing Capability A means shall be provided to heat all vacuum surfaces in a given section to any desired temperature, ranging from ambient to 150°C, with a maximum variation of 10°C between the coolest and warmest surfaces. All ion pumps and gauges shall be bakeable to 300°C. Ramping of temperatures shall be controlled to minimize the stresses on vacuum connections. There shall be no particulate generation or shedding caused by placement or removal of the insulation.

4.6 Special Environmental Requirements The LIGO vacuum equipment and laser areas house instrumentation which is potentially highly sensitive to vibration and acoustic noise, shock-induced damage or misalignment, electromagnetic interference, and contamination. The requirements below are subject to future revision.

4.6.1 Shock Valve actuation or other intermittent device operation shall induce no more than 0.01 g peak-to-peak acceleration at any point within 1 meter of any chamber.

4.6.2 Acoustic Noise Acoustic noise from all simultaneously operating equipment in normal operation shall not exceed NC-20 (Noise Criterion 20) at any location within LIGO vacuum equipment and laser areas. Limited narrowband exemptions may be permitted subject to LIGO approval. Rough pumping equipment, used intermittently to initiate pumpdowns, may be exempted for limited periods as provided in Section 4.2.

4.6.3 Vibration The Vacuum Equipment shall be designed in such a way that vibration from all simultaneously operating vacuum equipment, in the absence of vibration from other sources, shall not induce motion of the walls of any vacuum chamber or of the facility floor within 1 meter of any chamber which exceeds the following spectral density limits (Table 2). Limited narrowband exemptions may be permitted subject to LIGO approval. Rough pumping equipment, used intermittently to initiate pumpdowns, may be exempted for limited periods as provided in Section 4.2. Compliance with this specification may be demonstrated by any combination of measurements and analysis, subject to LIGO approval.

Table 2 Maximum allowable spectral density of chamber or floor vibration induced by operation of LIGO vacuum equipment..

Frequency Band (Hz)	Vibration Limit $(\mathrm{m}/\sqrt{\mathrm{Hz}})$
0.1 — 10	3×10^{-11}
10 — 1000	$3 \times 10^{-9} \times (1\ \mathrm{Hz}/f)^2$
1000 — 10000	3×10^{-15}

4.6.4 Electromagnetic Emissions All electrical equipment shall meet the EMI and EMC requirements of VDE 0871 class A or equivalent.

4.6.5 Particulates and other contaminants No installed equipment shall emit or harbor particulates at a level inconsistent with maintenance of a clean environment conforming to Federal Standard 209 Class 50,000.

4.7 Interfaces The following interfaces shall be provided for and fully documented:

1. LIGO Interferometers to the vacuum equipment.*
2. Vacuum equipment to the beam tube.**
3. Vacuum equipment to the buildings and utilities.***
4. Vacuum equipment to process control system.***

* ICD to be provided by LIGO.

** ICD to be provided by Beam Tube Installer.

*** ICDs to be provided by the Vacuum Equipment Contractor.

4.8 Design Life The contractor shall design the vacuum equipment for a minimum serviceable life of 20 years.

4.9 Environmental Under normal operations, the vacuum equipment will be operated in a temperature and humidity controlled environment. In case of power or control failure, and during the construction phase, conditions will be dictated by diurnal and seasonal ranges. Exposure to these conditions shall not damage the vacuum equipment.

5. SUBSYSTEMS

5.1 Vacuum Enclosure Subsystem The vacuum enclosure includes all components such as chambers, tubes, flanges, elbows, tees, blank-offs, and other fittings, which form the barrier between atmosphere and vacuum. These components are required to be compatible with use at 1×10^{-9} torr. Specific requirements are below.

5.1.1 Materials All fabricated components exposed to vacuum shall be made from type 304L or 316L stainless steel, using low carbon weld filler wire, where required. Standard catalogue items of 304 or 316 stainless steel are acceptable if not available in 304L or 316L. Copper, aluminum, and prebaked Viton may be used for seals. Vacuum feedthroughs may utilize UHV compatible glass or ceramic. All other materials are subject to LIGO approval. Copies of mill test reports of chamber, tube and flange materials shall be furnished.

Internal surface finish is subject to LIGO approval (highly reflective surfaces are to be avoided).

5.1.2 Cleaning All surfaces exposed to vacuum shall be cleaned in accordance with procedures approved by LIGO prior to fabrication and installation; surface recontamination shall be prevented during all subsequent processes.

All items shall be wrapped or sealed after cleaning to maintain cleanliness through handling, transportation, and storage. Care shall be taken to minimize exposure to corrosive environments, such as those containing chloride compounds.

No visible contaminant (viewed with the naked eye, under both natural and ultraviolet light) of any form shall be left within the vacuum enclosures when installed (for example: water, dust, sand, hydrocarbon film, etc.).

5.1.3 Welding All welding exposed to vacuum shall be done by the tungsten-arc inert-gas (TIG) process. Welding techniques shall deviate from the ASME Code in accordance with the best ultra high vacuum practice to eliminate any "virtual leaks" in the welds; i.e., all vacuum welds shall be, wherever possible, internal and continuous; all external welds added to these for structural purposes shall be intermittent to eliminate trapped volumes. Defective welds shall be repaired by removal to sound metal and rewelding.

All vacuum weld procedures shall include steps to avoid contamination of the heat affected zone with air, hydrogen, or water. This requires that inert purge gas, such as argon, be used to flood the vacuum side of heated portions.

5.1.4 Alignment and Dimensions All chambers shall be aligned to within 2mm of the design optical axis in both transverse directions and to within 25mm of the design position in the axial direction. Unless noted otherwise, dimensions of chambers (including interconnecting tubes) refer to nominal internal dimensions.

5.1.5 Mechanical Loads All vacuum components shall be anchored to the floor or to each other in such manner as to restrict all motion to bellows units. The design of the vacuum enclosure shall allow for strains and stresses due to the following:

1. normal cycling of the station HVAC (heating, ventilating, and air conditioning) system (expected to maintain temperature within a range of +/- 2°C);
2. variations in atmospheric pressure;
3. vacuum cycling of other sections of the vacuum enclosure;
4. bakeout of any vacuum section;
5. failure or non-operation of the HVAC.

5.1.6 Design Each vacuum element with a diameter greater than 12 inches shall be designed according to the latest edition of ASME Boiler and Pressure Vessel Code, Section VIII, Division 1 and its subsequent addenda (except as noted in 5.1.3), even though vacuum chambers lie outside of the scope of that document. Code certification and stamping are not required. All separable parts shall be fully interchangeable between assemblies. Adequate clearance shall be provided for assembly of mating flanges, and for handles. External access shall be provided to all vacuum seams for leak checking.

All vacuum elements heavier than 50 lbs shall have lift lugs installed and each chamber assembly shall have an electrical ground connection (removable for diagnostic purposes).

Calculations shall be made to determine design features, including the need for and the size of any reinforcements due to openings. Chambers shall be designed to withstand the loadings exerted by all applicable loads in accordance with the provisions of all applicable codes and standards. All chambers shall be designed to be free standing. To determine the probability of earthquakes and seismic coefficients in various areas of the United States, Standard ANSI A58.1 (ASCE Minimum Design Loads for Buildings and Other Structures) shall be applied.

5.1.7 Chambers All optics are housed in three types of chambers. These chambers contain the seismic isolators and alignment mechanisms which support the optical elements. The three chambers are designated BSC, HAM and TMC.

5.1.7.1 Beam Splitter Chamber (BSC) The Beam Splitter Chamber (BSC) configuration is shown in Figure 8.

5.1.7.2 Horizontal Axis Module (HAM) The Horizontal Axis Module (HAM) configuration is shown in Figure 9. One spare HAM is required at the Washington site.

5.1.7.3 Test Mass Chamber (TMC) The Test Mass Chamber configuration is shown in Figures 10 and 11. It includes special features which permit isolation and removal of an interferometer's Test Mass Assemblies with minimal disturbance to the beam paths of other interferometers operating concurrently at the same site.

An integrated airlock enables isolation of the TMC Dome from the lower chamber body (which is integral with the beam manifold and may not be vented while another interferometer is in operation). The airlock shall provide a 152 cm diameter clear aperture when open. When closed it shall withstand atmospheric pressure (only from above), with maximum leak rate determined as for Gate Valves. It is required to stroke from fully open to sealed, or from sealed to fully open, in five minutes or less. The Dome shall have provisions for evacuation, vent and purge, and seal annulus evacuation and vent which are fully independent of those for other volumes. The airlock shall be interlocked to exclude operation with unacceptable pressure differentials or unretracted equipment.

5.1.8 Attachment Brackets All three chamber types shall have internal attachment brackets as shown in Figure 12. These brackets will be used to support lightweight optical components.

5.1.9 Flanges and Ports Dual O-ring flanges shall be designed for convenient, quick and easy disassembly and assembly, consistent with reliable sealing. The design shall allow replacement of the inner O-ring with a metal seal at some time in the future. O-rings shall be vacuum quality Viton, free of lubricant, and baked to remove contaminants. O-ring grooves shall retain the O-ring during assembly/disassembly. Flange centering pins shall be tapered, rounded, and replaceable; centering pins for flange sets in the vertical plane shall support the weight of the mating cover. Except for the case of chamber to chamber connections, flange centering pins shall be included in the chamber flange of flange sets in the vertical plane, and the lower flange of flange sets in the horizontal plane. Port designs shall provide for maximum aperture and minimum neck length. Where applicable designs shall conform to ISO Standard 2861.

5.1.10 Access Connectors The 152 cm diameter short tube sections located at each BSC chamber on the diagonal are defined as access connectors, and shall be designed for convenient removal and installation. As a minimum the total axial space required at these locations is 90 cm. The bellows portion shall be as short as practical to allow addition of side access ports in the future.

5.1.11 Optical Baffles All connecting tubes shall be designed to allow for installation of optical baffles at a later date. This requirement can be met by allowing access to all internal surfaces.

5.1.12 Annular Spaces The annuli of each chamber shall be connected to a single flange (in the case of the TMCs, a separate valve set is required to isolate the Dome annulus). Pumping speed between this flange and any point of the pumped annulus is to be greater than 0.3 liters/sec for air, in molecular flow. Interconnecting tubing shall be routed close to the chamber wall, with all connections to be welded or CF flanges.

5.1.13 Fasteners Flange fasteners shall be of high quality, appropriate for efficient assembly and disassembly. All fasteners shall be plated or made of alloys which allow use without lubricants. Where possible plate nuts shall be used.

5.1.14 Component Leak Rate The contractor shall ensure that all leaks greater than 1 x 10^{-9} torr•liter/second of helium on each chamber or tube section are repaired at the site of manufacture according to LIGO approved procedures. Leak checking procedures shall conform to ASTM E498 "Standard Test Methods for Leaks Using the Mass Spectrometer Leak Detector".

5.1.15 Workmanship, Finish, and Appearance The finished product shall be free of weld spatter, cutoff spatter, free iron, weld oxidation and defects. There shall be no grinding or abrasion of completed welds or internal vacuum surfaces.

5.1.16 Marking Each separable part (except fasteners, seals, and interchangeable, standard blank flanges) shall be permanently marked with a unique identification number in a location readily viewed.

5.2 Pumping Subsystem Vacuum pumps include portable roughing pumps, annulus pumps, main ion pumps, getter pumps, and 80K pumps. The roughing pumps are used to pump the systems down from atmosphere to 10^{-6} torr. The ion pumps, getter pumps, and 80K pumps are used for vibration-free pumping during normal operation.

The main pumping phases include:

1. Initial Pumpdown (from 760 torr to less than 1 torr): Roots roughing pump sets are to be used. The duration of this phase is limited to 4 hours per vacuum section. See Section 4.2.
2. *Intermediate Pumpdown (from 1 torr to less than 10^{-6} torr):* Turbo molecular pump sets are to be used. The duration of this phase is expected to be of order 24 hours. Low noise and vibration are required.
3. Final Pumpdown and normal operation (below 10^{-6} torr): No mechanical pumps may be used. Ion, getter and cryogenic pumps are to provide continuous pumping without vibration.

5.2.1 Roughing Pumps The roughing pumps shall consist of two types of portable pump stations, the main roughing pump set and the turbo molecular pump sets. The main roughing pump set shall be used for pumping from atmosphere to less than 1 torr while the turbo molecular pump set shall be used for pumping from 1 torr to less than 10^{-6} torr. The main roughing pump sets are exempt from the vibration and acoustic noise limits. The turbo molecular pump sets, however, shall be designed to operate for extended periods of time without contributing to vibration and noise levels beyond those described in Section 4.6.

The design of the roughing pumps shall preclude contaminating the beam tubes and chambers during the life of the equipment, even with equipment failures and operator mistakes.

5.2.1.1 Main Roughing Pump Sets Each main roughing pump set shall consist of a roots blower backed by one or more roughing pumps. Five sets are required at each site. The minimum pumping speed at 1 torr at the pump inlet shall be 500 CFM and at 0.1 torr, 1000 CFM. There shall be no oil in the pumping path. The roots blower shall incorporate a "canned" motor. The pump set shall be self contained so that under power failure or pump failure, interlocks shall prevent the pumped chambers from being vented or exposed to a non-operating pump. The pump set shall be capable of roughing volumes as large as the 2 km beam tube module (volume >2000 m^3) without overheating. Provisions for connection to the control system shall be provided. Provision for sealed connection to a ducted facility exhaust system shall be provided.

There shall be vacuum gauges located at each pump inlet (both the roots pump and the backing pump) and there shall be auxiliary valved (manual) ports to allow connection of a leak detector. All unused connections shall be fitted with blankoff flanges.

5.2.1.2 Turbo Molecular Pump Sets Each turbo molecular pump set shall consist of a "wide range" magnetically levitated turbo molecular pump backed by an oil free pump (diaphragm, piston, or scroll pump). Five sets are required at each site. The minimum pumping speed at the roughing port shall be 1400 liters/sec for nitrogen at 10^{-3} torr. Throughput at a backing pressure of 1 torr shall be at least 5 torr liters/second. The pump set shall be capable of pumping large volumes (>2000 m^3) without overheating. The pump set shall be self contained so that under power failure or pump failure, interlocks shall prevent the pumped chambers from being vented or exposed to a non-operating pump. Provisions for connection to the control system shall be provided.

There shall be vacuum gauges located at each pump inlet (both the turbo pump and the backing pump) and there shall be auxiliary valved (manual) ports to allow connection of a leak detector or auxiliary backing turbo. All unused connections shall be fitted with blankoff flanges.

5.2.2 Main Ion Pumps The main ion pumps, positioned as shown in Figures 2 and 3, have nominal pumping speeds of 2500 liter/sec minimum for nitrogen. Other configurations using ion pumps or combined ion pump/getter pump assemblies are allowed. The minimum life of the pumps shall be 40,000 hours or more at an operating pressure of 10^{-6} torr. Noble gas diode-type ion pumps shall be used. If required for starting purposes, or to avoid the use of custom power supplies, multiple power supplies and feedthroughs may be employed to operate each pump. Maximum allowable ion pump starting pressure shall be at least 1 x 10^{-5} torr. Ion pump and getter controllers shall be mountable in standard 19 inch racks.

5.2.3 80K Pumps There are two types of 80K pumps: long and short. The long 80K pumps shall have a cylindrical cold surface 3.7 m long by a nominal 1.2 m diameter and the short 80K pumps shall have a cold surface 1.2 m long by a nominal 1.2 m diameter. All other features of the 80K pumps shall be identical. The pumping surface shall be coaxial with the beam tube axis, and provide a clear aperture of $\geq$ 1.05 m, warm or cold. The 80K pumps may be of the liquid nitrogen, continuous flow, or refrigerated design. In any case the vibration requirements of section 4.6 shall be met.

Certain parts of the 80K pumps may have large thermal gradients which may give rise to local, intermittent release of gas. The design shall preclude the sudden and direct release of this gas into the optical path.

Each 80K pump shall have a removable beam tube section at one end to allow insertion of optics components. The minimum length required for this section is 60 cm.

5.2.4 Getter Pumps LIGO plans to install getter pumps of a nominal 2000 liters/sec pump speed (hydrogen) on the beam tube at each 250 meter pump port. This will be done after one year of operation to ensure that the beam tube gas loads are understood. These pumps are not to be provided by this contract.

5.2.5 Annulus Pumps Auxiliary turbo molecular pump sets (auxiliary turbo carts) shall be provided for roughing of the annular spaces. Five pump sets are required for each site. The pump sets shall be self contained so that under power failure or pump failure, interlocks shall prevent the pumped chambers from being vented. Provisions for connection to the control system shall be provided. These pump sets shall use an oil free backing pump to minimize the risk of contamination of the annuli.

Each chamber shall have a 200l/s (maximum) ion pump to maintain the annular vacuum. The ion pump shall be isolatable from the annuli with a hand valve. Noble gas diode pumps shall be used. The ion pump controllers shall be mountable in standard 19 inch racks.

5.3 Valve Subsystem

5.3.1 Gate Valves All gate valves shall be stainless steel with metal sealed flanges or weld fittings where appropriate, and metal bellows stem feedthroughs. Only non-contaminating and non-migratory lubrication shall be used on the internal mechanisms. Valve body and flange leakage shall be measured to be less than 10^{-10} torr•liter/sec of helium before installation. 122 cm and larger gate valves shall have double viton gate seals. Annular spaces between gate valve seals shall be isolatable and pumped with an ion pump when the valve is closed. All gate seals shall be leak free to a level of 10^{-9} torr•liter/sec of helium.

Valves of the same size and type shall be identical to minimize the number of required spare parts. All valves shall be rated for 10000 cycles before service is required.

All valves, regardless of operation (electric, pneumatic, or manual), shall be protected from accidental operation. Such protection may be provided by mechanical, electrical, or procedural means. In instances where accidental venting is possible, redundant means shall be employed.

5.3.2 Small Valves Small valves (less than 15cm aperture), such as right angle manual valves, shall be all metal and bakeable. Exceptions are those valves which are used on the o-ring annuli and those which are mounted on the portable pump stations. These may be viton sealed. All metal sealed valves shall be rated for 10000 cycles before service is required.

5.4 Vent and Purge Subsystem Components inside each of the chambers shall be protected against particulate contamination at all times: when chambers are open, while venting to air, during opening and closing, and when closed, including pumpdown. This protection shall be equivalent to exposure within a Fed. Std. 209 Class 100 clean room. The vacuum enclosure area of each station will be designed as a Fed. Std. 209 Class 50,000 clean room. Vent and purge systems shall be provided with valved and pressure limited, Class 100 air with a water vapor dew point of less than −60 degrees Celsius. There shall be two 100 CFM systems available in the corner stations and 50 CFM systems elsewhere. The air compressors shall be mounted outside the buildings in designated areas. The purge system shall allow for the connection of air shower manifolds in the chambers, used to distribute purge gas over the optical components inside the chambers. Additionally, portable soft-wall cleanrooms shall be provided to allow coverage of open chamber ports. A total of 13 portable units are required (8 for the Washington site).

5.5 Bakeout Subsystem Insulation and heating equipment shall be modular so as to allow efficient removal and placement. There need only be enough equipment to bake the largest contiguous vacuum section at one time; however, the equipment shall be capable of baking any of the vacuum sections. Temperature sensors shall be installed at positions representing minimum and maximum temperatures. Bakeout controls shall be sufficient to insure that the performance requirements are met.

5.6 Monitor and Control Subsystem Vacuum monitoring and control equipment includes Pirani gauges, ion gauges (cold cathode), process controllers for the large valves, and process controllers for the 80K pumps. Gauge tubes shall be mounted on 2 3/4 inch metal seal CF flanges at the locations shown in Figures 2 and 3. There shall be two auxiliary ports (one 2 3/4 and one 4 1/2 inch CF) complete with all metal valves and blankoffs for each chamber. The 4 1/2 inch CF port is reserved for RGA sensors (to be provided by LIGO).

There shall be sufficient controls logic (including hardware and software) to safely operate and commission each vacuum section. Any local operator interfaces or control panels necessary for acceptance testing shall be provided by the contractor. Site wide functions such as data logging and control room operations will be provided by the LIGO control system. The interfaces to this system shall consist of discrete digital and analog signals. Signal types, cabling and connectors are subject to LIGO approval. The suggested signal levels are listed below:

1. Analog Input — 0 to 10 VDC, input impedance greater than 1 Kohm.
2. Analog Input — 4–20 mA, input impedance 600 ohms nominal.
3. Analog Output — 0 to 10 VDC, output current drive 10 mA minimum.
4. Analog Output — 4–20 mA, voltage compliance 15 VDC maximum.
5. Discrete Input — 24 VDC, input impedance greater than 1 Kohm, or contact closure with contacts rated at 24VDC, 500mA.
6. Discrete Output — 24 VDC, 100 mA maximum.
7. Discrete Contact Output — 24 VDC, 1 A maximum.
8. RTD Temperature Measurement — ISO 385 curve platinum RTDs, 100 or 1 Kohm.
9. Thermocouple Measurement — Types B, R, S, E, T, J, K.

Input is defined as an input to LIGO controls from the Vacuum Equipment. Output is defined as output from LIGO controls to the Vacuum Equipment. Electronics racks and cable trays will be provided by LIGO.

5.6.1 Vacuum Gauges Vacuum instrumentation shall be provided for pressures from atmospheric down to $1x10^{-9}$ torr (N_2 equivalent). Each chamber and beam tube section which can be isolated shall have installed one Pirani gauge, and one cold cathode gauge. Controllers shall be provided for all instruments. Connectors for all vacuum gauges shall have locking, positive contact to the mating vacuum feedthrough, properly shield the high voltage and signal connectors, and provide proper strain relief.

5.6.1.1 Pirani Gauges Pirani gauges shall operate from atmosphere to 10^{-4} torr. The gauge controller shall be mountable in a standard 19 inch rack. The controller shall have a digital display and at least one setable process control contact or setpoint. The gauges shall be installed on CF flanges and be bakeable to 250 degrees Celsius.

5.6.1.2 Cold Cathode Gauges Cold cathode gauges shall operate from 10^{-3} torr to $1x10^{-9}$ torr. The gauge controller shall be mountable in a standard 19 inch rack. The controller shall have a digital display and at least one setable process control contact or setpoint. The gauges shall be installed on CF flanges and be bakeable to 250 degrees Celsius.

6. QUALITY ASSURANCE

6.1 Test Plans Detailed plans including descriptions of the test equipment and procedures for the qualification, screening, and acceptance tests shall be approved by LIGO prior to use. Of particular interest are the qualification requirements for large gate valves.

6.2 Control of Contamination Detailed plans to insure control of cleanliness shall be approved by LIGO.

6.3 Component Acceptance Tests

6.3.1 Chamber and Tube Leak Tests The contractor shall document helium leak rates on each vacuum chamber or tube section as part of the fabrication process. No vacuum chamber or fabricated tube section shall be field installed without first demonstrating acceptable leakage.

6.3.2 Pumps Each electrically powered vacuum pump shall be tested (or certified) for speed, ultimate pressure, leakage, noise and vibration, and operation of protective features, before shipment from the manufacturer.

6.3.3 Valve Tests Each vacuum valve shall be tested for leakage prior to shipment from the manufacturer. For dual gate seals, each seal shall be individually tested. As well, each vacuum valve (including each individual gate seal) shall be tested for leakage after installation on the LIGO vacuum system. Operation of each valve shall also be demonstrated.

LIGO

6.4 System Acceptance Tests

6.4.1 Leakage All vacuum leaks greater than the limit set by the system requirements section shall be measured, repaired and documented.

6.4.2 Pumpdown Pumpdown from atmosphere to ultimate pressure (100 hours pumping) shall be performed on all vacuum sections and documented.

6.4.3 Noise and Vibration Acoustic noise shall be measured and documented at the vacuum chamber walls with vacuum equipment operating in each of the 3 modes described in Section 5.2. Additionally, background levels shall be measured and documented as well. Vibration levels at the floor near the chambers shall be measured and documented, both with and without simultaneous operation of all of the vacuum equipment.

6.4.4 Control and Monitoring Operation of each vacuum gauge shall be demonstrated after installation.

Operation of each vacuum pump and each valve shall be demonstrated after installation.

Operation, temperature uniformity, and temperature stability of the bakeout system shall be demonstrated.

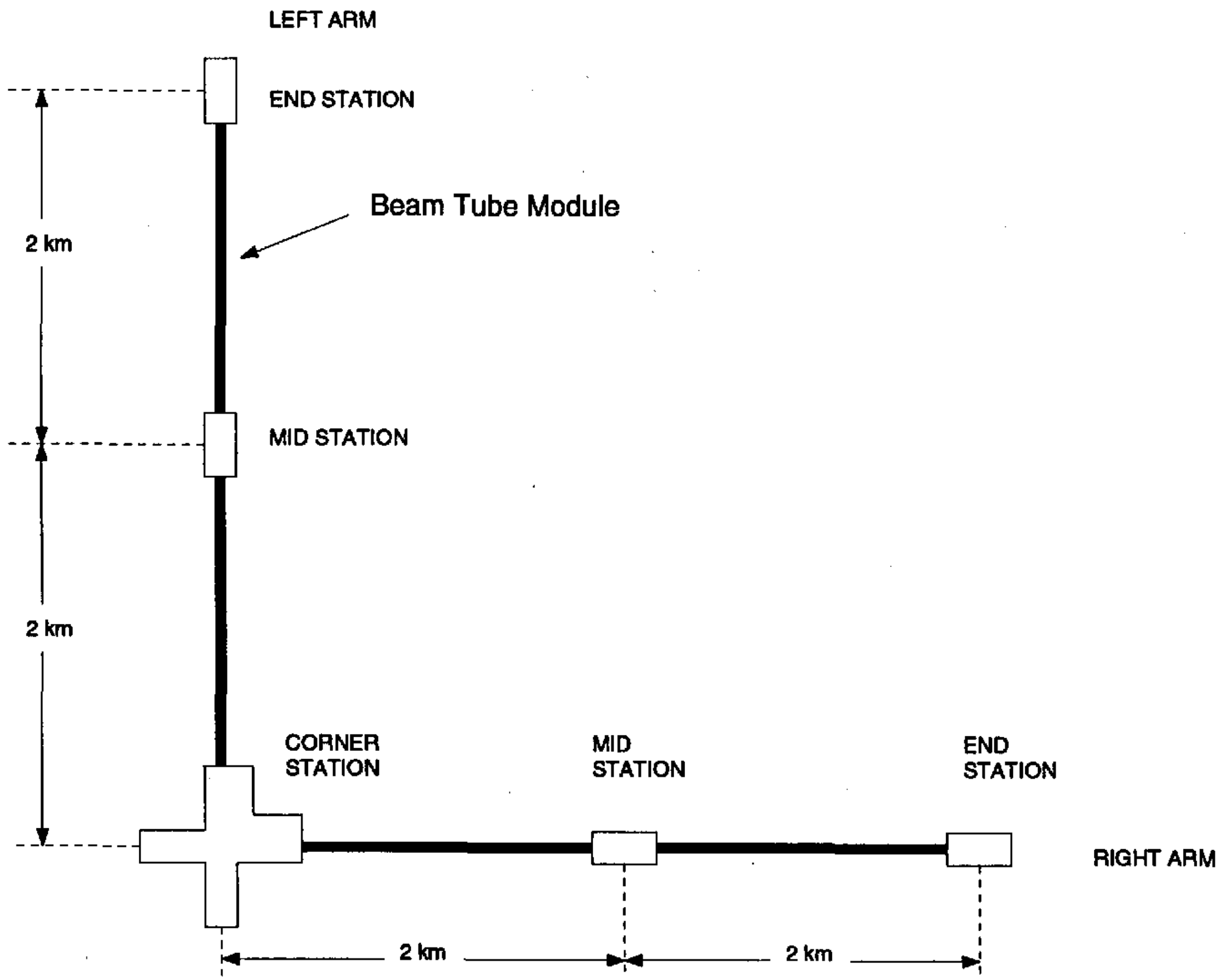
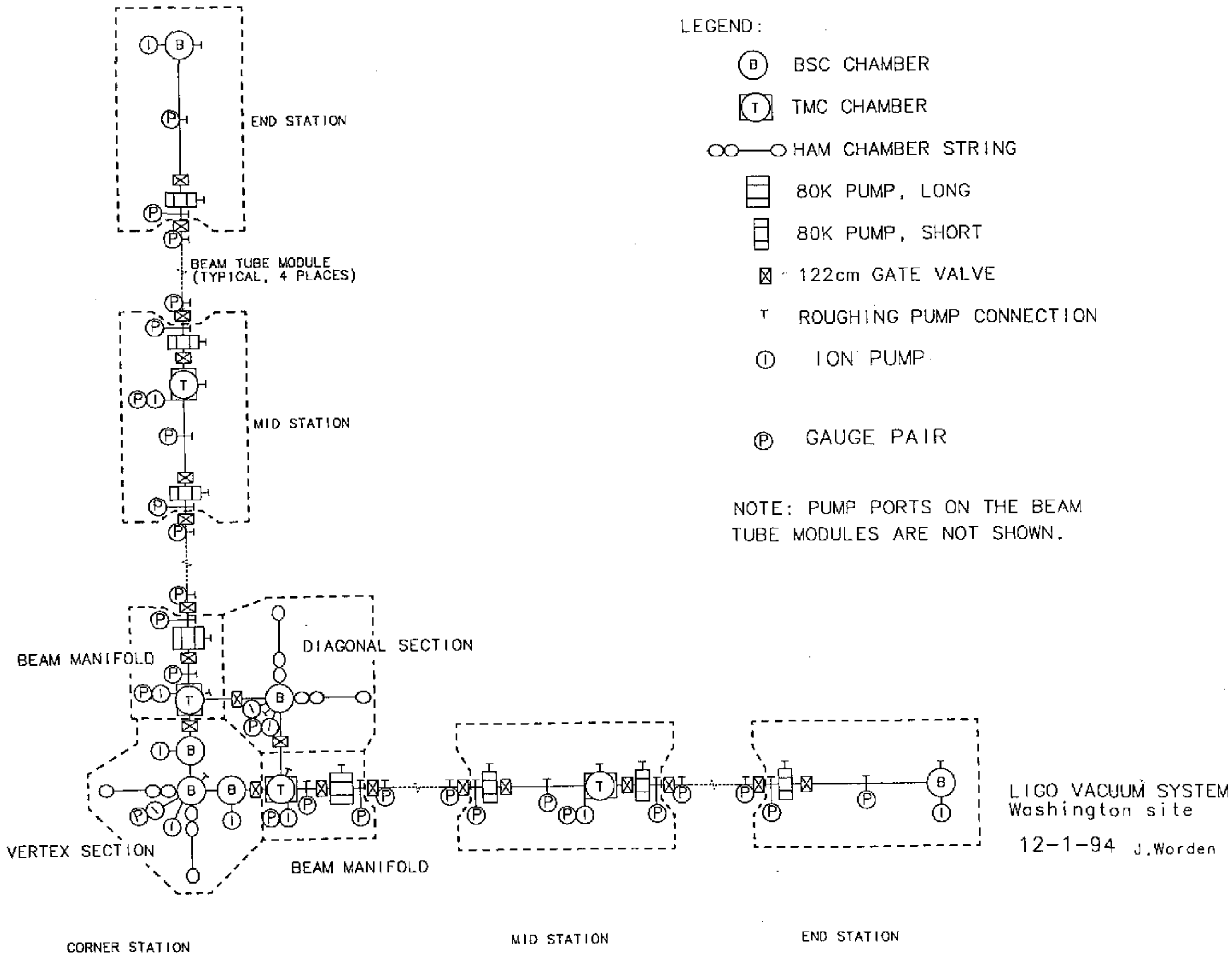


Figure 1. LIGO Geometry



LEGEND:
BSC CHAMBER
TMC CHAMBER
HAM CHAMBER STRING
80K PUMP, LONG
80K PUMP, SHORT
122cm GATE VALVE
ROUGHING PUMP CONNECTION
ION PUMP
GAUGE PAIR
NOTE: PUMP PORTS ON THE BEAM TUBE MODULES ARE NOT SHOWN.
END STATION
BEAM TUBE MODULE (TYPICAL, 4 PLACES)
MID STATION
BEAM MANIFOLD
DIAGONAL SECTION
VERTEX SECTION
BEAM MANIFOLD
LIGO VACUUM SYSTEM
Washington site
12-1-94 J.Worden
CORNER STATION
MID STATION
END STATION

Figure 2

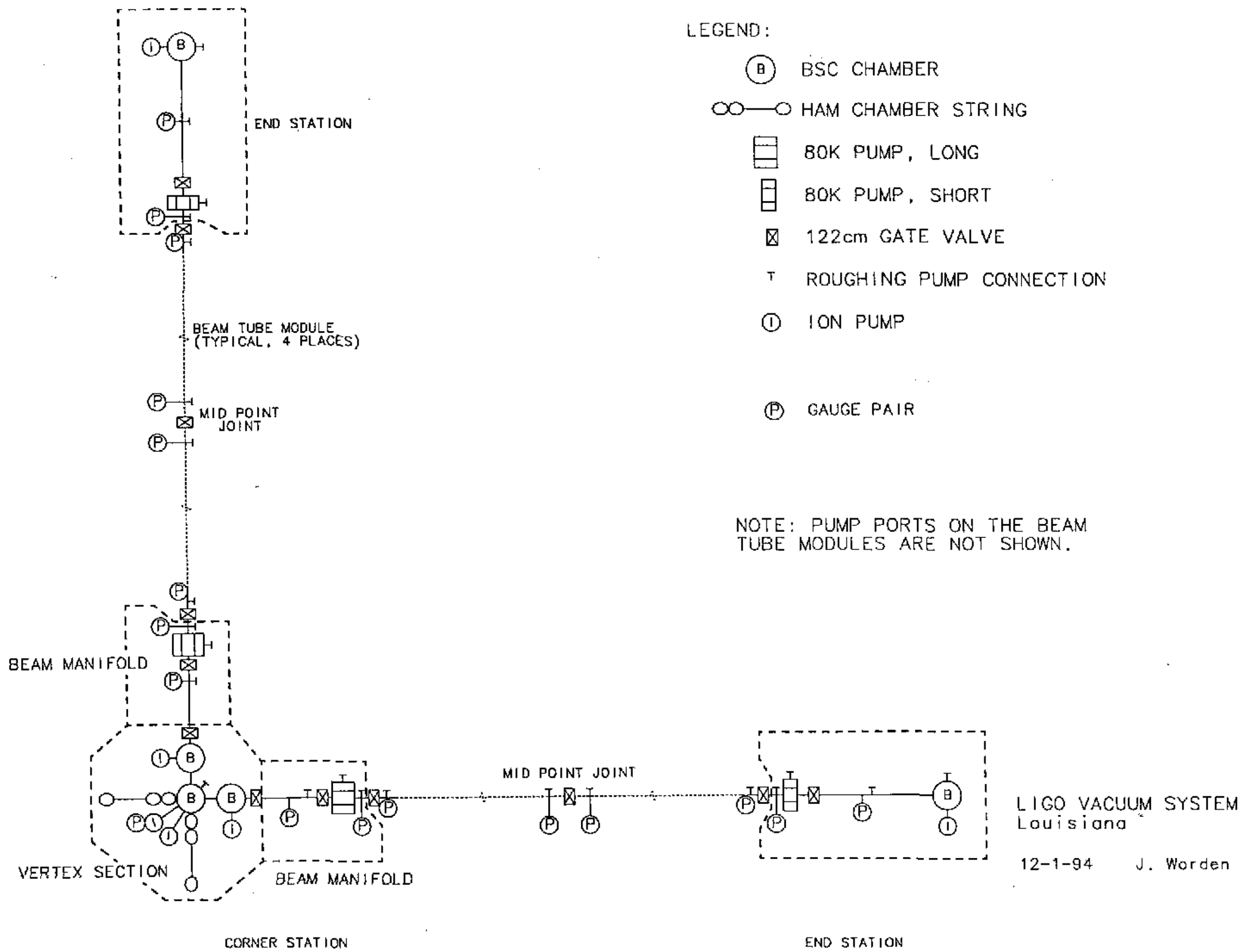

LEGEND:
BSC CHAMBER
HAM CHAMBER STRING
80K PUMP, LONG
80K PUMP, SHORT
122cm GATE VALVE
ROUGHING PUMP CONNECTION
ION PUMP
GAUGE PAIR
NOTE: PUMP PORTS ON THE BEAM TUBE MODULES ARE NOT SHOWN.
END STATION
BEAM TUBE MODULE (TYPICAL, 4 PLACES)
MID POINT JOINT
BEAM MANIFOLD
VERTEX SECTION
BEAM MANIFOLD
MID POINT JOINT
CORNER STATION
END STATION
LIGO VACUUM SYSTEM
Louisiana
12-1-94 J. Worden

Figure 3.

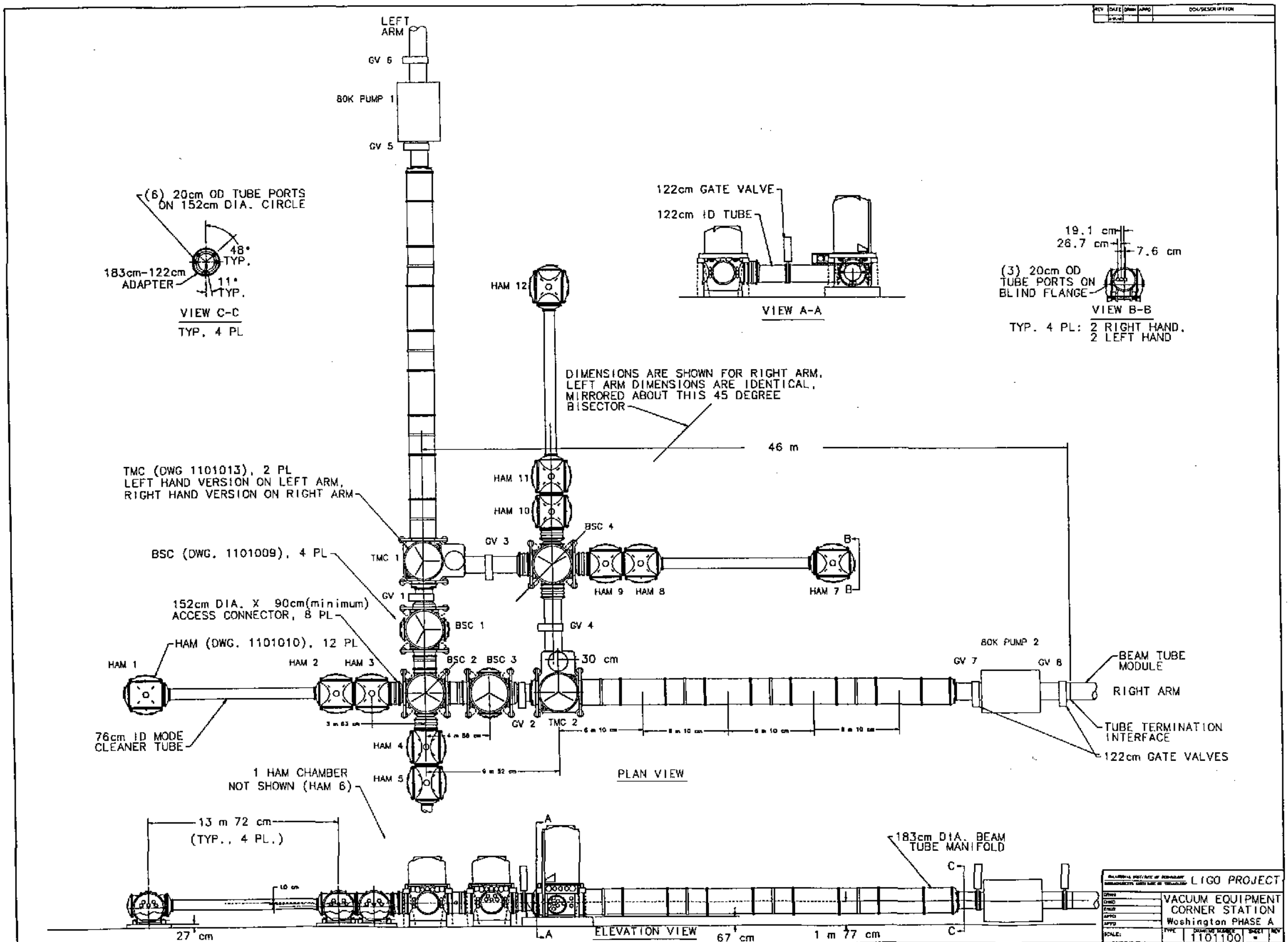

LEFT ARM
GV 6
80K PUMP 1
GV 5
(6) 20cm OD TUBE PORTS ON 152cm DIA. CIRCLE
48° TYP.
183cm-122cm ADAPTER
11° TYP.
VIEW C-C
TYP. 4 PL
122cm GATE VALVE
122cm ID TUBE
VIEW A-A
19.1 cm
26.7 cm
7.6 cm
(3) 20cm OD TUBE PORTS ON BLIND FLANGE
VIEW B-B
TYP. 4 PL: 2 RIGHT HAND, 2 LEFT HAND
HAM 12
DIMENSIONS ARE SHOWN FOR RIGHT ARM, LEFT ARM DIMENSIONS ARE IDENTICAL, MIRRORED ABOUT THIS 45 DEGREE BISECTOR
46 m
TMC (DWG 1101013), 2 PL
LEFT HAND VERSION ON LEFT ARM,
RIGHT HAND VERSION ON RIGHT ARM
HAM 11
HAM 10
BSC 4
BSC (DWG. 1101009), 4 PL
TMC 1
GV 3
HAM 9
HAM 8
HAM 7
B
GV 1
152cm DIA. X 90cm(minimum) ACCESS CONNECTOR, 8 PL
BSC 1
GV 4
HAM (DWG. 1101010), 12 PL
80K PUMP 2
HAM 1
HAM 2
HAM 3
BSC 2
BSC 3
30 cm
GV 7
GV 8
BEAM TUBE MODULE
RIGHT ARM
76cm ID MODE CLEANER TUBE
GV 2
TMC 2
TUBE TERMINATION INTERFACE
122cm GATE VALVES
HAM 4
HAM 5
1 HAM CHAMBER NOT SHOWN (HAM 6)
PLAN VIEW
13 m 72 cm
(TYP., 4 PL.)
A
183cm DIA. BEAM TUBE MANIFOLD
C
27 cm
ELEVATION VIEW
67 cm
1 m 77 cm
LIGO PROJECT
VACUUM EQUIPMENT CORNER STATION
Washington PHASE A
1101100

Figure 4

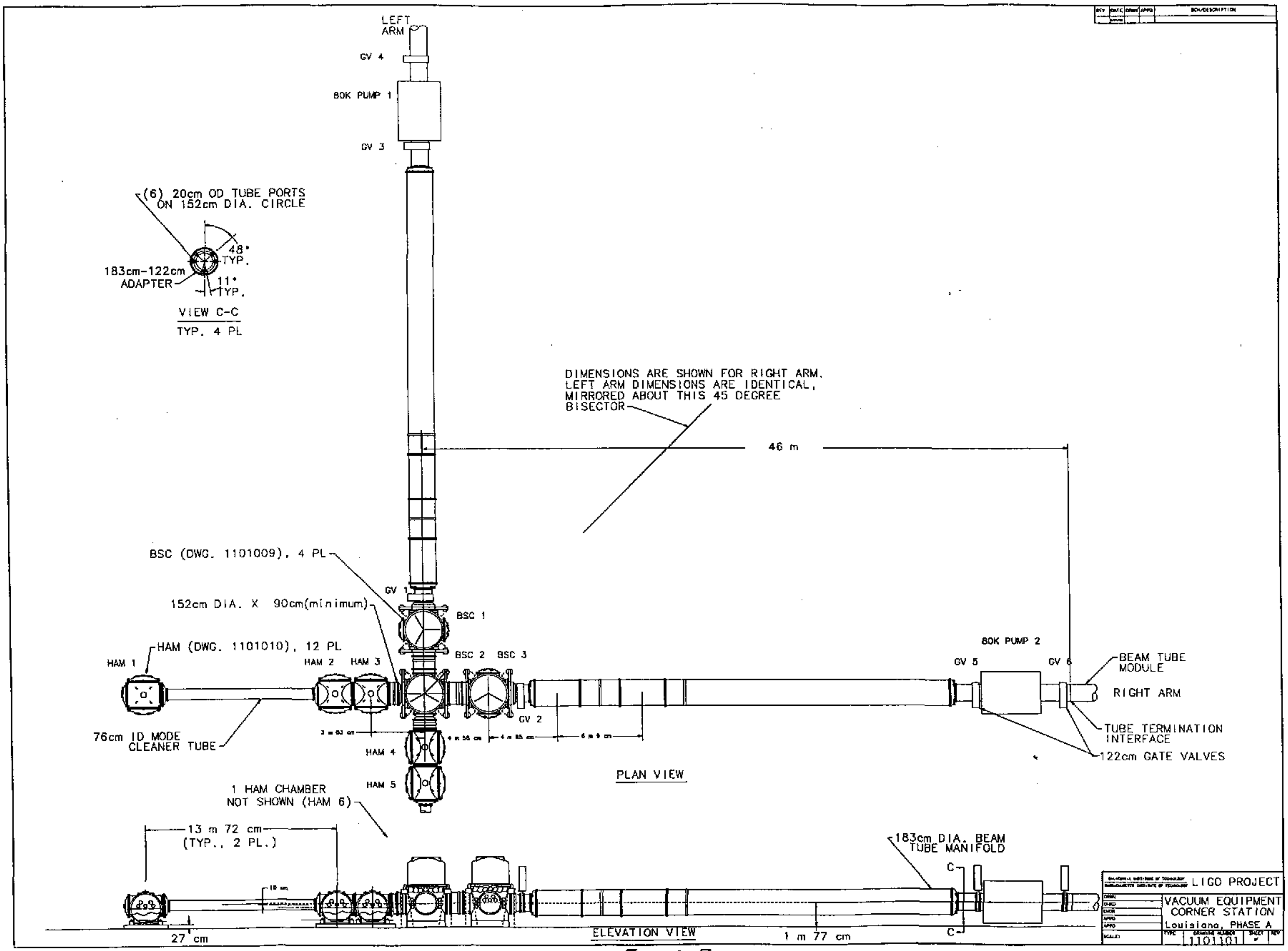
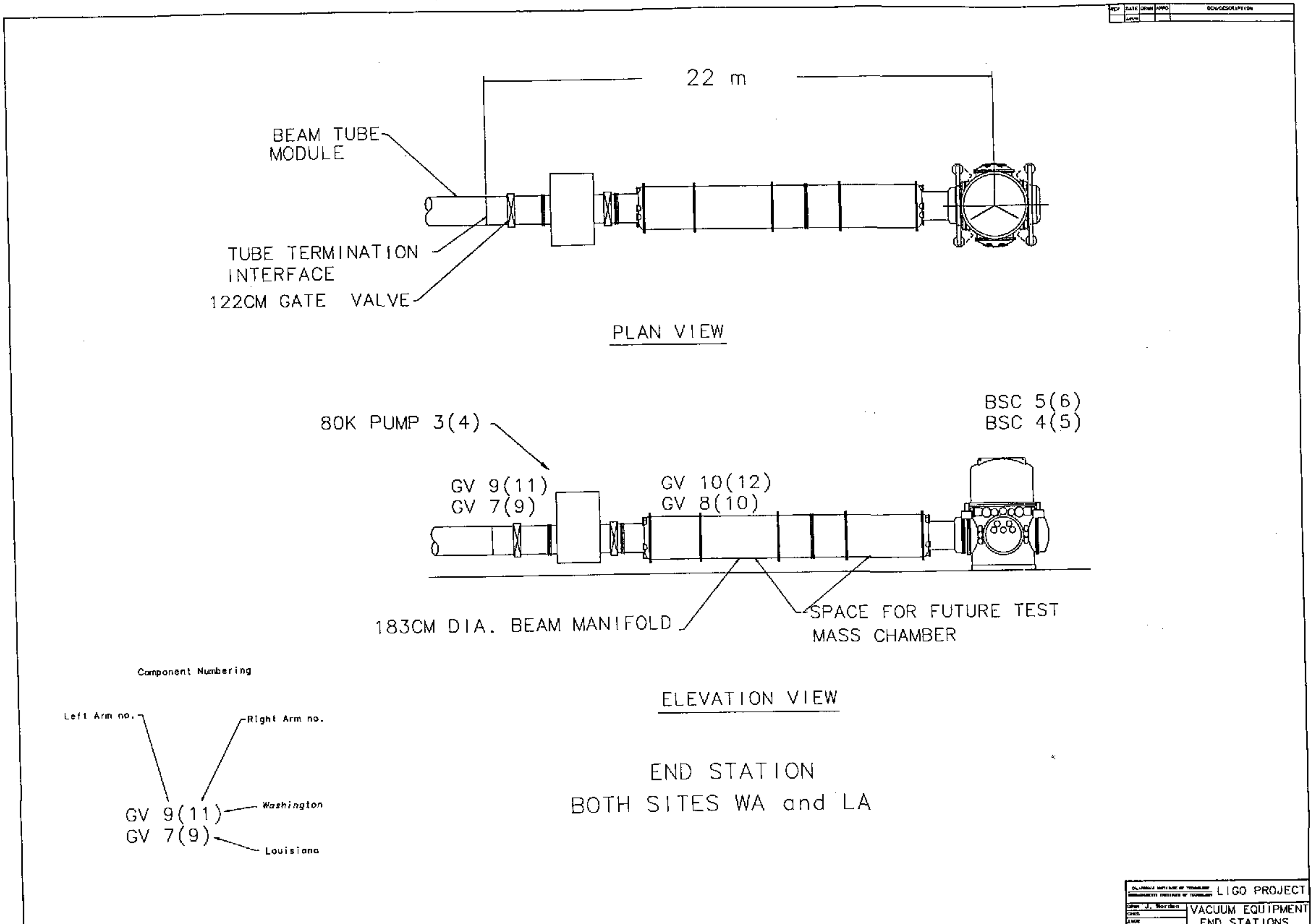
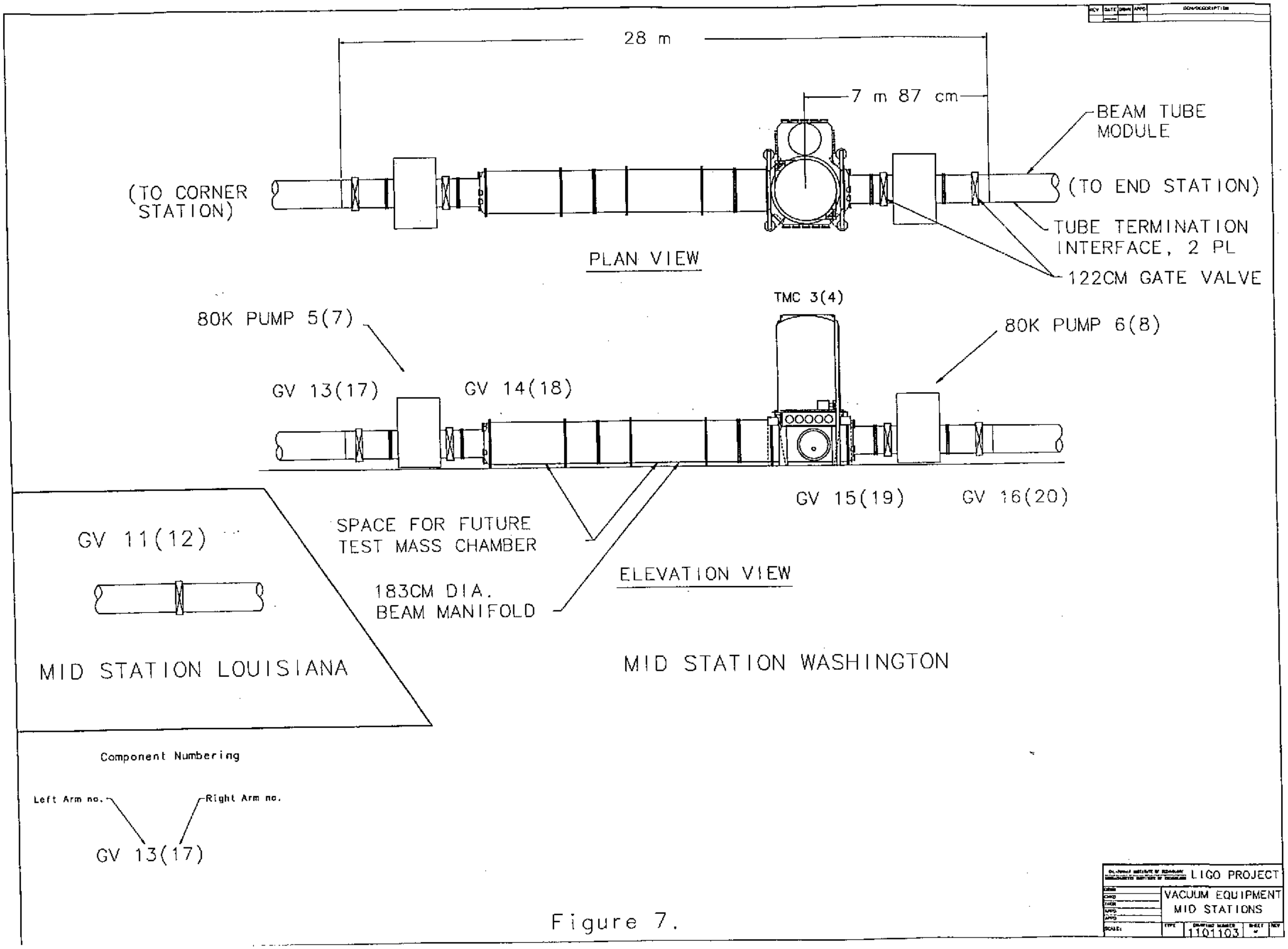

LEFT ARM
GV 4
80K PUMP 1
GV 3
(6) 20cm OD TUBE PORTS ON 152cm DIA. CIRCLE
48° TYP.
183cm-122cm ADAPTER
11° TYP.
VIEW C-C
TYP. 4 PL
DIMENSIONS ARE SHOWN FOR RIGHT ARM. LEFT ARM DIMENSIONS ARE IDENTICAL, MIRRORED ABOUT THIS 45 DEGREE BISECTOR
46 m
BSC (DWG. 1101009), 4 PL
GV 1
152cm DIA. X 90cm(minimum)
BSC 1
HAM (DWG. 1101010), 12 PL
HAM 1
HAM 2
HAM 3
BSC 2
BSC 3
80K PUMP 2
GV 5
GV 6
BEAM TUBE MODULE
RIGHT ARM
GV 2
76cm ID MODE CLEANER TUBE
HAM 4
HAM 5
TUBE TERMINATION INTERFACE
122cm GATE VALVES
PLAN VIEW
1 HAM CHAMBER NOT SHOWN (HAM 6)
13 m 72 cm (TYP., 2 PL.)
183cm DIA. BEAM TUBE MANIFOLD
C
C
ELEVATION VIEW
27 cm
1 m 77 cm
LIGO PROJECT
VACUUM EQUIPMENT CORNER STATION
Louisiana, PHASE A
1101101

Figure 5



22 m
BEAM TUBE
MODULE
TUBE TERMINATION
INTERFACE
122CM GATE VALVE
PLAN VIEW
80K PUMP 3(4)
BSC 5(6)
BSC 4(5)
GV 9(11)
GV 7(9)
GV 10(12)
GV 8(10)
183CM DIA. BEAM MANIFOLD
SPACE FOR FUTURE TEST
MASS CHAMBER
ELEVATION VIEW
Component Numbering
Left Arm no.
Right Arm no.
GV 9(11)
Washington
GV 7(9)
Louisiana
END STATION
BOTH SITES WA and LA
LIGO PROJECT
J. Worden
VACUUM EQUIPMENT
END STATIONS
1101102

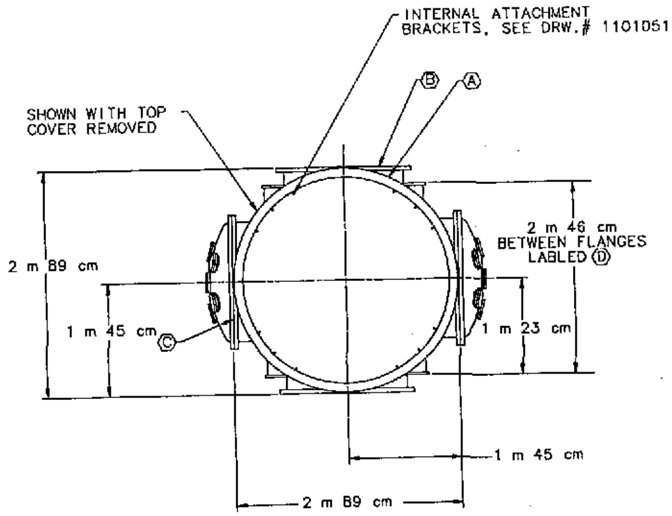
Figure 6.



28 m
7 m 87 cm
BEAM TUBE MODULE
(TO CORNER STATION)
(TO END STATION)
TUBE TERMINATION INTERFACE, 2 PL
122CM GATE VALVE
PLAN VIEW
TMC 3(4)
80K PUMP 5(7)
80K PUMP 6(8)
GV 13(17)
GV 14(18)
GV 15(19)
GV 16(20)
GV 11(12)
SPACE FOR FUTURE TEST MASS CHAMBER
183CM DIA. BEAM MANIFOLD
ELEVATION VIEW
MID STATION LOUISIANA
MID STATION WASHINGTON
Component Numbering
Left Arm no.
Right Arm no.
GV 13(17)
LIGO PROJECT
VACUUM EQUIPMENT MID STATIONS
1101103

Figure 7.

REV	DATE	DRWN	APPD	DCN/DESCRIPTION



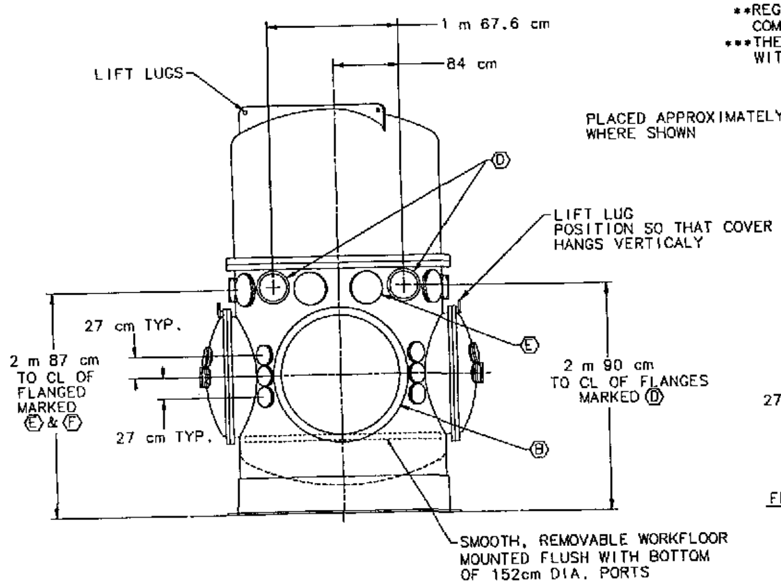
NOTES:
1. HEADS ARE ASME F&D.
2. INCLUDE CENTERING PINS ON NOZZLE FLANGES WHERE APPROPRIATE.
3. VIEWPORT (ITEM Ⓖ) MEASUREMENTS REFER TO INTERSECTION OF VIEWPORT AXIS WITH OUTER SURFACE OF VACUUM WALL.

4. TOLERANCES, UNLESS OTHERWISE SPECIFIED: LINEAR, ±0.25 CM
ANGULAR, ± 1 DEGREE

5. NOZZLE SCHEDULE PER TABLE BELOW:

ITEM	SIZE	QUANTITY	FLANGE TYPE	PURPOSE
Ⓐ	264cm ID TUBE	1	O/O-O/METAL*	MAJOR ACCESS
Ⓑ	152cm ID TUBE	2	O/O-O/METAL*	LASER BEAM, ACCESS (MINIMIZE NECK LENGTH)
Ⓒ	152cm ID TUBE	2	O/O-O/METAL*, WITH BLIND FLANGE	ACCESS (MINIMIZE NECK LENGTH)
Ⓓ	35cm OD TUBE	4	CONFLAT**	SUPPORT BEAMS REFERENCE ICD # TBD
Ⓔ	35cm OD TUBE***	8	CONFLAT**, WITH BLIND FLANGE	AIR SHWR, BACK-TO-AIR PURGE ROUGHING & ION PUMPS, UTILITY
Ⓕ	25cm OD TUBE***	6	CONFLAT**, WITH BLIND FLANGE	ELECTRICAL FEEDTHROUGHS
Ⓖ	20cm OD TUBE***	22	CONFLAT**, WITH BLIND FLANGE	OBSERVATION, BEAM PICK-OFFS
Ⓗ	3.8cm OD TUBE	1	CONFLAT**, WITH BLIND FLANGE	ANNULUS PUMPOUT (NOT SHOWN)

*DUAL O-RING DESIGN, WITH CAPABILITY OF REPLACING INBOARD O-RING WITH METAL SEAL. THESE FLANGES EACH INCLUDE AN ANNULAR CHANNEL BETWEEN O-RINGS, MANIFOLDED TO A SINGLE PUMPOUT PORT ON EACH CHAMBER, WITH CONFLAT** SEAL.
**REGISTERED TRADEMARK, VARIAN VACUUM PRODUCTS; COMPATIBLE ALTERNATES ARE ACCEPTABLE.
***THESE FLANGES ARE TANGENT TO LOCAL VACUUM WALL, WITH MINIMUM NECK LENGTH.



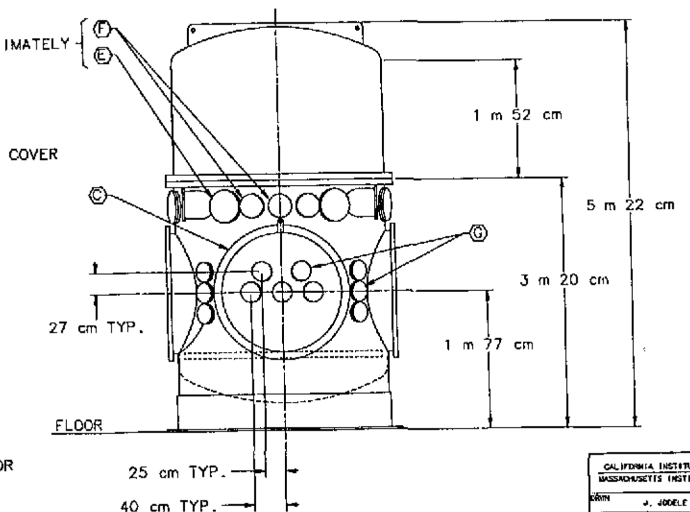
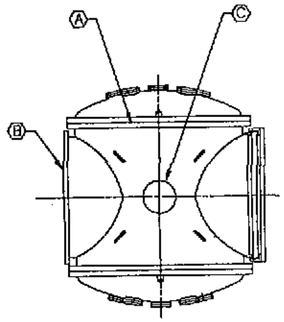


Figure 8.

CALIFORNIA INSTITUTE OF TECHNOLOGY / MASSACHUSETTS INSTITUTE OF TECHNOLOGY	LIGO PROJECT
DRN J. JODELE / CHK	BEAM SPLITTER CHAMBER (BSC)
SCALE:	DRAWING NUMBER 1101009 · SHEET 1 of 1 · REV.

REV	DATE	DRWN	APPD	DCN/DESCRIPTION

NOTES:
1. HEADS ARE ASME F&D.
3. INCLUDE CENTERING PINS ON NOZZLE FLANGES WHERE APPROPRIATE.
3. VIEWPORT (ITEM Ⓕ) MEASUREMENTS REFER TO INTERSECTION OF VIEWPORT AXIS WITH OUTER SURFACE OF VACUUM WALL.
4. TOLERANCES, UNLESS OTHERWISE SPECIFIED: LINEAR, ±0.25 CM
ANGULAR, ± 1 DEGREE
5. NOZZLE SCHEDULE PER TABLE BELOW:

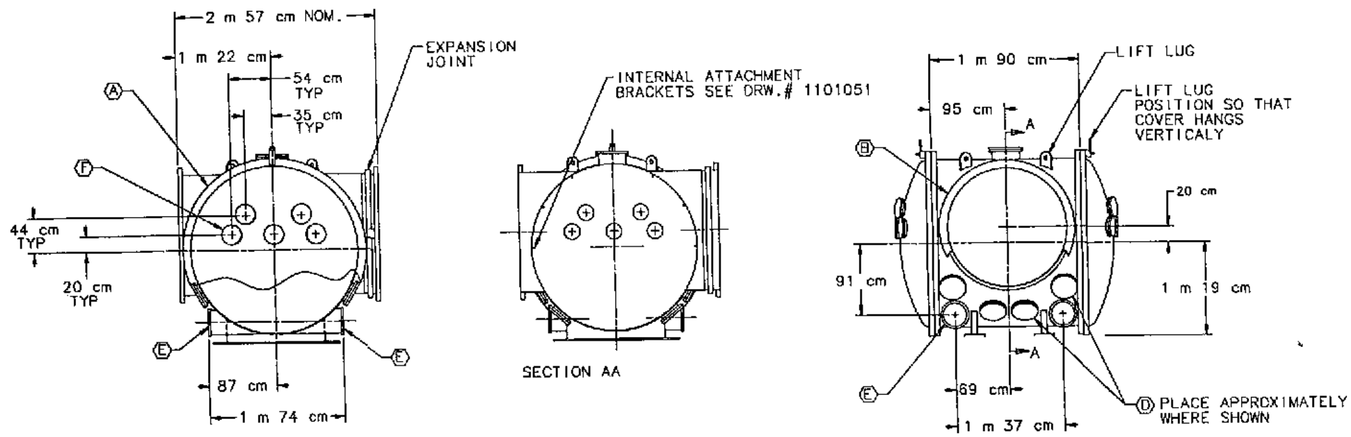


ITEM	SIZE	QUANTITY	FLANGE TYPE	PURPOSE
Ⓐ	213cm ID TUBE	2	O/O-O/METAL*	MAJOR ACCESS
Ⓑ	152cm ID TUBE	2	O/O-O/METAL*	LASER BEAM
Ⓒ	35cm TUBE ***	1	CONFLAT**, WITH BLIND FLANGE	ION PUMP/AIR SHOWERS, BACK-TO-AIR PURGE
Ⓓ	25cm OD TUBE***	8	CONFLAT**, WITH BLIND FLANGE	ELECTRICAL FEEDTHROUGHS, UTILITY
Ⓔ	30cm OD TUBE	4	CONFLAT**	SUPPORT BEAMS REFERENCE ICD # TBD
Ⓕ	20cm OD TUBE***	10	CONFLAT**, WITH BLIND FLANGE	OBSERVATION, PICKOFFS
Ⓖ	3.8cm TUBE	1	CONFLAT**, WITH BLIND FLANGE	ANNULUS PUMPOUT (NOT SHOWN)

* DUAL O-RING DESIGN, WITH CAPABILITY OF REPLACING INBOARD O-RING WITH METAL SEAL. THESE FLANGES EACH INCLUDE AN ANNULAR CHANNEL BETWEEN O-RINGS, MANIFOLDED TO A SINGLE PUMPOUT PORT ON EACH CHAMBER, WITH CONFLAT** SEAL.

** REGISTERED TRADEMARK, VARIAN VACUUM PRODUCTS; COMPATIBLE ALTERNATIVES ARE ACCEPTIBLE

*** THESE FLANGES ARE TANGENT TO LOCAL VACUUM WALL, WITH MINIMUM NECK LENGTH



CALIFORNIA INSTITUTE OF TECHNOLOGY / MASSACHUSETTS INSTITUTE OF TECHNOLOGY		LIGO PROJECT
DRWN J. VODELE		HORIZONTAL ACCESS MODULE (HAM)
CHK		
SCALE:	DRAWING NUMBER 1101010	SHEET 1 OF 1 REV.

Figure 9.

REV	DATE	DRWN	APPD	DCN/DESCRIPTION

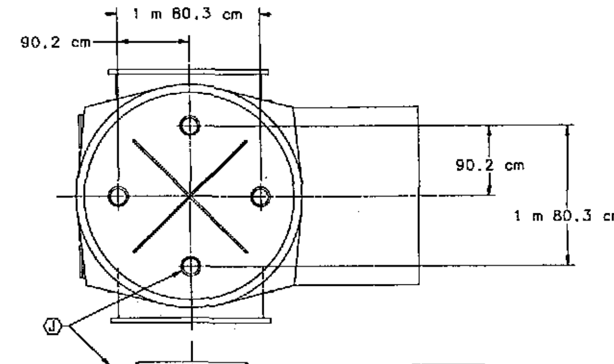
NOTES:
1. HEADS ARE ASME F&D.
2. INCLUDE CENTERING PINS ON NOZZLE FLANGES WHERE APPROPRIATE.
3. VIEWPORT (ITEM Ⓗ) MEASUREMENTS REFER TO INTERSECTION OF VIEWPORT AXIS WITH OUTER SURFACE OF VACUUM WALL.
4. TOLERANCES, UNLESS OTHERWISE SPECIFIED: LINEAR, ±0.25 CM ANGULAR, ± 1 DEGREE
5. NOZZLE SCHEDULE PER TABLE BELOW:

ITEM	SIZE	QUANTITY	FLANGE TYPE	PURPOSE
Ⓐ	264cm ID TUBE	1	O/O-O/METAL*	MAJOR ACCESS
Ⓑ	183cm ID TUBE	2	METAL SEAL	LASER BEAM
Ⓒ	122cm ID TUBE	1	O/O-O/METAL*	LASER BEAM
Ⓓ	122cm ID TUBE	1	O/O-O/METAL*, WITH BLIND FLANGE	EMERGENCY ACCESS (MINIMIZE NECK LENGTH)
Ⓔ	35cm OD TUBE	4	CONFLAT**	SUPPORT BEAMS REFERENCE ICD #TBD
Ⓕ	35cm OD TUBE	4	CONFLAT**, WITH BLIND FLANGE	ELECTRICAL FEEDTHROUGHS ROUGHING & ION PUMPS, UTILITY
Ⓖ	25cm OD TUBE	10	CONFLAT**, WITH BLIND FLANGE	ELECTRICAL FEEDTHROUGHS, BACK-TO-AIR PURGE
Ⓗ	20cm OD TUBE***	12	CONFLAT**, WITH BLIND FLANGE	OBSERVATION, BEAM PICKOFFS
Ⓘ	3.8cm OD TUBE	2	CONFLAT**, WITH BLIND FLANGE	ANNULUS PUMPOUT (NOT SHOWN)
Ⓙ	20cm OD TUBE	4	CONFLAT**	SEISMIC ISOLATION LIFT MECHANISM

*DUAL O-RING DESIGN, WITH CAPABILITY OF REPLACING INBOARD O-RING WITH METAL SEAL. THESE FLANGES EACH INCLUDE AN ANNULAR CHANNEL BETWEEN O-RINGS. ANNULAR CHANNEL OF Ⓒ TO BE MANIFOLDED TO A SINGLE PUMPOUT PORT Ⓘ. ANNULAR CHANNEL OF Ⓐ TIED TO SEPERATE PUMPOUT PORT Ⓘ.

**REGISTERED TRADEMARK, VARIAN VACUUM PRODUCTS COMPATIBLE ALTERNATIVES ARE ACCEPTABLE

***THESE FLANGES ARE TANGENT TO LOCAL VACUUM WALL, WITH MINIMUM NECK LENGTH



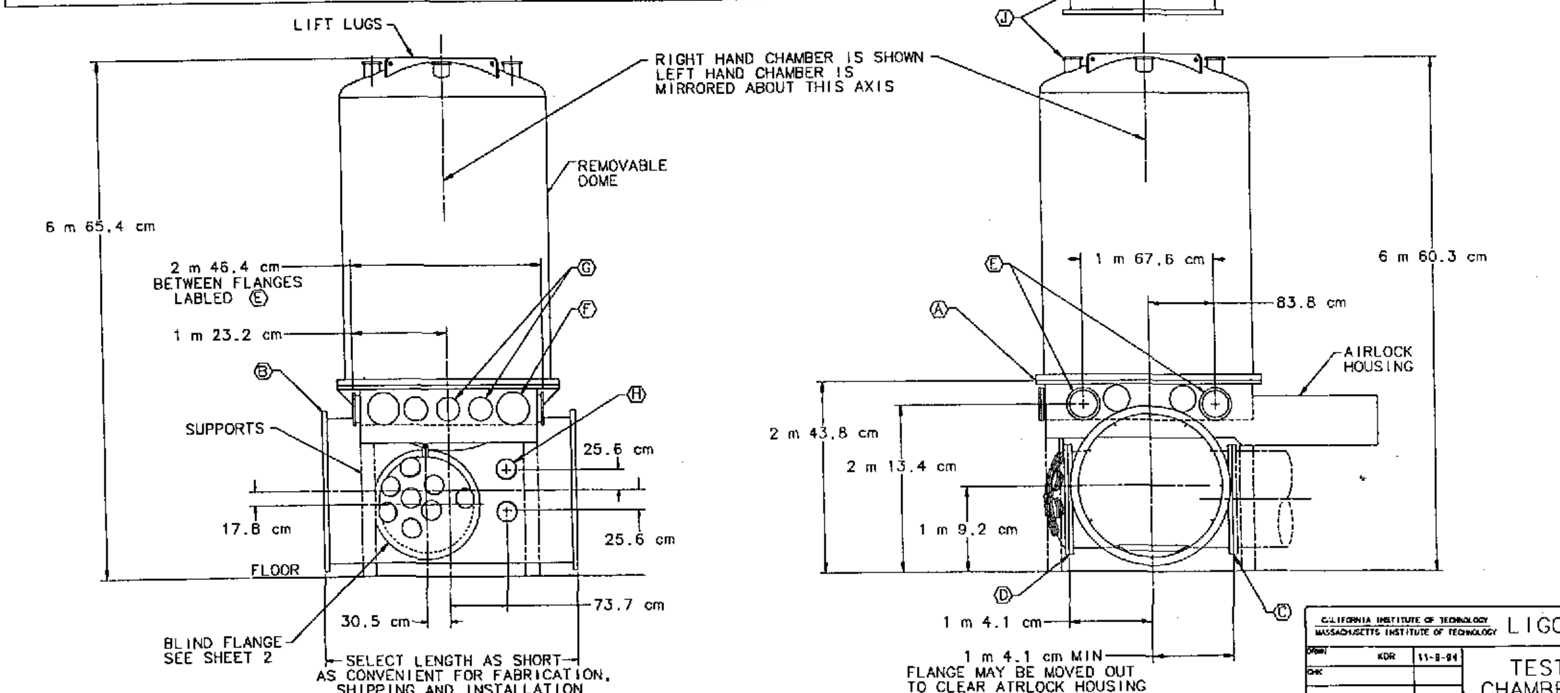


Figure 10.

CALIFORNIA INSTITUTE OF TECHNOLOGY / MASSACHUSETTS INSTITUTE OF TECHNOLOGY	LIGO PROJECT
DRWN KDR 11-8-94 / CHK	TEST MASS CHAMBER (TMC)
SCALE:	DRAWING NUMBER 1101013 · SHEET 1 of 2 · REV.

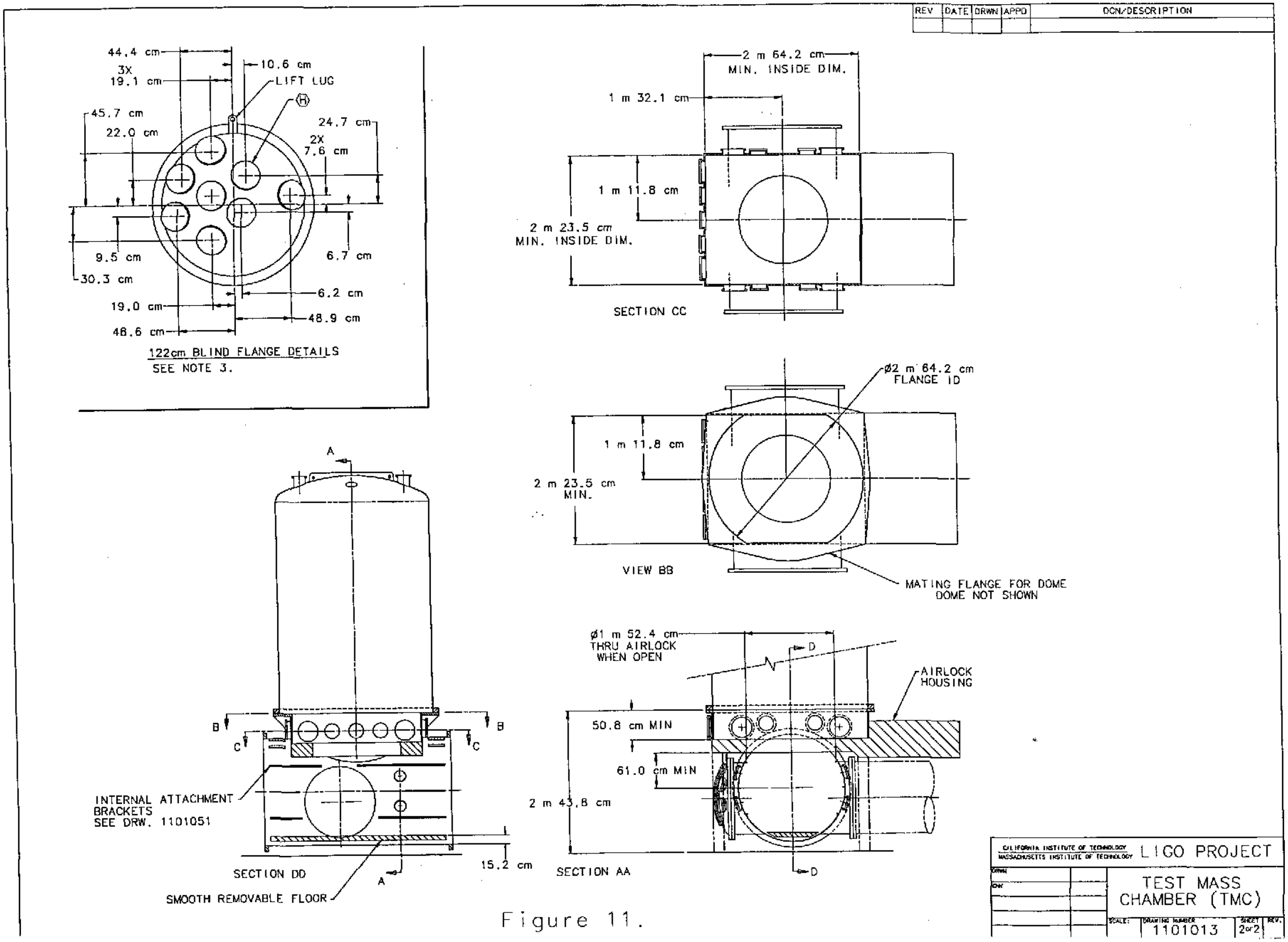
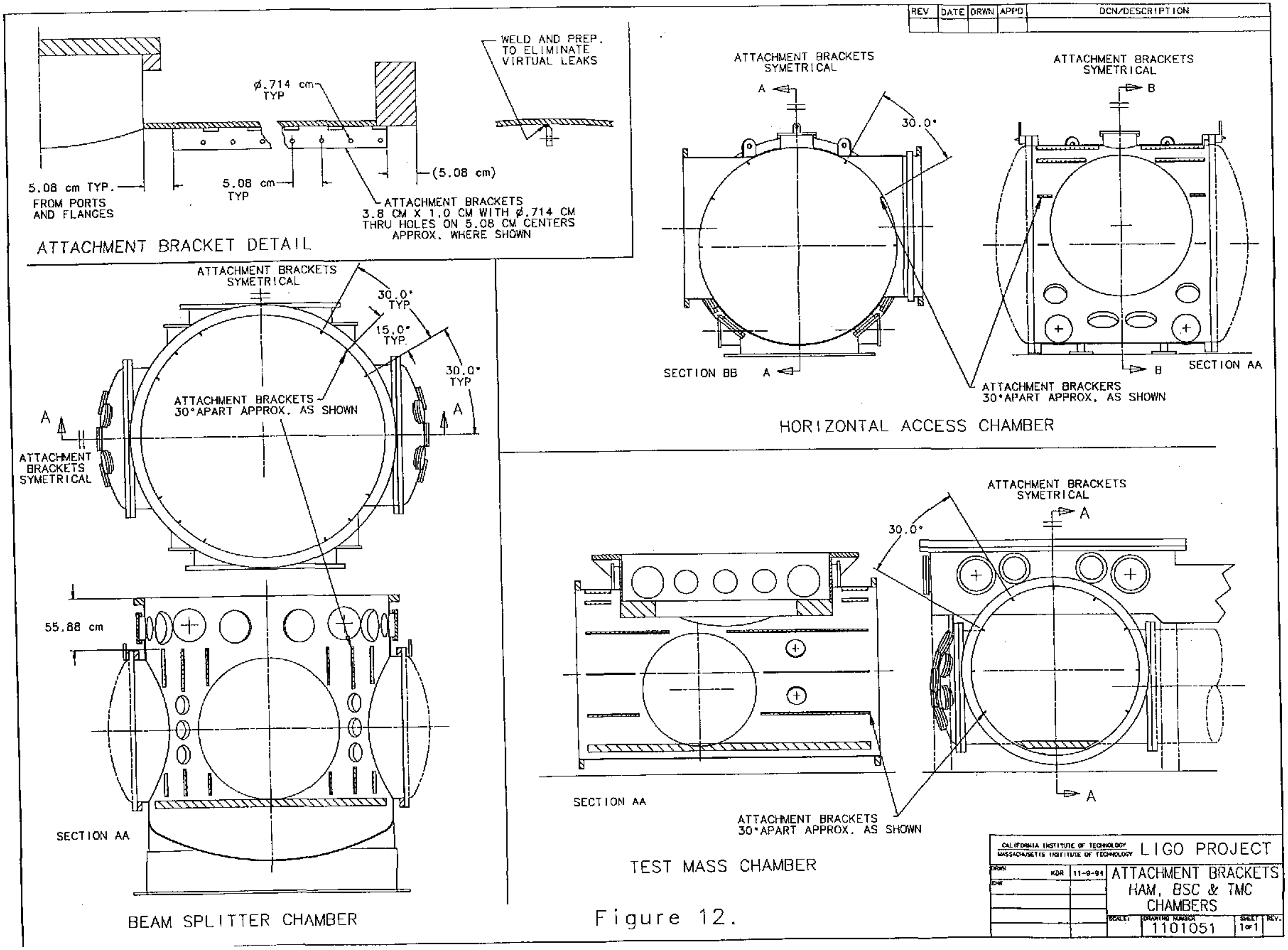

REV
DATE
DRWN
APPD
DCN/DESCRIPTION
44.4 cm
10.6 cm
3X
19.1 cm
LIFT LUG
45.7 cm
22.0 cm
24.7 cm
2X
7.6 cm
9.5 cm
6.7 cm
30.3 cm
6.2 cm
19.0 cm
48.9 cm
48.6 cm
122cm BLIND FLANGE DETAILS
SEE NOTE 3.
2 m 64.2 cm
MIN. INSIDE DIM.
1 m 32.1 cm
1 m 11.8 cm
2 m 23.5 cm
MIN. INSIDE DIM.
SECTION CC
ø2 m 64.2 cm
FLANGE ID
1 m 11.8 cm
2 m 23.5 cm
MIN.
VIEW BB
MATING FLANGE FOR DOME
DOME NOT SHOWN
ø1 m 52.4 cm
THRU AIRLOCK
WHEN OPEN
AIRLOCK
HOUSING
50.8 cm MIN
61.0 cm MIN
2 m 43.8 cm
SECTION AA
INTERNAL ATTACHMENT
BRACKETS
SEE DRW. 1101051
15.2 cm
SECTION DD
SMOOTH REMOVABLE FLOOR
CALIFORNIA INSTITUTE OF TECHNOLOGY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LIGO PROJECT
TEST MASS
CHAMBER (TMC)
1101013
2 OF 2

Figure 11.



REV
DATE
DRWN
APPD
DCN/DESCRIPTION
WELD AND PREP. TO ELIMINATE VIRTUAL LEAKS
ø.714 cm TYP
5.08 cm TYP. FROM PORTS AND FLANGES
5.08 cm TYP
(5.08 cm)
ATTACHMENT BRACKETS 3.8 CM X 1.0 CM WITH ø.714 CM THRU HOLES ON 5.08 CM CENTERS APPROX. WHERE SHOWN
ATTACHMENT BRACKET DETAIL
ATTACHMENT BRACKETS SYMETRICAL
30.0° TYP
15.0° TYP.
30.0° TYP
ATTACHMENT BRACKETS 30°APART APPROX. AS SHOWN
A
A
ATTACHMENT BRACKETS SYMETRICAL
55.88 cm
SECTION AA
BEAM SPLITTER CHAMBER
ATTACHMENT BRACKETS SYMETRICAL
A
30.0°
SECTION BB
A
ATTACHMENT BRACKETS SYMETRICAL
B
B
SECTION AA
ATTACHMENT BRACKERS 30°APART APPROX. AS SHOWN
HORIZONTAL ACCESS CHAMBER
ATTACHMENT BRACKETS SYMETRICAL
A
30.0°
A
SECTION AA
ATTACHMENT BRACKETS 30°APART APPROX. AS SHOWN
TEST MASS CHAMBER
CALIFORNIA INSTITUTE OF TECHNOLOGY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LIGO PROJECT
DRWN KDR 11-9-94
CHK
ATTACHMENT BRACKETS HAM, BSC & TMC CHAMBERS
SCALE:
DRAWING NUMBER 1101051
SHEET 1 OF 1
REV.

Figure 12.

VACUUM EQUIPMENT SPECIFICATION
LIGO FACILITY

LIGO Document 1100003

PREPARED BY: John Worden

APPROVED BY:

EFFECTIVE DATE: July 18, 1994

CALIFORNIA INSTITUTE OF TECHNOLOGY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

LIGO PROJECT

DOCUMENT CONTROL PAGE

DOCUMENT CUSTODIAN: worden

FILE: vecontr/vesnew

REVISION	DATE	BY	DESCRIPTION OR DCN	APPROVED

Contents

1. SCOPE

This specification defines the technical requirements for the design, procurement, delivery, qualification, installation, and acceptance testing of the LIGO (Laser Interferometer Gravitational-Wave Observatory) vacuum equipment.

The LIGO includes two installations at widely separated sites, near Hanford, WA and Livingston, LA. Each installation includes laser interferometers in an L shape with 4-km long arms, a vacuum system for the sensitive interferometer components and optical beams, and other support facilities. The vacuum equipment consists of interconnected vacuum vessels, pumping systems, valves and a monitoring and control system for each site. The vacuum equipment will be located in structures called stations, located at the corners, mid points, and ends of the L-shaped pattern. See Figure 1.

The vacuum tube joining the vacuum equipment in the stations is provided under separate contract, and is described by LIGO 1100004, Beam Tubes Specification.

Cleaning, alignment and leak checking are critical processes. Vacuum levels during operation may range from a nominal 10^{-6} torr at the chambers to 10^{-9} torr in the beamtube.

2. APPLICABLE DOCUMENTS

If more than one document applies to a technical requirement, the more stringent standard shall have precedence. Requirements set forth in this specification shall have final precedence.

2.1 Industry Documents

2.1.1 American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code

- Pressure Vessels, Section VIII, Division I
- Welding and Brazing Qualifications, Section IX

2.1.2 American Society of Civil Engineers

- Minimum Design Loads for Buildings and Other Structures, ASCE 7–88

2.1.3 "Standards of Expansion Joint Manufacturer's Association", published by Expansion Joint Manufacturer's Association (EJMA)

2.1.4 National Fire Protection Association (NFPA) Standards

- No. 70—National Electrical Code

2.2 Government Standards

- Building and safety codes: local, state, and federal, including OSHA

2.3 LIGO Documents

2.3.1 LIGO Drawings

- LIGO Drawing 1101100, Vacuum Equipment, Corner Station, Washington Site, Phase A, attached
- LIGO Drawing 1101101, Vacuum Equipment, Corner Station, Louisiana Site, Phase A, attached
- LIGO Drawing 1101102, Vacuum Equipment, End Stations, Phase A, attached
- LIGO Drawing 1101103, Vacuum Equipment, Mid Stations, Washington Site, Phase A, attached
- LIGO Drawing 1101009, Beam Splitter Chamber (BSC)
- LIGO Drawing 1101010, Horizontal Axis Module (HAM)
- LIGO Drawing 1101011, 10" Isolation Bellows
- LIGO Drawing 1101012, 7" Isolation Bellows
- LIGO Drawing 1101013, Test Mass Chamber, Type 1 (TMC-1)
- LIGO Drawing 1101018, Support Beam Assembly, Large Chambers
- LIGO Drawing 1101041, Support Beam Assembly, HAM Chambers

2.3.2 LIGO Specifications

- LIGO 1100004, Beam Tubes Specification

2.4 Interface Control Documents

2.4.1 Provided by the Vacuum Equipment Contractor

- Vendor document XXXX, Vacuum Equipment to Beam Tube Interface
- Vendor document XXXX, Vacuum System to Station Enclosure and Utilities Interface
- Vendor document XXXX, Vacuum vent/purge air system to internal air showers.
- Vendor document XXXX, Vacuum Equipment to Process Control System

3. SYSTEM DESCRIPTION

The LIGO vacuum system is divided into two parts: the beam tube modules and the vacuum equipment. The beam tube modules are two kilometers long and are addressed in a separate contract. The vacuum equipment is housed in buildings located at the intersection (corner) and ends of the beam tube modules. These buildings are the corner station, mid stations, and end stations. The vacuum equipment consists of the following subsystems:

1. Vacuum enclosure subsystem
2. Pumping subsystem
3. Valve subsystem
4. Vent and purge subsystem
5. Bakeout subsystem
6. Monitor and control subsystem

Together these subsystems, along with the beam tube modules, make up the vacuum system. The Washington site schematic is shown in Figure 2 and the Louisiana site schematic is shown in Figure 3. A description of the system according to station is given below.

3.1 Corner Station Washington Site The vacuum enclosure for the corner station of the Washington Site is shown in Figure 4 (a reduced LIGO drawing #1101100). Three types of vacuum chambers enclose the optical components of the laser interferometers: test mass chambers (TMC), beam splitter chambers

(BSC), and horizontal access modules (HAM). One of the BSCs shall be located at the intersection of the two arms in the Washington site corner station. As shown in Figure 4, an array of nine HAMs shall connect with the diagonal chamber, as extensions of the arms. Interconnecting two sets of HAM groups are 76 cm diameter mode cleaner tubes. Along each arm, an additional BSC and TMC shall be located in that order. A section of 183 cm diameter tube shall provide for the addition of TMCs in future expansions. A second BSC (with HAM array) shall be located on a 45 degree diagonal between the arms, and two 122 cm tubes shall connect this to the TMCs, through 122 cm diameter isolation valves. The corner station building will be built with enough room for the future addition of up to four TMC/BSC/HAM groupings. Removal of access covers from the chambers will allow for servicing the optical components during normal operations; the seals on these covers shall be designed as double O-rings for economical reuse during the early period of operation when access is more frequent and permeation is more tolerable; later, the inboard O-ring may be replaced with a metal seal. A clean air vent and purge system shall be provided to break vacuum and maintain cleanliness of the optical components whenever a chamber is open.

The corner station pumping system shall include two LN_2 (liquid nitrogen) pumps near the beam tube interfaces, getter pumps, and main ion pumps as shown in Figure 2. Ion pumps shall also be used to pump the annulus of all double O-ring seals. Rough pumping from atmosphere shall be done with portable pump stations.

3.2 Corner Station Louisiana Site The vacuum equipment for the corner station at the Louisiana site is similar to that at the Washington site, except that initially there shall be no TMCs, and only one of the BSC/HAM groupings shall be installed. See Figure 5 (a reduced LIGO drawing #1101101) for details.

3.3 End Stations Both Sites The vacuum equipment for the end stations is shown in Figure 6 (a reduced LIGO drawing #1101102). Vacuum enclosures shall include one BSC initially.

The pumping system shall include one LN_2 pump with isolation valves, getter pumps, and ion pumps for both the enclosure and the annulus. Rough pumping from atmosphere shall be done with portable pump stations.

3.4 Mid Station Washington Site The vacuum equipment for the mid stations is shown in Figure 7 (a reduced LIGO drawing #1101103). Vacuum enclosures shall include one TMC initially.

The pumping system shall include two LN_2 pumps with isolation valves, getter pumps and ion pumps for both the enclosure and the annulus. Rough pumping from atmosphere shall be done with portable pump stations.

3.5 Midpoint Pumping Station Louisiana Site No chambers are to be housed here. A 122 cm diameter gate valve allows isolation of the adjoining beam tube modules. A valved and instrumented roughing port and an independent, separately valved getter pump set shall be located on each side of this gate valve. Refer to Figure 3.

4. SYSTEM REQUIREMENTS

4.1 Leak Rate All leaks greater than 1 x 10^{-8} torr•liters/sec of helium shall be repaired according to Caltech approved procedures.

4.2 Pump Down Time Each vacuum section (an isolatable volume), without interferometer components, shall pump down from atmosphere to 1 x 10^{-6} torr in less than 24 hours. In the case of the vertex and diagonal vacuum sections, two pump stations may be connected at once to accomplish this. Otherwise, only a single pump station shall be connected at one time.

4.3 Ultimate Pressures Each vacuum section (empty) shall attain 5 x 10^{-9} torr after 100 hours of pumping with the ion pumps and open to the LN_2 pumps. The prior conditioning permitted is a 48 hour bakeout followed by a vent and purge for 24 hours.

4.4 System Control and Protection Each vacuum section shall have sufficient instrumentation and hardware to allow safe and reliable operation of valves, pumps and gauges under all conditions. Control logic shall be specified to allow incorporation into a commercial process control system to be supplied by Caltech at a later date.

4.5 Bakeout/Degassing Capability A means shall be provided to heat all vacuum surfaces to any desired temperature, ranging from ambient to 150°C. All ion pumps and gauges shall be bakeable to 300°C. Ramping of temperatures shall be controlled to minimize the stresses on vacuum connections. There shall be no particulate generation or shedding caused by placement or removal of the insulation.

Alternate means using photo-induced and/or ion-induced desorption may be utilized if cost effective degassing is obtained.

4.6 Special Environmental Requirements The LIGO vacuum equipment and laser areas house instrumentation which is potentially highly sensitive to vibration and acoustic noise, shock-induced damage or misalignment, electromagnetic interference, and contamination. The following requirements on installed equipment have been developed without detailed consideration of cost impact. They are subject to future revision.

4.6.1 Shock Valve actuation or other intermittent device operation shall induce no more than 0.01 g peak-to-peak acceleration at any point within 1 meter of any chamber.

4.6.2 Acoustic Noise Acoustic noise from all simultaneously operating equipment (including turbopumps and their backing pumps, gauge and pump controllers and supplies, but EXEMPTING main mechanical roughing pumps on intermittent duty) shall not exceed PNC-40 (Preferred Noise Criterion 40) at any location within LIGO vacuum equipment and laser areas. Limited narrowband exemptions may be permitted subject to Caltech approval.

4.6.3 Vibration Vibration from all simultaneously operating equipment (EXEMPTING main mechanical roughing pumps on intermittent duty) shall not cause the vibration measured at any point within 1 meter of any chamber to exceed the LIGO *Site* Vibration Baseline (Figure {FIG. TO BE SUPPLIED BY LISA FAIRLY SOON}) by more than 6 dB (a factor of two in amplitude) at any frequency between 0.1 Hz and 10 kHz. Limited narrowband exemptions may be permitted subject to Caltech approval.

4.6.4 Electromagnetic Emissions All electrical equipment shall conform to {IEC? ISO? IEEE?} standard # {?????} limiting electromagnetic radiation, emission and powerline contamination. {VOLKER WILL BE PROVIDING SOME ACTUAL STANDARDS TO ADHERE TO FOR EMI; I WILL BUG HIM ABOUT IT SHORTLY}

4.6.5 Particulates and other contaminants No installed equipment shall emit or harbor particulates at a level inconsistent with maintenance of a clean environment conforming to Federal Standard 209D Class 50,000.

4.7 Interfaces The following interfaces shall be provided for and documented accordingly:

1. Vacuum equipment to beam tube.**
2. Vacuum system to station enclosure and utilities.
3. Vacuum vent/purge air system to internal air showers.
4. Vacuum equipment to process control system.

** For the purposes of this proposal the interface shall be taken as the "Tube Termination Interface" on Figure 4.

4.8 Design Life The contractor shall design the vacuum equipment for a minimum serviceable life of 20 years.

4.9 Environmental Under normal operations, the vacuum equipment will be operated in a temperature and humidity controlled environment. In case of power or control failure, and during the construction phase, conditions will be dictated by diurnal and seasonal ranges. Exposure to these conditions shall not damage the vacuum equipment.

5. SUBSYSTEMS

5.1 Vacuum Enclosure Subsystem The vacuum enclosure includes all components such as chambers, tubes, flanges, elbows, tees, blank-offs, and other fittings, which form the barrier between atmosphere and vacuum. These components are required to be compatible with use at 1×10^{-9} torr. Specific requirements are below.

5.1.1 Materials All fabricated components exposed to vacuum shall be made from type 304L or 316L stainless steel, using low carbon weld filler wire, where required. Standard catalogue items of 304 or 316 stainless steel are acceptable if not available in 304L or 316L. Copper and aluminum may be used for seals. All other materials are subject to Caltech approval. Copies of mill test reports of chamber, tube and flange materials shall be furnished.

Internal surface finish is subject to Caltech approval.

5.1.2 Cleaning All surfaces exposed to vacuum shall be cleaned in accordance with procedures approved by Caltech prior to fabrication and installation; surface recontamination shall be prevented during all subsequent processes.

All items shall be wrapped or sealed after cleaning to maintain cleanliness through handling, transportation, and storage. Care shall be taken to minimize exposure to corrosive environments, such as chloride compounds.

No visible contaminant (as viewed under both natural and "blacklight") of any form shall be left within the vacuum enclosures when installed (for example: water, dust, sand, hydrocarbon film, etc.).

5.1.3 Welding All welding exposed to vacuum shall be done by the tungsten-arc inert-gas (TIG) process. Welding techniques shall deviate from the ASME Code in accordance with the best ultra high vacuum practice to eliminate any "virtual leaks" in the welds; i.e., all vacuum welds shall be, wherever possible, internal and continuous; all external welds added to these for structural purposes shall be intermittent to eliminate trapped volumes. Defective welds shall be repaired by removal to sound metal and rewelding.

All vacuum weld procedures shall include steps to avoid contamination of the heat affected zone with air, hydrogen, or water. This requires that inert purge gas, such as argon, be used to remove unwanted gases over the vacuum side of heated portions.

5.1.4 Alignment and Dimensions All chambers shall be aligned to within 2mm of the design optical axis in both transverse directions and to within 25mm of the design position in the axial direction. Unless noted otherwise, dimensions of chambers (including interconnecting tubes) refer to nominal internal dimensions.

5.1.5 Mechanical Loads All vacuum components shall be anchored to the floor or to each other in such manner as to restrict all motion to bellows units. The design of the vacuum enclosure shall allow for strains and stresses due to the following:

1. normal cycling of the station HVAC (heating, ventilating, and air conditioning) system (expected to maintain temperature within a range of +/- 2°C);
2. variations in atmospheric pressure;
3. vacuum cycling of other sections of the vacuum enclosure;
4. bakeout of any vacuum section;
5. failure or non-operation of the HVAC.

5.1.6 Design Each vacuum element with a diameter greater than 12 inches shall be designed according to the latest edition of ASME Boiler and Pressure Vessel Code, Section VIII, Division 1 and its subsequent addenda (except as noted in 3.5.5.5), even though vacuum chambers lie outside of the scope of that document. Code certification and stamping are not required. All separable parts shall be fully interchangeable between assemblies. Adequate clearance shall be provided for assembly of mating flanges, and for handles. External access shall be provided to all vacuum seams for leak checking.

All vacuum elements heavier than 50 lbs shall have lift lugs installed and each chamber assembly shall have an electrical ground connection (removable for diagnostic purposes).

Calculations shall be made to determine design features, including the need for and the size of any reinforcements due to openings. Chambers shall be designed to withstand the loadings exerted by all applicable loads in accordance with the provisions of all applicable codes and standards. All chambers shall be designed to be free standing. To determine the probability of earthquakes and seismic coefficients in various areas of the United States, Standard ANSI A58.1 (ASCE Minimum Design Loads for Buildings and Other Structures) shall be applied.

5.1.7 Chambers All optics are housed in three types of chambers. These chambers contain the seismic isolators and alignment mechanisms which support the optical elements. The three chambers are BSC, HAM and TMC.

5.1.7.1 Beam Splitter Chamber (BSC) The Beam Splitter Chamber (BSC) configuration is shown in Figure 8. Note that the Support Beam Assembly(Figure 9) and four 10" Isolation Bellows(Figure 10) are to be provided by others.

5.1.7.2 Horizontal Axis Module (HAM) The Horizontal Axis Module (HAM) configuration is shown in Figure 11. Note that the Support Beam Assembly (Figure 12)and four 7" Isolation Bellows (Figure 13) are to be provided by others.

5.1.7.3 Test Mass Chamber (TMC) The Test Mass Chamber configuration is shown in Figure 14. It includes special features which permit isolation and removal of an interferometer's Test Mass Assemblies with minimal disturbance to the beam paths of other interferometers operating concurrently at the same site. Cited specifications have been developed without consideration of cost. Note that the Support Beam Assembly(Figure 9) and four 10" Isolation Bellows(Figure 10) are to be provided by others.

5.1.7.3.1 Integrated Airlock The airlock enables isolation of the TMC Dome from the lower chamber body (which is integral with the beam tube manifold and *may not* be *vented* while another interferometer is in operation). The Airlock shall provide a 152 cm dia. clear aperture when open. When closed it shall withstand atmospheric pressure (only from above), with maximum leak rate determined as for Gate Valves. It is required to stroke from fully open to sealed, or from sealed to fully open, in five minutes or less. The Dome must have provisions for evacuation, vent and purge, and seal annulus evacuation and vent which are fully independent of those for other volumes. The Airlock shall be interlocked to exclude operation with unacceptable pressure differentials or unretracted equipment.

5.1.8 Flanges Dual O-ring flanges shall be designed for convenient, quick and easy disassembly and assembly, consistent with reliable sealing. The design shall allow replacement of the inner O-ring with a metal seal at some time in the future. O-rings shall be vacuum quality Viton, free of lubricant, and baked to remove contaminants. O-ring grooves shall retain the O-ring during assembly/disassembly. Flange centering pins shall be tapered, rounded, and replaceable; centering pins for flange sets in the vertical plane shall support the weight of the mating cover. Except for the case of chamber to chamber connections, flange centering pins shall be included in the chamber flange of flange sets in the vertical plane, and the lower flange of flange sets in the horizontal plane. Flange neck (wall) thickness shall be the minimum practical (considering vacuum and other loads), to maximize available aperture area.

5.1.9 Access Connectors The 152 cm diameter short tube sections located at each BSC chamber on the diagonal are defined as access connectors, and shall be designed for convenient removal and installation. The minimum axial space required at these locations is 60 cm.

5.1.10 Optical Baffles All connecting tubes shall be designed to allow for installation of optical baffles at a later date. This requirement can be met by allowing access to all internal surfaces.

5.1.11 Annular Spaces All annuluses of each chamber shall be connected to a single flange. Pumping speed between this flange and any point of the pumped annulus is to be greater than 0.3 liters/sec for air, in molecular flow. Multiple annuluses may be connected together to minimize the number of ion pumps and valves. Interconnecting tubing shall be routed close to the chamber wall, with all connections to be welded or CF flanges.

5.1.12 Fasteners Flange fasteners shall be of high quality, appropriate for efficient assembly and disassembly. All fasteners shall be plated or made of alloys which allow use without lubricants. Where possible plate nuts shall be used.

5.1.13 Component Leak Rate The contractor shall ensure that all leaks greater than 1 x 10^{-9} torr•liter/second of helium on each chamber or tube section are repaired at the site of manufacture.

5.1.14 Workmanship, Finish, and Appearance The finished product shall have a workmanlike finish and be free of weld spatter, cutoff spatter, free iron, weld oxidation and injurious defects. There shall be no grinding or abrasion of completed welds or internal vacuum surfaces.

5.1.15 Marking Each separable part (except fasteners, seals, and interchangeable, standard blank flanges) shall be permanently marked with a unique identification number in a location readily viewed.

5.2 Pumping Subsystem Vacuum pumps include portable roughing pumps, annulus pumps, main ion pumps, getter pumps, and LN_2 pumps. The roughing pumps are used to pump the systems down from atmosphere to 10^{-6} torr. The ion pumps, getter pumps, and LN_2 pumps are used for vibration-free pumping during normal operation.

The main pumping phases include:

1. Initial Pumpdown: (from 760 torr to less than 1 torr) main roughing pump sets, noise and vibration expected, minimized, and tolerated for the short periods of time;
2. Intermediate Pumpdown: (from 1 torr to less than 10^{-6} torr) regeneration of LN_2 pumps and getter pumps: turbo molecular pump sets, low noise and vibration, extended time periods;
3. Final Pumpdown: (maintaining vacuum) roughing and turbo pumps are turned off; ion, getter and LN_2 pumps provide continuous operation.

5.2.1 Roughing Pumps The roughing pumps shall consist of two types of portable pump stations, the main roughing pump set and the turbo molecular pump sets. The main roughing pump set shall be used for pumping from atmosphere to less than 1 torr while the turbo molecular pump set shall be used for pumping from 1 torr to less than 10^{-6} torr. The main roughing pump sets are exempt from the vibration and acoustic noise limits. The turbo molecular pump sets, however, shall be designed to operate for extended periods of time without contributing to vibration and noise levels beyond those described in Section 3.2.6.

The design of the roughing pumps shall preclude contaminating the beam tubes and chambers during the life of the equipment, even with equipment failures and operator mistakes.

5.2.1.1 Main Roughing Pump Sets Each main roughing pump set shall consist of a roots blower backed by one or more mechanical pumps. If feasible there shall be no oil in the pumping path. The roots blower shall incorporate a "canned" motor. The pump set shall be self contained so that under power failure or pump failure, interlocks shall prevent the pumped chambers from being vented or exposed to pump oil. Provisions for connection to the control system shall be provided. Provision for sealed connection to a ducted facility exhaust system shall be provided.

There shall be vacuum gauges located at each pump inlet (both the roots pump and the backing pump) and there shall be auxiliary valved (manual) ports to allow connection of a leak detector at any location. All unused connections shall be fitted with blankoff flanges.

5.2.1.2 Turbo Molecular Pump Sets Each turbo molecular pump set shall consist of a "wide range" magnetically levitated turbo molecular pump backed by a dry pump (diaphragm, piston, or scroll pump). The minimum pumping speed at the roughing port shall be 1400 liters/sec for nitrogen at 10^{-3} torr. Throughput at a backing pressure of 10 torr shall be at least 15 torr liters/second. The pump set shall be self contained so that under power failure or pump failure, interlocks shall prevent the pumped chambers from being vented. Provisions for connection to the control system shall be provided.

There shall be vacuum gauges located at each pump inlet (both the turbo pump and the backing pump) and there shall be auxiliary valved (manual) ports to allow connection of a leak detector or auxiliary backing turbo at any location. All unused connections shall be fitted with blankoff flanges.

5.2.2 Main Ion Pumps The LIGO ion pumps shall have nominal pumping speeds of 3000 liter/sec minimum for nitrogen. Each of these pumps may physically consist of multiples of smaller units. Their expected life shall be

80,000 hours or more at an operating pressure of 10^{-6} torr. Noble gas diode pumps shall be used. There shall be a minimum of three and a maximum of six power supply/controllers for each ion pump. The maximum starting pressure shall be 10^{-5} torr. The ion pump controllers shall be mountable in standard 19 inch racks.

5.2.3 LN_2 Pumps There are two types of LN_2 pumps: long and short. The long LN_2 pumps shall have a cold surface 3.7 m long, and the short LN2 pumps shall have a cold surface 1.2 m long. All other features of the LN_2 pumps shall be identical. The LN_2 pumping surface shall be coaxial with the beam tube axis, and provide a clear aperture of $\geq$ 1.05 m, warm or cold. The insulated vacuum space shall be separated from the beam tube vacuum and shall have it's own pumping ports and instrumentation.

Certain parts of the LN_2 pumps may have large thermal gradients which may give rise to local, intermittent release of gas. The design shall preclude the sudden and direct release of this gas into the optical path.

Each LN_2 pump shall be capable of operating at full pumping speed with a minimum of 90 days between LN_2 transfers, even with a thick layer of condensed gas (emissivity = 1). There shall be provisions to minimize the LN_2 consumption, including multilayer insulation, polished surfaces away from the optical paths, and low loss supports.

5.2.4 Getter Pumps Getter pumps of 10000 to 20000 liters/sec pump speed (hydrogen) shall be mounted near the LN_2 pumps (on the beam tube side) to pump the non-condensible active gases. These shall be UHV compatible and isolatable to enable regeneration or replacement.

5.2.5 Annulus Pumps Turbo molecular pump sets shall be provided for roughing of the annulus spaces. The pump set shall be self contained so that under power failure or pump failure, interlocks shall prevent the pumped chambers from being vented. Provisions for connection to the control system shall be provided. These pump sets shall not allow contamination of the annuluses with oil.

Ion pumps shall be provided to maintain the annulus vacuum; they shall hold the maximum annulus pressure to less than 10^{-3} torr. Noble gas diode pumps shall be used. The same pump may be used for several adjacent annuluses provided the required pressures are achieved. The ion pump controllers shall be mountable in standard 19 inch racks.

5.3 Valve Subsystem

5.3.1 Gate Valves All gate valves shall be stainless steel with metal sealed flanges or weld fittings where appropriate, and metal bellows stem feedthroughs. Only non-contaminating and non-migratory lubrication shall be used on the internal mechanisms. Valve body and flange leakage shall be measured to be less than 10^{-10} torr•liter/sec of helium before installation. 48 inch and larger gate valves shall have double viton gate seals. Annular spaces between gate valve seals shall be isolated and independent of other annulus volumes for pumping and venting requirements. Smaller valves shall have a single viton seal. All gate seals shall be leak free to a level of 10^{-9} torr•liter/sec of helium.

Valves of the same size and type shall be identical to minimize the number of required spare parts.

All valves, regardless of operation (electric, pneumatic, or manual), shall be protected from accidental operation. Such protection may be provided by mechanical, electrical, or procedural means. In instances where accidental venting is possible, redundant means shall be employed.

5.3.2 Small Valves Small valves (less than 15cm aperture), such as right angle manual valves exposed to the beam chamber, shall be all metal and bakeable. Valves used on the o-ring annuluses and those which are mounted on the portable pump stations may be viton sealed.

5.4 Vent and Purge Subsystem Components inside each of the chambers shall be protected against particulate contamination at all times: when chambers are open, while venting to air, during opening and closing, and when closed, including pumpdown. This protection shall be equivalent to exposure within a Fed. Std. 209 Class 100 clean room. The vacuum enclosure area of each station will be designed as a Fed. Std. 209 Class 50,000 clean room. Vent and purge systems shall be provided with valved and pressure limited, non-condensing, Class 100 air with a water vapor dew point of less than —20 degrees Celsius. The purge system shall allow for the connection of air shower manifolds in the chambers, used to distribute purge gas over the optical components inside the chambers.

5.5 Bakeout Subsystem Insulation and heating equipment shall be modular so as to allow efficient removal and placement. There need only be enough equipment to bake the largest contiguous vacuum section at one time; however, the equipment shall be capable of baking any of the vacuum sections. Temperature sensors shall be installed at positions representing minimum and maximum temperatures. Bakeout controls shall be sufficient to insure that the performance requirements are met.

Alternate degassing methods such as photo-induced and/or ion-induced desorption may be employed provided they can be shown to be cost effective or cleaner (no insulation needed).

5.6 Monitor and Control Subsystem Vacuum monitoring equipment includes Pirani gauges, ion gauges (cold cathode), leak detectors, RGAs and auxiliary ports. Gauge tubes shall be mounted on 2 3/4 inch metal seal CF flanges at the locations shown in Figures 2 and 3. Ports(4 1/2 inch CF) shall be provided for RGA sensors. The RGA type and model will be selected by Caltech at a future date. There shall be two auxiliary ports (one 2 3/4 and one 4 1/2 inch CF) complete with all metal valves and blankoffs for each chamber.

Vacuum controls includes the control logic, interlocks, and instrumentation required to allow safe and reliable operation of valves, pumps and gauges under all conditions. There shall be sufficient logic to allow control of the entire system (one site) from a central location in the corner station. The control logic will be incorporated into a commercial process control system to be provided by Caltech. The interfaces to this system shall consist of discreet digital and analog signals. Signal types, cabling and connectors are subject to Caltech approval.

Electronics racks and cable trays will be provided by Caltech.

5.6.1 Monitoring Instruments Vacuum instrumentation shall be provided for pressures from atmospheric down to 10^{-10} torr. Each chamber and beam tube section which can be isolated shall have installed one Pirani gauge, and one cold cathode gauge. Controllers shall be provided for all instruments. All vacuum feedthroughs shall be alumina ceramic.

5.6.1.1 Pirani Gauges Pirani gauges shall operate from atmosphere to 10^{-4} torr. The gauge controller shall be mountable in a standard 19 inch rack. The controller shall have a digital display and at least one setable process control contact or setpoint. The gauges shall be installed on CF flanges and be bakeable to 300 degrees Celsius.

5.6.1.2 Cold Cathode Gauges Cold cathode gauges shall operate from 10^{-3} torr to 10^{-10} torr. The gauge controller shall be mountable in a standard

19 inch rack. The controller shall have a digital display and at least one setable process control contact or setpoint. The gauges shall be installed on CF flanges and be bakeable to 300 degrees Celsius.

5.6.2 Control Logic In order to prevent accidental venting all gate valves with pneumatic or electric operators shall have at least 2 independent levels of interlock protection provided. All high voltage (greater than 24 volts in vacuum) devices shall be interlocked to prevent or minimize filament burnout, high current flow, glow discharge, or arcing. The design of the interlocks and control logic shall not preclude incorporation into the process control system (to be provided by Caltech). The vacuum system shall be designed to allow local protection and control as well as centralized control, monitoring and logging.

5.6.3 Helium Leak Detectors The helium leak detectors shall be mobile and have a minimum detectable leak rate of less than 1×10^{-10} torr•liter/sec for helium. The leak detector shall be turbopumped and shall be designed for connection to the backing side of the pump stations. The leak detector shall not permit oil backstreaming to the test port. Calibrated helium leaks shall be provided with each detector.

6. QUALITY ASSURANCE

6.1 Test Plans Detailed plans including descriptions of the test equipment and procedures for the qualification, screening, and acceptance tests shall be approved by Caltech prior to use.

6.2 Control of Contamination Detailed plans to insure control of cleanliness shall be approved by Caltech.

6.3 Component Acceptance Tests

6.3.1 Chamber and Tube Leak Tests The contractor shall measure total helium leakage rates on each vacuum chamber or tube section as part of the fabrication process. No vacuum chamber or fabricated tube section shall be field installed without first demonstrating acceptable leakage.

6.3.2 Pumps Each electrically powered vacuum pump shall be tested (or certified) for speed, ultimate pressure, leakage, noise and vibration, and operation of protective features, before shipment from the manufacturer.

6.3.3 Valve Tests Each vacuum valve shall be tested for leakage prior to shipment from the manufacturer. For dual gate seals, each seal shall be individually tested. As well, each vacuum valve (including each individual gate seal) shall be tested for leakage after installation on the LIGO vacuum system. Operation of each valve shall also be demonstrated.

6.4 System Acceptance Tests

6.4.1 Leakage All vacuum leaks greater than the limit set by the system requirements section shall be measured, repaired and documented.

6.4.2 Pumpdown Pumpdown from atmosphere to ultimate pressure (100 hours pumping) shall be performed on all vacuum sections and documented.

6.4.3 Noise and Vibration Acoustic noise shall be measured and documented at the vacuum chamber walls with all the vacuum equipment operating simultaneously; background levels shall be measured and documented as well. Vibration levels at the floor near the chambers shall be measured and documented, both with and without simultaneous operation of all of the vacuum equipment.

6.4.4 Control and Monitoring Operation of each vacuum gauge shall be demonstrated after installation.

Operation of each vacuum pump and each valve shall be demonstrated after installation.

Operation, temperature uniformity, and temperature stability of the bakeout system shall be demonstrated.

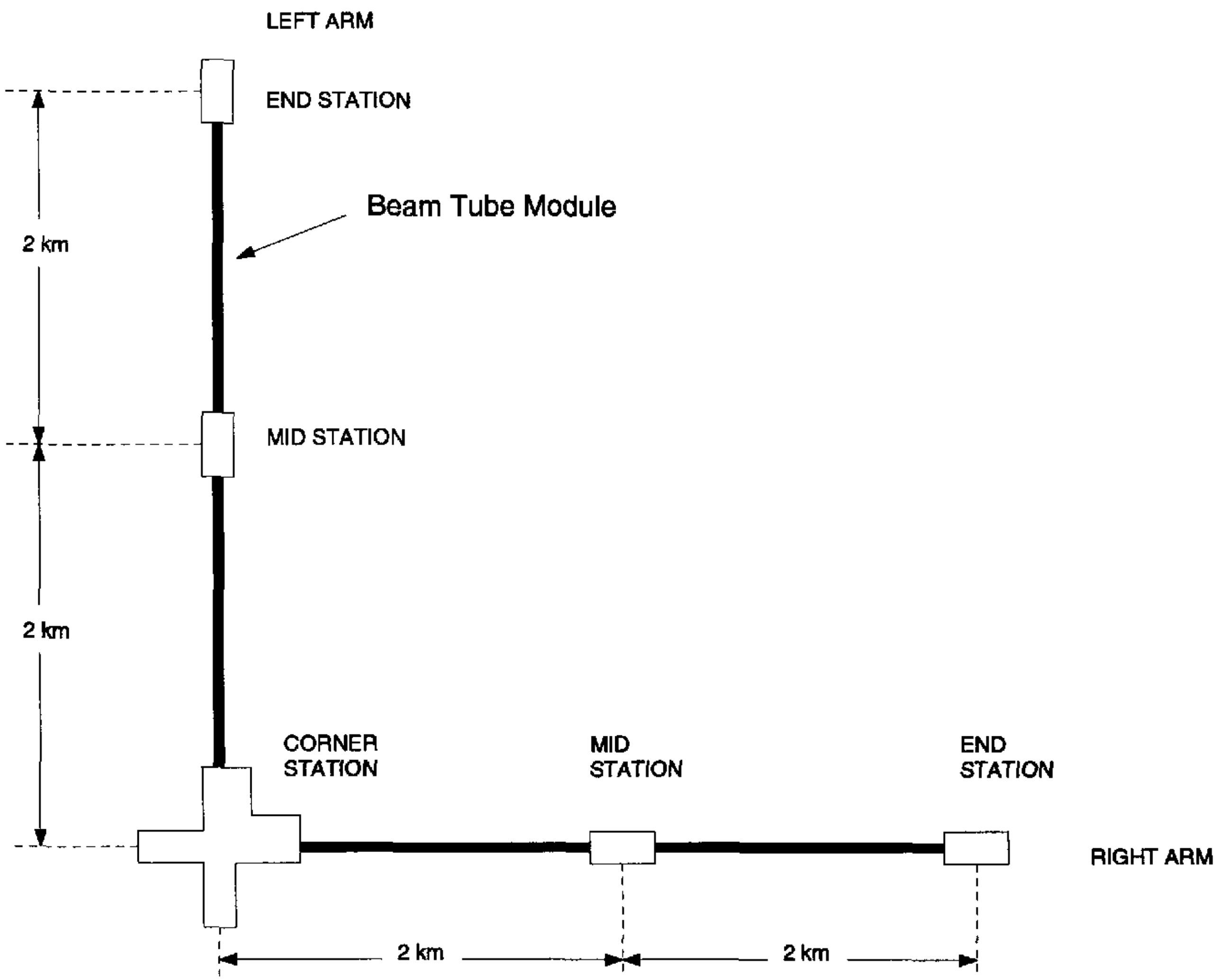


Figure 1. LIGO Geometry

VACUUM EQUIPMENT SPECIFICATION
LIGO FACILITY

LIGO Document 1100003

PREPARED BY: John Worden

APPROVED BY:

EFFECTIVE DATE: July 18, 1994

CALIFORNIA INSTITUTE OF TECHNOLOGY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

LIGO PROJECT

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Contents

LIGO

1. SCOPE

This specification defines the technical requirements for the design, procurement, delivery, qualification, installation, and acceptance testing of the LIGO (Laser Interferometer Gravitational-Wave Observatory) vacuum equipment.

The LIGO includes two installations at widely separated sites, near Hanford, WA and Livingston, LA. Each installation includes laser interferometers in an L shape with 4-km long arms, a vacuum system for the sensitive interferometer components and optical beams, and other support facilities. The vacuum equipment consists of interconnected vacuum vessels, pumping systems, valves and a monitoring and control system for each site. The vacuum equipment will be located in structures called stations, located at the corners, mid points, and ends of the L-shaped pattern. See Figure 1.

The vacuum tube joining the vacuum equipment in the stations is provided under separate contract, and is described by LIGO 1100004, Beam Tubes Specification.

Cleaning, alignment and leak checking are critical processes. Vacuum levels during operation may range from a nominal 10^{-6} torr at the chambers to 10^{-9} torr in the beamtube.

2. APPLICABLE DOCUMENTS

If more than one document applies to a technical requirement, the more stringent standard shall have precedence. Requirements set forth in this specification shall have final precedence.

2.1 Industry Documents

2.1.1 American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code

- Pressure Vessels, Section VIII, Division I
- Welding and Brazing Qualifications, Section IX

2.1.2 American Society of Civil Engineers

- Minimum Design Loads for Buildings and Other Structures, ASCE 7–88

2.1.3 "Standards of Expansion Joint Manufacturer's Association", published by Expansion Joint Manufacturer's Association (EJMA)

2.1.4 National Fire Protection Association (NFPA) Standards

- No. 70—National Electrical Code

2.2 Government Standards

- Building and safety codes: local, state, and federal, including OSHA

2.3 LIGO Documents

2.3.1 LIGO Drawings

- LIGO Drawing 1101100, Vacuum Equipment, Corner Station, Washington Site, Phase A, attached
- LIGO Drawing 1101101, Vacuum Equipment, Corner Station, Louisiana Site, Phase A, attached
- LIGO Drawing 1101102, Vacuum Equipment, End Stations, Phase A, attached
- LIGO Drawing 1101103, Vacuum Equipment, Mid Stations, Washington Site, Phase A, attached
- LIGO Drawing 1101009, Beam Splitter Chamber (BSC)
- LIGO Drawing 1101010, Horizontal Axis Module (HAM)
- LIGO Drawing 1101011, 10" Isolation Bellows
- LIGO Drawing 1101012, 7" Isolation Bellows
- LIGO Drawing 1101013, Test Mass Chamber, Type 1 (TMC-1)
- LIGO Drawing 1101018, Support Beam Assembly, Large Chambers
- LIGO Drawing 1101041, Support Beam Assembly, HAM Chambers

2.3.2 LIGO Specifications

- LIGO 1100004, Beam Tubes Specification

2.4 Interface Control Documents

2.4.1 Provided by the Vacuum Equipment Contractor

- Vendor document XXXX, Vacuum Equipment to Beam Tube Interface
- Vendor document XXXX, Vacuum System to Station Enclosure and Utilities Interface
- Vendor document XXXX, Vacuum vent/purge air system to internal air showers.
- Vendor document XXXX, Vacuum Equipment to Process Control System

3. SYSTEM DESCRIPTION

The LIGO vacuum system is divided into two parts: the beam tube modules and the vacuum equipment. The beam tube modules are two kilometers long and are addressed in a separate contract. The vacuum equipment is housed in buildings located at the intersection (corner) and ends of the beam tube modules. These buildings are the corner station, mid stations, and end stations. The vacuum equipment consists of the following subsystems:

1. Vacuum enclosure subsystem
2. Pumping subsystem
3. Valve subsystem
4. Vent and purge subsystem
5. Bakeout subsystem
6. Monitor and control subsystem

Together these subsystems, along with the beam tube modules, make up the vacuum system. The Washington site schematic is shown in Figure 2 and the Louisiana site schematic is shown in Figure 3. A description of the system according to station is given below.

3.1 Corner Station Washington Site The vacuum enclosure for the corner station of the Washington Site is shown in Figure 4 (a reduced LIGO drawing #1101100). Three types of vacuum chambers enclose the optical components of the laser interferometers: test mass chambers (TMC), beam splitter chambers

(BSC), and horizontal access modules (HAM). One of the BSCs shall be located at the intersection of the two arms in the Washington site corner station. As shown in Figure 4, an array of nine HAMs shall connect with the diagonal chamber, as extensions of the arms. Interconnecting two sets of HAM groups are 76 cm diameter mode cleaner tubes. Along each arm, an additional BSC and TMC shall be located in that order. A section of 183 cm diameter tube shall provide for the addition of TMCs in future expansions. A second BSC (with HAM array) shall be located on a 45 degree diagonal between the arms, and two 122 cm tubes shall connect this to the TMCs, through 122 cm diameter isolation valves. The corner station building will be built with enough room for the future addition of up to four TMC/BSC/HAM groupings. Removal of access covers from the chambers will allow for servicing the optical components during normal operations; the seals on these covers shall be designed as double O-rings for economical reuse during the early period of operation when access is more frequent and permeation is more tolerable; later, the inboard O-ring may be replaced with a metal seal. A clean air vent and purge system shall be provided to break vacuum and maintain cleanliness of the optical components whenever a chamber is open.

The corner station pumping system shall include two LN_2 (liquid nitrogen) pumps near the beam tube interfaces, getter pumps, and main ion pumps as shown in Figure 2. Ion pumps shall also be used to pump the annulus of all double O-ring seals. Rough pumping from atmosphere shall be done with portable pump stations.

3.2 Corner Station Louisiana Site The vacuum equipment for the corner station at the Louisiana site is similar to that at the Washington site, except that initially there shall be no TMCs, and only one of the BSC/HAM groupings shall be installed. See Figure 5 (a reduced LIGO drawing #1101101) for details.

3.3 End Stations Both Sites The vacuum equipment for the end stations is shown in Figure 6 (a reduced LIGO drawing #1101102). Vacuum enclosures shall include one BSC initially.

The pumping system shall include one LN_2 pump with isolation valves, getter pumps, and ion pumps for both the enclosure and the annulus. Rough pumping from atmosphere shall be done with portable pump stations.

3.4 Mid Station Washington Site The vacuum equipment for the mid stations is shown in Figure 7 (a reduced LIGO drawing #1101103). Vacuum enclosures shall include one TMC initially.

The pumping system shall include two LN_2 pumps with isolation valves, getter pumps and ion pumps for both the enclosure and the annulus. Rough pumping from atmosphere shall be done with portable pump stations.

3.5 Midpoint Pumping Station Louisiana Site No chambers are to be housed here. A 122 cm diameter gate valve allows isolation of the adjoining beam tube modules. A valved and instrumented roughing port and an independent, separately valved getter pump set shall be located on each side of this gate valve. Refer to Figure 3.

Is this merely use of Caltech procedures (those in use at Caltech) or is it really a parochial reference?

4. SYSTEM REQUIREMENTS

4.1 Leak Rate All leaks greater than 1×10^{-8} torr•liters/sec of helium shall be repaired according to Caltech approved procedures.

Is this a "Caltech procurement" document.

4.2 Pump Down Time Each vacuum section (an isolatable volume), without interferometer components, shall pump down from atmosphere to 1×10^{-6} torr in less than 24 hours. In the case of the vertex and diagonal vacuum sections, two pump stations may be connected at once to accomplish this. Otherwise, only a single pump station shall be connected at one time.

4.3 Ultimate Pressures Each vacuum section (empty) shall attain 5×10^{-9} torr after 100 hours of pumping with the ion pumps and open to the LN_2 pumps. The prior conditioning permitted is a 48 hour bakeout followed by a vent and purge for 24 hours.

4.4 System Control and Protection Each vacuum section shall have sufficient instrumentation and hardware to allow safe and reliable operation of valves, pumps and gauges under all conditions. Control logic shall be specified to allow incorporation into a commercial process control system to be supplied by Caltech at a later date.

4.5 Bakeout/Degassing Capability A means shall be provided to heat all vacuum surfaces to any desired temperature, ranging from ambient to 150°C. All ion pumps and gauges shall be bakeable to 300°C. Ramping of temperatures shall be controlled to minimize the stresses on vacuum connections. There shall be no particulate generation or shedding caused by placement or removal of the insulation.

Alternate means using photo-induced and/or ion-induced desorption may be utilized if cost effective degassing is obtained.

4.6 Special Environmental Requirements The LIGO vacuum equipment and laser areas house instrumentation which is potentially highly sensitive to vibration and acoustic noise, shock-induced damage or misalignment, electromagnetic interference, and contamination. The following requirements on installed equipment have been developed without detailed consideration of cost impact. They are subject to future revision.

4.6.1 Shock Valve actuation or other intermittent device operation shall induce no more than 0.01 g peak-to-peak acceleration at any point within 1 meter of any chamber.

4.6.2 Acoustic Noise Acoustic noise from all simultaneously operating equipment (including turbopumps and their backing pumps, gauge and pump controllers and supplies, but EXEMPTING main mechanical roughing pumps on intermittent duty) shall not exceed PNC-40 (Preferred Noise Criterion 40) at any location within LIGO vacuum equipment and laser areas. Limited narrowband exemptions may be permitted subject to Caltech approval.

4.6.3 Vibration Vibration ~~from all~~ simultaneously operating equipment (EXEMPTING main mechanical roughing pumps on intermittent duty) shall not cause the vibration measured at any point within 1 meter of any chamber to exceed the LIGO Site Vibration Baseline (Figure {FIG. TO BE SUPPLIED BY LISA FAIRLY SOON}) ~~by more~~ than 6 dB (a factor of two in amplitude) at any frequency between 0.1 Hz and 10 kHz. Limited narrowband ~~exemptions may be~~ permitted subject to Caltech approval. 10%

4.6.4 Electromagnetic Emissions All electrical equipment shall conform to {IEC? ISO? IEEE?} standard # {?????} limiting electromagnetic radiation, emission and powerline contamination. {VOLKER WILL BE PROVIDING SOME ACTUAL STANDARDS TO ADHERE TO FOR EMI; I WILL BUG HIM ABOUT IT SHORTLY}

4.6.5 Particulates and other contaminants No installed equipment shall emit or harbor particulates at a level inconsistent with maintenance of a clean environment conforming to Federal Standard 209D Class 50,000.

4.7 Interfaces The following interfaces shall be provided for and documented accordingly:

1. Vacuum equipment to beam tube.**
2. Vacuum system to station enclosure and utilities.
3. Vacuum vent/purge air system to internal air showers.
4. Vacuum equipment to process control system.

** For the purposes of this proposal the interface shall be taken as the "Tube Termination Interface" on Figure 4.

4.8 Design Life The contractor shall design the vacuum equipment for a minimum serviceable life of 20 years.

4.9 Environmental Under normal operations, the vacuum equipment will be operated in a temperature and humidity controlled environment. In case of power or control failure, and during the construction phase, conditions will be dictated by diurnal and seasonal ranges. Exposure to these conditions shall not damage the vacuum equipment.

5. SUBSYSTEMS

5.1 Vacuum Enclosure Subsystem The vacuum enclosure includes all components such as chambers, tubes, flanges, elbows, tees, blank-offs, and other fittings, which form the barrier between atmosphere and vacuum. These components are required to be compatible with use at 1 x 10^{-9} torr. Specific requirements are below.

5.1.1 Materials All fabricated components exposed to vacuum shall be made from type 304L or 316L stainless steel, using low carbon weld filler wire, where required. Standard catalogue items of 304 or 316 stainless steel are acceptable if not available in 304L or 316L. ~~Copper~~ and aluminum may be used for seals. All other materials are subject to Caltech approval. Copies of mill test reports of chamber, tube and flange materials ~~shall be~~ furnished.

Internal surface finish is subject to Caltech approval.

5.1.2 Cleaning All surfaces exposed to vacuum shall be cleaned in accordance with procedures approved by Caltech prior to fabrication and installation; surface recontamination shall be prevented during all subsequent processes.

All items shall be wrapped or sealed after cleaning to maintain cleanliness through handling, transportation, and storage. Care shall be taken to minimize exposure to corrosive environments, such as chloride compounds.

No visible contaminant (as viewed under both natural and "blacklight") of any form shall be left within the vacuum enclosures when installed (for example: water, dust, sand, hydrocarbon film, etc.).

5.1.3 Welding All welding exposed to vacuum shall be done by the tungsten-arc inert-gas (TIG) process. Welding techniques shall deviate from the ASME Code in accordance with the best ultra high vacuum practice to eliminate any "virtual leaks" in the welds; i.e., all vacuum welds shall be, wherever possible, internal and continuous; all external welds added to these for structural purposes shall be intermittent to eliminate trapped volumes. Defective welds shall be repaired by removal to sound metal and rewelding.

All vacuum weld procedures shall include steps to avoid contamination of the heat affected zone with air, hydrogen, or water. This requires that inert purge gas, such as argon, be used to remove unwanted gases over the vacuum side of heated portions.

5.1.4 Alignment and Dimensions All chambers shall be aligned to within 2mm of the design optical axis in both transverse directions and to within 25mm of the design position in the axial direction. Unless noted otherwise, dimensions of chambers (including interconnecting tubes) refer to nominal internal dimensions.

5.1.5 Mechanical Loads All vacuum components shall be anchored to the floor or to each other in such manner as to restrict all motion to bellows units. The design of the vacuum enclosure shall allow for strains and stresses due to the following:

1. normal cycling of the station HVAC (heating, ventilating, and air conditioning) system (expected to maintain temperature within a range of +/- 2°C);
2. variations in atmospheric pressure;
3. vacuum cycling of other sections of the vacuum enclosure;
4. bakeout of any vacuum section;
5. failure or non-operation of the HVAC.

5.1.6 Design Each vacuum element with a diameter greater than 12 inches shall be designed according to the latest edition of ASME Boiler and Pressure Vessel Code, Section VIII, Division 1 and its subsequent addenda (except as noted in 3.5.5.5), even though vacuum chambers lie outside of the scope of that document. Code certification and stamping are not required. All separable parts shall be fully interchangeable between assemblies. Adequate clearance shall be provided for assembly of mating flanges, and for handles. External access shall be provided to all vacuum seams for leak checking.

All vacuum elements heavier than 50 lbs shall have lift lugs installed and each chamber assembly shall have an electrical ground connection (removable for diagnostic purposes).

Calculations shall be made to determine design features, including the need for and the size of any reinforcements due to openings. Chambers shall be designed to withstand the loadings exerted by all applicable loads in accordance with the provisions of all applicable codes and standards. All chambers shall be designed to be free standing. To determine the probability of earthquakes and seismic coefficients in various areas of the United States, Standard ANSI A58.1 (ASCE Minimum Design Loads for Buildings and Other Structures) shall be applied.

5.1.7 Chambers All optics are housed in three types of chambers. These chambers contain the seismic isolators and alignment mechanisms which support the optical elements. The three chambers are BSC, HAM and TMC.

5.1.7.1 Beam Splitter Chamber (BSC) The Beam Splitter Chamber (BSC) configuration is shown in Figure 8. Note that the Support Beam Assembly(Figure 9) and four 10" Isolation Bellows(Figure 10) are to be provided by others.

5.1.7.2 Horizontal Axis Module (HAM) The Horizontal Axis Module (HAM) configuration is shown in Figure 11. Note that the Support Beam Assembly (Figure 12)and four 7" Isolation Bellows (Figure 13) are to be provided by others.

5.1.7.3 Test Mass Chamber (TMC) The Test Mass Chamber configuration is shown in Figure 14. It includes special features which permit isolation and removal of an interferometer's Test Mass Assemblies with minimal disturbance to the beam paths of other interferometers operating concurrently at the same site. Cited specifications have been developed without consideration of cost. Note that the Support Beam Assembly(Figure 9) and four 10" Isolation Bellows(Figure 10) are to be provided by others.

5.1.7.3.1 Integrated Airlock The airlock enables isolation of the TMC Dome from the lower chamber body (which is integral with the beam tube manifold and may not be vented while another interferometer is in operation). The Airlock shall provide a 152 cm dia. clear aperture when open. When closed it shall withstand atmospheric pressure (only from above), with maximum leak rate determined as for Gate Valves. It is required to stroke from fully open to sealed, or from sealed to fully open, in five minutes or less. The Dome must have provisions for evacuation, vent and purge, and seal annulus evacuation and vent which are fully independent of those for other volumes. The Airlock shall be interlocked to exclude operation with unacceptable pressure differentials or unretracted equipment.

5.1.8 Flanges Dual O-ring flanges shall be designed for convenient, quick and easy disassembly and assembly, consistent with reliable sealing. The design shall allow replacement of the inner O-ring with a metal seal at some time in the future. O-rings shall be vacuum quality Viton, free of lubricant, and baked to remove contaminants. O-ring grooves shall retain the O-ring during assembly/disassembly. Flange centering pins shall be tapered, rounded, and replaceable; centering pins for flange sets in the vertical plane shall support the weight of the mating cover. Except for the case of chamber to chamber connections, flange centering pins shall be included in the chamber flange of flange sets in the vertical plane, and the lower flange of flange sets in the horizontal plane. Flange neck (wall) thickness shall be the minimum practical (considering vacuum and other loads), to maximize available aperture area.

5.1.9 Access Connectors The 152 cm diameter short tube sections located at each BSC chamber on the diagonal are defined as access connectors, and shall be designed for convenient removal and installation. The minimum axial space required at these locations is 60 cm.

5.1.10 Optical Baffles All connecting tubes shall be designed to allow for installation of optical baffles at a later date. This requirement can be met by allowing access to all internal surfaces.

5.1.11 Annular Spaces All annuluses of each chamber shall be connected to a single flange. Pumping speed between this flange and any point of the pumped annulus is to be greater than 0.3 liters/sec for air, in molecular flow. Multiple annuluses may be connected together to minimize the number of ion pumps and valves. Interconnecting tubing shall be routed close to the chamber wall, with all connections to be welded or CF flanges.

5.1.12 Fasteners Flange fasteners shall be of high quality, appropriate for efficient assembly and disassembly. All fasteners shall be plated or made of alloys which allow use without lubricants. Where possible plate nuts shall be used.

5.1.13 Component Leak Rate The contractor shall ensure that all leaks greater than 1 x 10^{-9} torr•liter/second of helium on each chamber or tube section are repaired at the site of manufacture.

5.1.14 Workmanship, Finish, and Appearance The finished product shall have a workmanlike finish and be free of weld spatter, cutoff spatter, free iron, weld oxidation and injurious defects. There shall be no grinding or abrasion of completed welds or internal vacuum surfaces.

5.1.15 Marking Each separable part (except fasteners, seals, and interchangeable, standard blank flanges) shall be permanently marked with a unique identification number in a location readily viewed.

5.2 Pumping Subsystem Vacuum pumps include portable roughing pumps, annulus pumps, main ion pumps, getter pumps, and LN_2 pumps. The roughing pumps are used to pump the systems down from atmosphere to 10^{-6} torr. The ion pumps, getter pumps, and LN_2 pumps are used for vibration-free pumping during normal operation.

The main pumping phases include:

1. Initial Pumpdown: (from 760 torr to less than 1 torr) main roughing pump sets, noise and vibration expected, minimized, and tolerated for the short periods of time;
2. Intermediate Pumpdown: (from 1 torr to less than 10^{-6} torr) regeneration of LN_2 pumps and getter pumps: turbo molecular pump sets, low noise and vibration, extended time periods;
3. Final Pumpdown: (maintaining vacuum) roughing and turbo pumps are turned off; ion, getter and LN_2 pumps provide continuous operation.

5.2.1 Roughing Pumps The roughing pumps shall consist of two types of portable pump stations, the main roughing pump set and the turbo molecular pump sets. The main roughing pump set shall be used for pumping from atmosphere to less than 1 torr while the turbo molecular pump set shall be used for pumping from 1 torr to less than 10^{-6} torr. The main roughing pump sets are exempt from the vibration and acoustic noise limits. The turbo molecular pump sets, however, shall be designed to operate for extended periods of time without contributing to vibration and noise levels beyond those described in Section 3.2.6.

The design of the roughing pumps shall preclude contaminating the beam tubes and chambers during the life of the equipment, even with equipment failures and operator mistakes.

5.2.1.1 Main Roughing Pump Sets Each main roughing pump set shall consist of a roots blower backed by one or more mechanical pumps. If feasible there shall be no oil in the pumping path. The roots blower shall incorporate a "canned" motor. The pump set shall be self contained so that under power failure or pump failure, interlocks shall prevent the pumped chambers from being vented or exposed to pump oil. Provisions for connection to the control system shall be provided. Provision for sealed connection to a ducted facility exhaust system shall be provided.

There shall be vacuum gauges located at each pump inlet (both the roots pump and the backing pump) and there shall be auxiliary valved (manual) ports to allow connection of a leak detector at any location. All unused connections shall be fitted with blankoff flanges.

5.2.1.2 Turbo Molecular Pump Sets Each turbo molecular pump set shall consist of a "wide range" magnetically levitated turbo molecular pump backed by a dry pump (diaphragm, piston, or scroll pump). The minimum pumping speed at the roughing port shall be 1400 liters/sec for nitrogen at 10^{-3} torr. Throughput at a backing pressure of 10 torr shall be at least 15 torr liters/second. The pump set shall be self contained so that under power failure or pump failure, interlocks shall prevent the pumped chambers from being vented. Provisions for connection to the control system shall be provided.

There shall be vacuum gauges located at each pump inlet (both the turbo pump and the backing pump) and there shall be auxiliary valved (manual) ports to allow connection of a leak detector or auxiliary backing turbo at any location. All unused connections shall be fitted with blankoff flanges.

5.2.2 Main Ion Pumps The LIGO ion pumps shall have nominal pumping speeds of 3000 liter/sec minimum for nitrogen. Each of these pumps may physically consist of multiples of smaller units. Their expected life shall be

80,000 hours or more at an operating pressure of 10^{-6} torr. Noble gas diode pumps shall be used. There shall be a minimum of three and a maximum of six power supply/controllers for each ion pump. The maximum starting pressure shall be 10^{-5} torr. The ion pump controllers shall be mountable in standard 19 inch racks.

5.2.3 LN_2 Pumps There are two types of LN_2 pumps: long and short. The long LN_2 pumps shall have a cold surface 3.7 m long, and the short LN2 pumps shall have a cold surface 1.2 m long. All other features of the LN_2 pumps shall be identical. The LN_2 pumping surface shall be coaxial with the beam tube axis, and provide a clear aperture of $\geq$ 1.05 m, warm or cold. The insulated vacuum space shall be separated from the beam tube vacuum and shall have it's own pumping ports and instrumentation.

Certain parts of the LN_2 pumps may have large thermal gradients which may give rise to local, intermittent release of gas. The design shall preclude the sudden and direct release of this gas into the optical path.

Each LN_2 pump shall be capable of operating at full pumping speed with a minimum of 90 days between LN_2 transfers, even with a thick layer of condensed gas (emissivity = 1). There shall be provisions to minimize the LN_2 consumption, including multilayer insulation, polished surfaces away from the optical paths, and low loss supports.

5.2.4 Getter Pumps Getter pumps of 10000 to 20000 liters/sec pump speed (hydrogen) shall be mounted near the LN_2 pumps (on the beam tube side) to pump the non-condensible active gases. These shall be UHV compatible and isolatable to enable regeneration or replacement.

5.2.5 Annulus Pumps Turbo molecular pump sets shall be provided for roughing of the annulus spaces. The pump set shall be self contained so that under power failure or pump failure, interlocks shall prevent the pumped chambers from being vented. Provisions for connection to the control system shall be provided. These pump sets shall not allow contamination of the annuluses with oil.

Ion pumps shall be provided to maintain the annulus vacuum; they shall hold the maximum annulus pressure to less than 10^{-3} torr. Noble gas diode pumps shall be used. The same pump may be used for several adjacent annuluses provided the required pressures are achieved. The ion pump controllers shall be mountable in standard 19 inch racks.

5.3 Valve Subsystem

5.3.1 Gate Valves All gate valves shall be stainless steel with metal sealed flanges or weld fittings where appropriate, and metal bellows stem feedthroughs. Only non-contaminating and non-migratory lubrication shall be used on the internal mechanisms. Valve body and flange leakage shall be measured to be less than 10^{-10} torr•liter/sec of helium before installation. 48 inch and larger gate valves shall have double viton gate seals. Annular spaces between gate valve seals shall be isolated and independent of other annulus volumes for pumping and venting requirements. Smaller valves shall have a single viton seal. All gate seals shall be leak free to a level of 10^{-9} torr•liter/sec of helium.

Valves of the same size and type shall be identical to minimize the number of required spare parts.

All valves, regardless of operation (electric, pneumatic, or manual), shall be protected from accidental operation. Such protection may be provided by mechanical, electrical, or procedural means. In instances where accidental venting is possible, redundant means shall be employed.

5.3.2 Small Valves Small valves (less than 15cm aperture), such as right angle manual valves exposed to the beam chamber, shall be all metal and bakeable. Valves used on the o-ring annuluses and those which are mounted on the portable pump stations may be viton sealed.

5.4 Vent and Purge Subsystem Components inside each of the chambers shall be protected against particulate contamination at all times: when chambers are open, while venting to air, during opening and closing, and when closed, including pumpdown. This protection shall be equivalent to exposure within a Fed. Std. 209 Class 100 clean room. The vacuum enclosure area of each station will be designed as a Fed. Std. 209 Class 50,000 clean room. Vent and purge systems shall be provided with valved and pressure limited, non-condensing, Class 100 air with a water vapor dew point of less than —20 degrees Celsius. The purge system shall allow for the connection of air shower manifolds in the chambers, used to distribute purge gas over the optical components inside the chambers.

5.5 Bakeout Subsystem Insulation and heating equipment shall be modular so as to allow efficient removal and placement. There need only be enough equipment to bake the largest contiguous vacuum section at one time; however, the equipment shall be capable of baking any of the vacuum sections. Temperature sensors shall be installed at positions representing minimum and maximum temperatures. Bakeout controls shall be sufficient to insure that the performance requirements are met.

Alternate degassing methods such as photo-induced and/or ion-induced desorption may be employed provided they can be shown to be cost effective or cleaner (no insulation needed).

5.6 Monitor and Control Subsystem Vacuum monitoring equipment includes Pirani gauges, ion gauges (cold cathode), leak detectors, RGAs and auxiliary ports. Gauge tubes shall be mounted on 2 3/4 inch metal seal CF flanges at the locations shown in Figures 2 and 3. Ports(4 1/2 inch CF) shall be provided for RGA sensors. The RGA type and model will be selected by Caltech at a future date. There shall be two auxiliary ports (one 2 3/4 and one 4 1/2 inch CF) complete with all metal valves and blankoffs for each chamber.

Vacuum controls includes the control logic, interlocks, and instrumentation required to allow safe and reliable operation of valves, pumps and gauges under all conditions. There shall be sufficient logic to allow control of the entire system (one site) from a central location in the corner station. The control logic will be incorporated into a commercial process control system to be provided by Caltech. The interfaces to this system shall consist of discreet digital and analog signals. Signal types, cabling and connectors are subject to Caltech approval.

Electronics racks and cable trays will be provided by Caltech.

5.6.1 Monitoring Instruments Vacuum instrumentation shall be provided for pressures from atmospheric down to 10^{-10} torr. Each chamber and beam tube section which can be isolated shall have installed one Pirani gauge, and one cold cathode gauge. Controllers shall be provided for all instruments. All vacuum feedthroughs shall be alumina ceramic.

5.6.1.1 Pirani Gauges Pirani gauges shall operate from atmosphere to 10^{-4} torr. The gauge controller shall be mountable in a standard 19 inch rack. The controller shall have a digital display and at least one setable process control contact or setpoint. The gauges shall be installed on CF flanges and be bakeable to 300 degrees Celsius.

5.6.1.2 Cold Cathode Gauges Cold cathode gauges shall operate from 10^{-3} torr to 10^{-10} torr. The gauge controller shall be mountable in a standard

19 inch rack. The controller shall have a digital display and at least one setable process control contact or setpoint. The gauges shall be installed on CF flanges and be bakeable to 300 degrees Celsius.

5.6.2 Control Logic In order to prevent accidental venting all gate valves with pneumatic or electric operators shall have at least 2 independent levels of interlock protection provided. All high voltage (greater than 24 volts in vacuum) devices shall be interlocked to prevent or minimize filament burnout, high current flow, glow discharge, or arcing. The design of the interlocks and control logic shall not preclude incorporation into the process control system (to be provided by Caltech). The vacuum system shall be designed to allow local protection and control as well as centralized control, monitoring and logging.

5.6.3 Helium Leak Detectors The helium leak detectors shall be mobile and have a minimum detectable leak rate of less than 1×10^{-10} torr•liter/sec for helium. The leak detector shall be turbopumped and shall be designed for connection to the backing side of the pump stations. The leak detector shall not permit oil backstreaming to the test port. Calibrated helium leaks shall be provided with each detector.

6. QUALITY ASSURANCE

6.1 Test Plans Detailed plans including descriptions of the test equipment and procedures for the qualification, screening, and acceptance tests shall be approved by Caltech prior to use.

6.2 Control of Contamination Detailed plans to insure control of cleanliness shall be approved by Caltech.

6.3 Component Acceptance Tests

6.3.1 Chamber and Tube Leak Tests The contractor shall measure total helium leakage rates on each vacuum chamber or tube section as part of the fabrication process. No vacuum chamber or fabricated tube section shall be field installed without first demonstrating acceptable leakage.

6.3.2 Pumps Each electrically powered vacuum pump shall be tested (or certified) for speed, ultimate pressure, leakage, noise and vibration, and operation of protective features, before shipment from the manufacturer.

6.3.3 Valve Tests Each vacuum valve shall be tested for leakage prior to shipment from the manufacturer. For dual gate seals, each seal shall be individually tested. As well, each vacuum valve (including each individual gate seal) shall be tested for leakage after installation on the LIGO vacuum system. Operation of each valve shall also be demonstrated.

6.4 System Acceptance Tests

6.4.1 Leakage All vacuum leaks greater than the limit set by the system requirements section shall be measured, repaired and documented.

6.4.2 Pumpdown Pumpdown from atmosphere to ultimate pressure (100 hours pumping) shall be performed on all vacuum sections and documented.

6.4.3 Noise and Vibration Acoustic noise shall be measured and documented at the vacuum chamber walls with all the vacuum equipment operating simultaneously; background levels shall be measured and documented as well. Vibration levels at the floor near the chambers shall be measured and documented, both with and without simultaneous operation of all of the vacuum equipment.

6.4.4 Control and Monitoring Operation of each vacuum gauge shall be demonstrated after installation.

Operation of each vacuum pump and each valve shall be demonstrated after installation.

Operation, temperature uniformity, and temperature stability of the bakeout system shall be demonstrated.

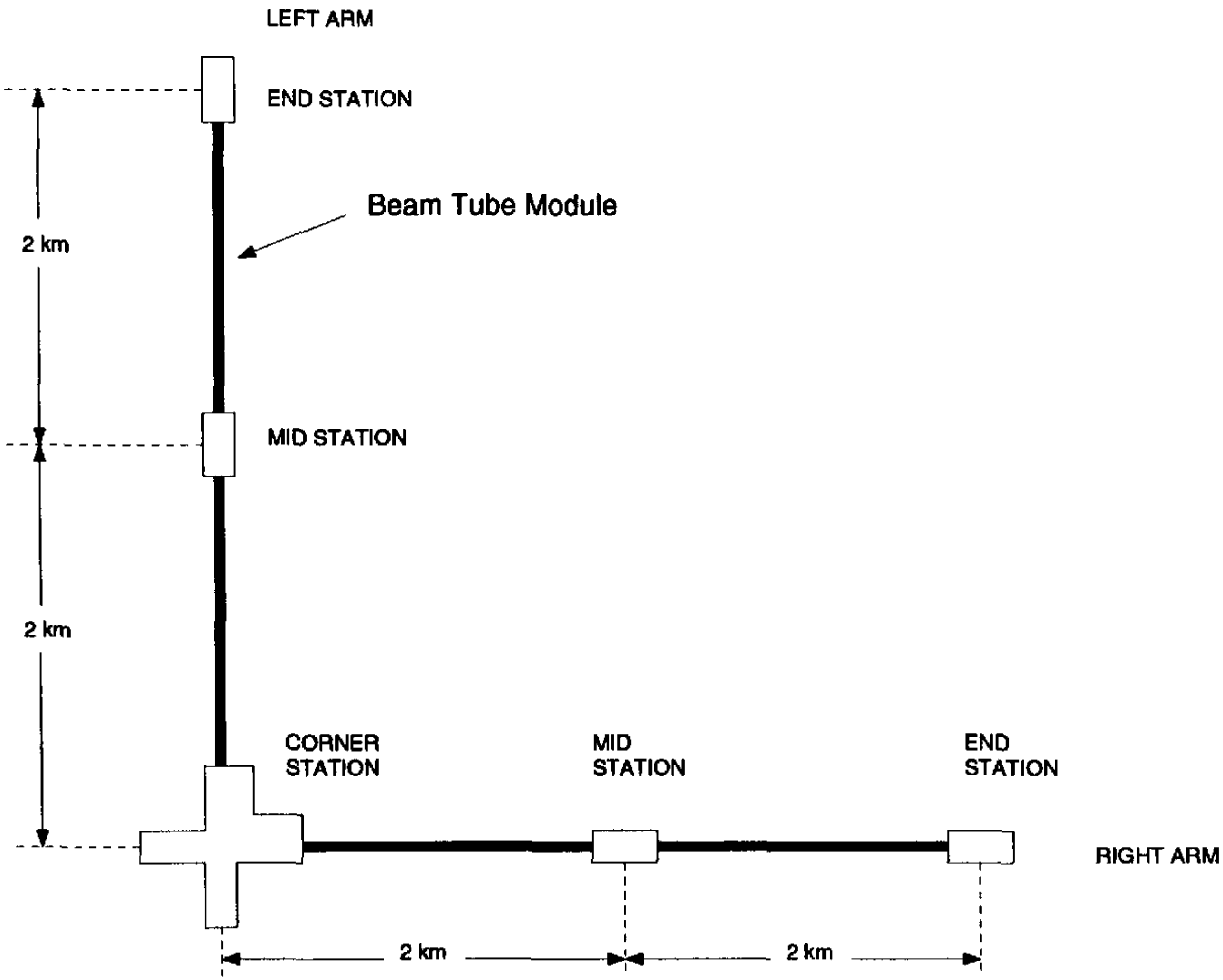
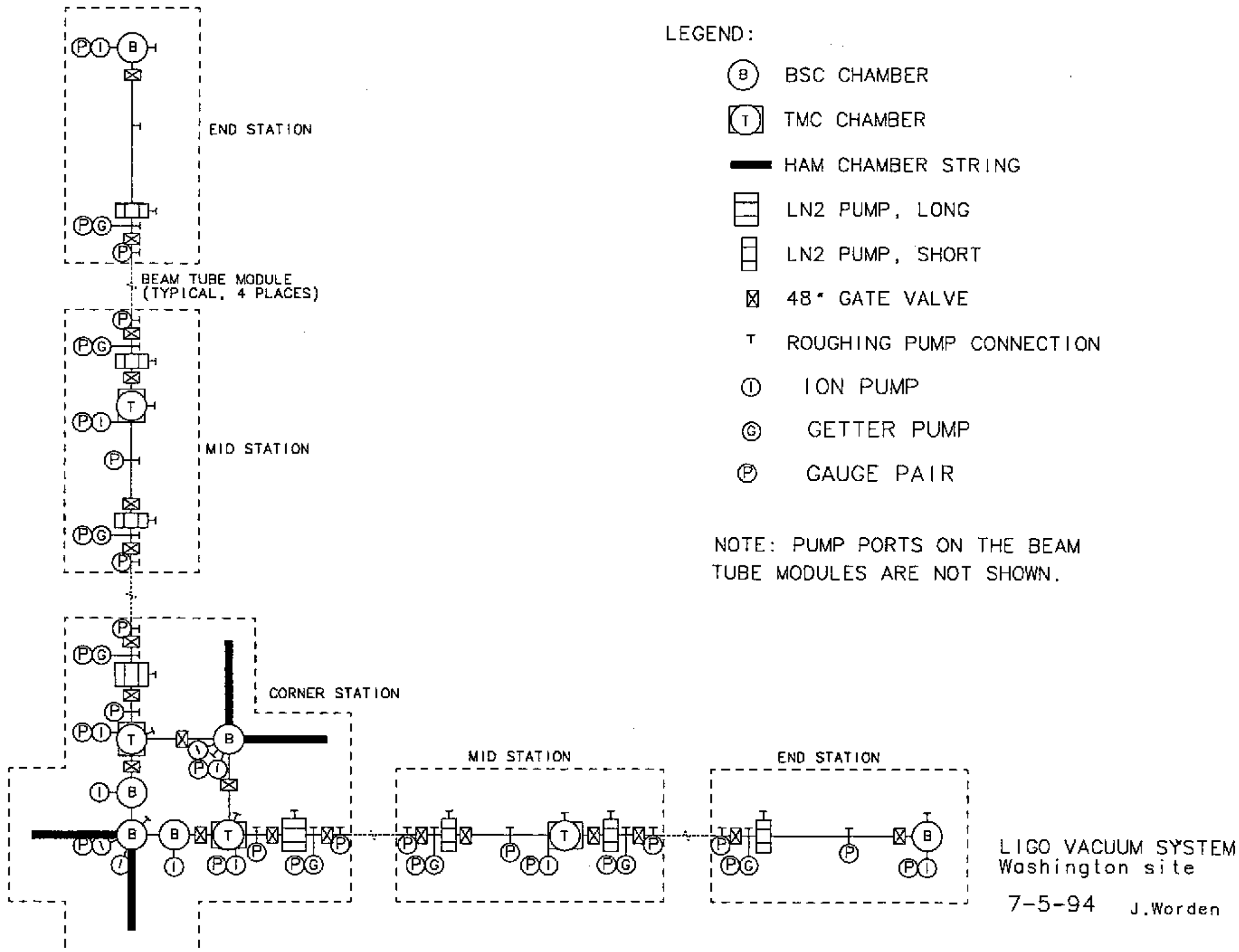
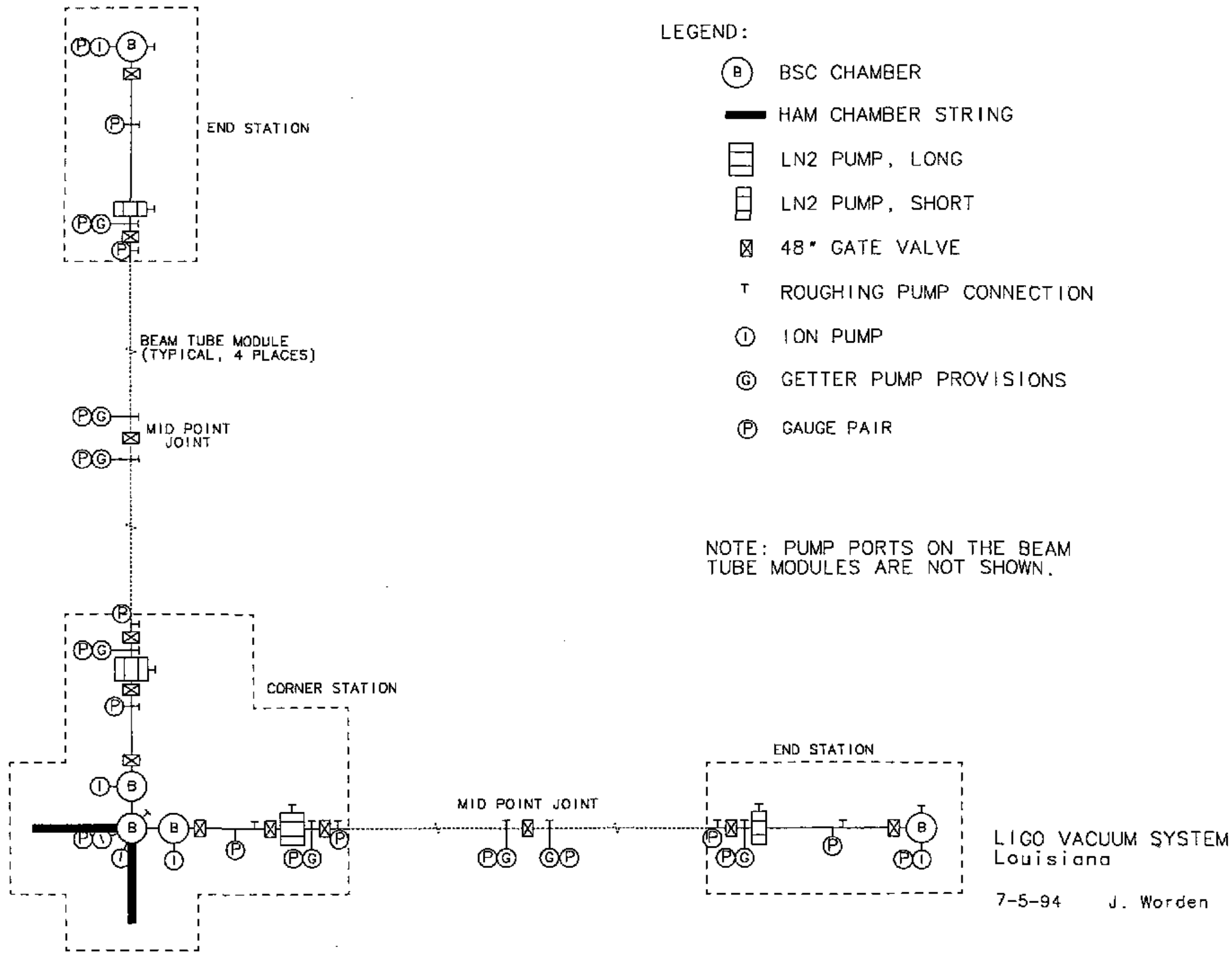


Figure 1. LIGO Geometry



END STATION
BEAM TUBE MODULE
(TYPICAL, 4 PLACES)
MID STATION
CORNER STATION
MID STATION
END STATION
LEGEND:
BSC CHAMBER
TMC CHAMBER
HAM CHAMBER STRING
LN2 PUMP, LONG
LN2 PUMP, SHORT
48" GATE VALVE
ROUGHING PUMP CONNECTION
ION PUMP
GETTER PUMP
GAUGE PAIR
NOTE: PUMP PORTS ON THE BEAM
TUBE MODULES ARE NOT SHOWN.
LIGO VACUUM SYSTEM
Washington site
7-5-94 J.Worden

Figure 2.



END STATION
BEAM TUBE MODULE
(TYPICAL, 4 PLACES)
MID POINT
JOINT
CORNER STATION
MID POINT JOINT
END STATION
LEGEND:
BSC CHAMBER
HAM CHAMBER STRING
LN2 PUMP, LONG
LN2 PUMP, SHORT
48" GATE VALVE
ROUGHING PUMP CONNECTION
ION PUMP
GETTER PUMP PROVISIONS
GAUGE PAIR
NOTE: PUMP PORTS ON THE BEAM
TUBE MODULES ARE NOT SHOWN.
LIGO VACUUM SYSTEM
Louisiana
7-5-94 J. Worden

Figure 3.

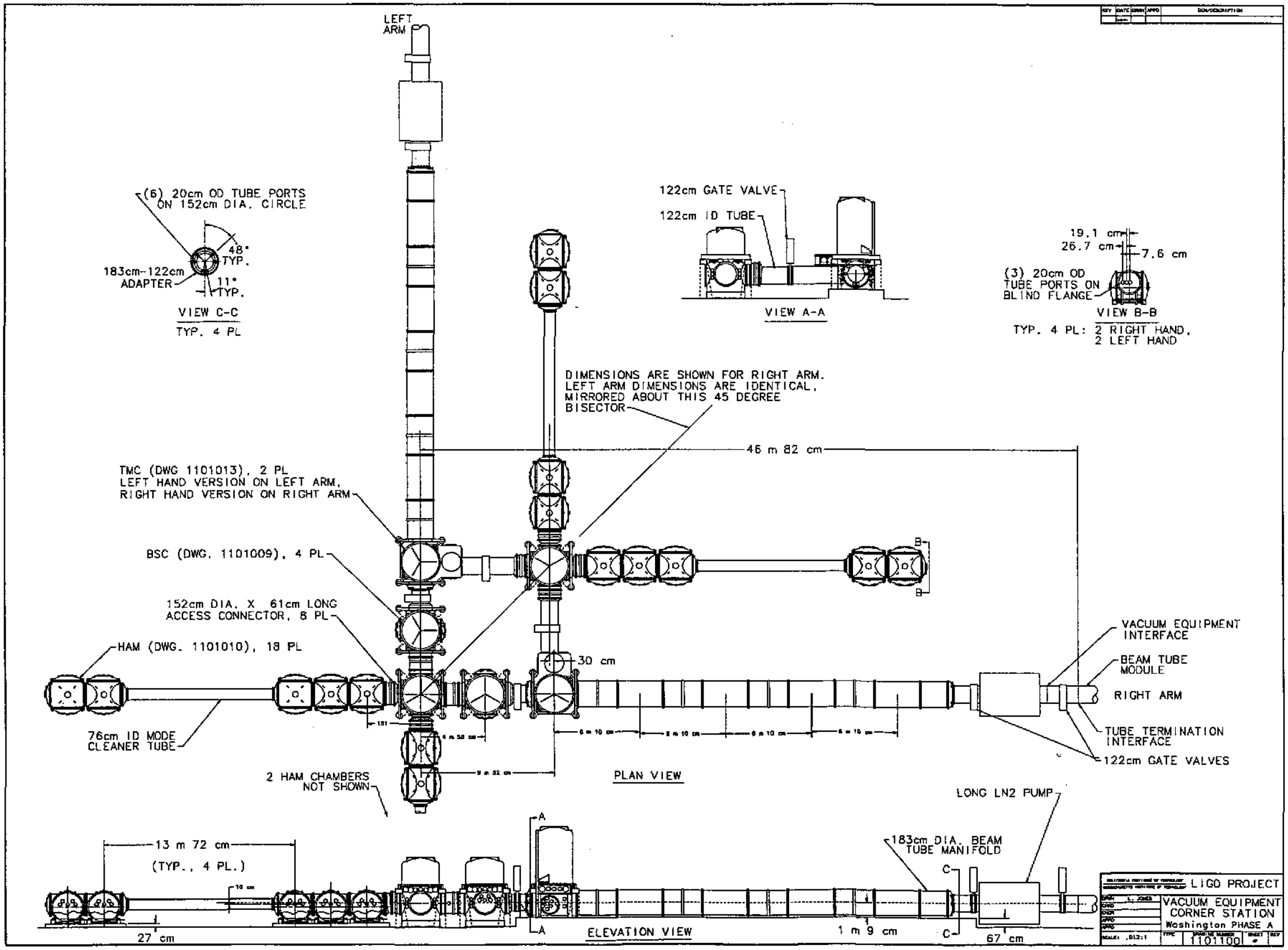

LEFT ARM
(6) 20cm OD TUBE PORTS ON 152cm DIA. CIRCLE
48° TYP.
183cm-122cm ADAPTER
11° TYP.
VIEW C-C
TYP. 4 PL
122cm GATE VALVE
122cm ID TUBE
VIEW A-A
19.1 cm
26.7 cm
7.6 cm
(3) 20cm OD TUBE PORTS ON BLIND FLANGE
VIEW B-B
TYP. 4 PL: 2 RIGHT HAND, 2 LEFT HAND
DIMENSIONS ARE SHOWN FOR RIGHT ARM. LEFT ARM DIMENSIONS ARE IDENTICAL, MIRRORED ABOUT THIS 45 DEGREE BISECTOR
46 m 82 cm
TMC (DWG 1101013), 2 PL LEFT HAND VERSION ON LEFT ARM, RIGHT HAND VERSION ON RIGHT ARM
BSC (DWG. 1101009), 4 PL
152cm DIA. X 61cm LONG ACCESS CONNECTOR, 8 PL
HAM (DWG. 1101010), 18 PL
30 cm
VACUUM EQUIPMENT INTERFACE
BEAM TUBE MODULE
RIGHT ARM
TUBE TERMINATION INTERFACE
122cm GATE VALVES
76cm ID MODE CLEANER TUBE
2 HAM CHAMBERS NOT SHOWN
PLAN VIEW
LONG LN2 PUMP
13 m 72 cm
(TYP., 4 PL.)
183cm DIA. BEAM TUBE MANIFOLD
27 cm
ELEVATION VIEW
1 m 9 cm
67 cm
LIGO PROJECT
VACUUM EQUIPMENT CORNER STATION
Washington PHASE A
1101100

Figure 4.

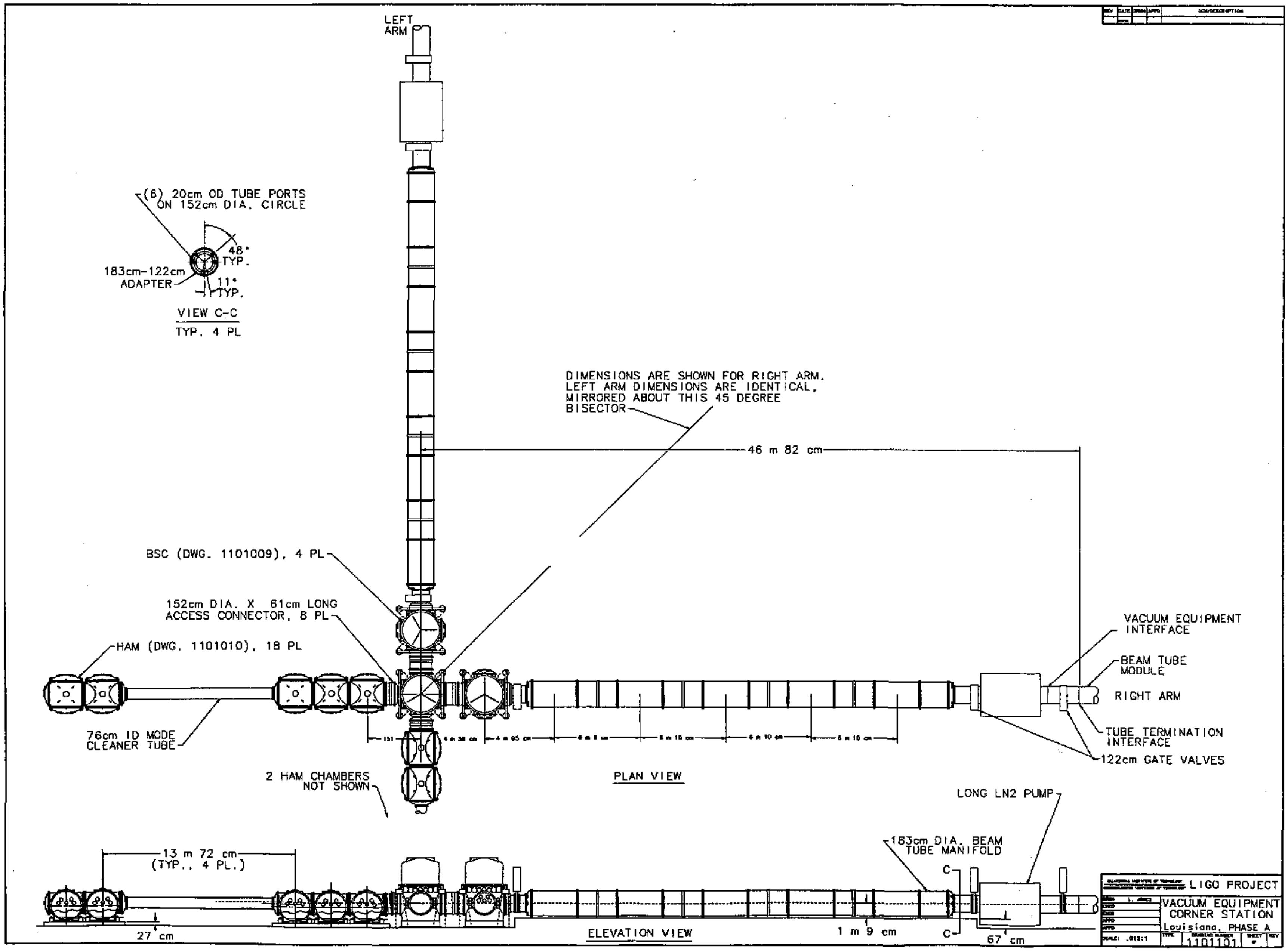
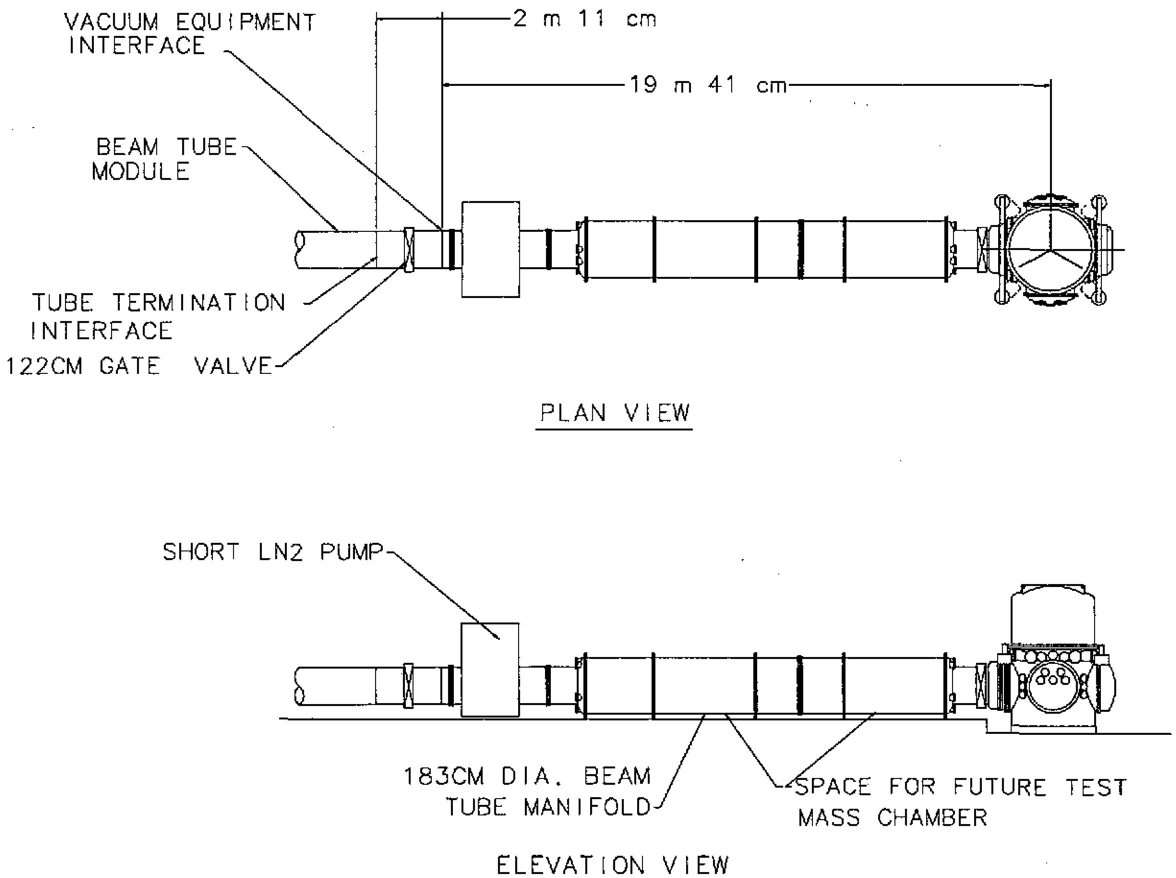

LEFT ARM
(6) 20cm OD TUBE PORTS ON 152cm DIA. CIRCLE
48° TYP.
183cm-122cm ADAPTER
11° TYP.
VIEW C-C
TYP. 4 PL
DIMENSIONS ARE SHOWN FOR RIGHT ARM. LEFT ARM DIMENSIONS ARE IDENTICAL, MIRRORED ABOUT THIS 45 DEGREE BISECTOR
46 m 82 cm
BSC (DWG. 1101009), 4 PL
152cm DIA. X 61cm LONG ACCESS CONNECTOR, 8 PL
HAM (DWG. 1101010), 18 PL
VACUUM EQUIPMENT INTERFACE
BEAM TUBE MODULE
RIGHT ARM
76cm ID MODE CLEANER TUBE
151
4 m 95 cm
TUBE TERMINATION INTERFACE
122cm GATE VALVES
2 HAM CHAMBERS NOT SHOWN
PLAN VIEW
LONG LN2 PUMP
13 m 72 cm (TYP., 4 PL.)
183cm DIA. BEAM TUBE MANIFOLD
C
27 cm
ELEVATION VIEW
1 m 9 cm
67 cm
LIGO PROJECT
VACUUM EQUIPMENT CORNER STATION
Louisiana, PHASE A
1101101

Figure 5.



END STATION
BOTH SITES

LIGO PROJECT
VACUUM EQUIPMENT END STATIONS
1101102

Figure 6.

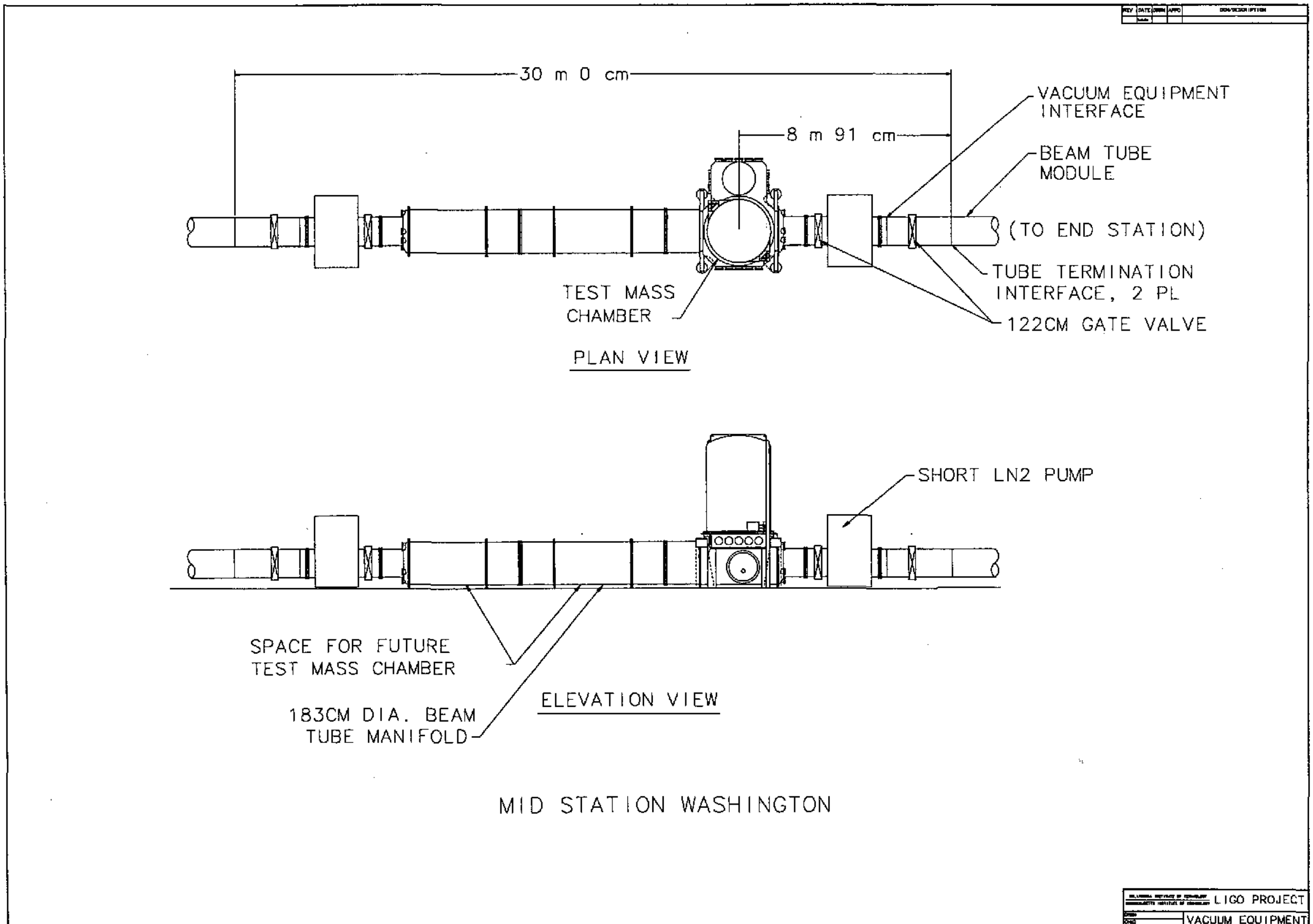
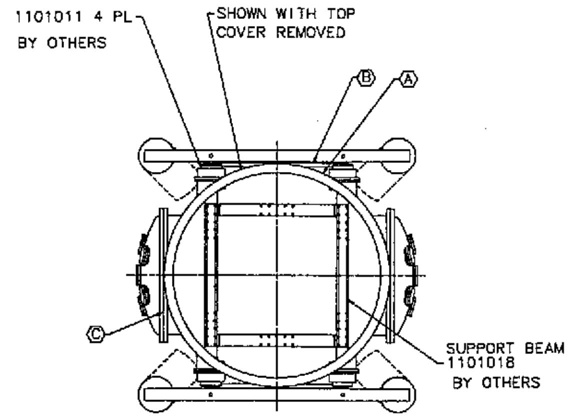

30 m 0 cm
8 m 91 cm
VACUUM EQUIPMENT INTERFACE
BEAM TUBE MODULE
(TO END STATION)
TUBE TERMINATION INTERFACE, 2 PL
122CM GATE VALVE
TEST MASS CHAMBER
PLAN VIEW
SHORT LN2 PUMP
SPACE FOR FUTURE TEST MASS CHAMBER
183CM DIA. BEAM TUBE MANIFOLD
ELEVATION VIEW
MID STATION WASHINGTON
LIGO PROJECT
VACUUM EQUIPMENT MID STATION Washington
1101103

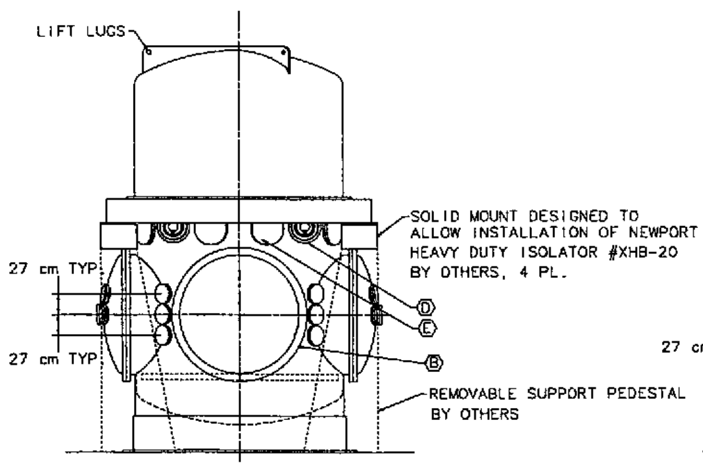
Figure 7.



NOTES:
1. HEADS ARE ASME F&D.
2. INCLUDE CENTERING PINS ON NOZZLE FLANGES WHERE APPROPRIATE.
3. VIEWPORT (ITEM G) MEASUREMENTS REFER TO INTERSECTION OF VIEWPORT AXIS WITH OUTER SURFACE OF VACUUM WALL.
4. TOLERANCES, UNLESS OTHERWISE SPECIFIED: LINEAR, ±0.25 CM
ANGULAR, ± 1 DEGREE
5. NOZZLE SCHEDULE PER TABLE BELOW:

ITEM	SIZE	QUANTITY	FLANGE TYPE	PURPOSE
A	264cm ID TUBE	1	O/O-O/METAL*	MAJOR ACCESS
B	152cm ID TUBE	2	O/O-O/METAL*	LASER BEAM, ACCESS (MINIMIZE NECK LENGTH)
C	152cm ID TUBE	2	O/O-O/METAL*, WITH BLIND FLANGE	ACCESS (MINIMIZE NECK LENGTH)
D	35cm OD TUBE	4	CONFLAT**	SUPPORT BEAMS
E	35cm OD TUBE***	8	CONFLAT**, WITH BLIND FLANGE	AIR SHWR, BACK-TO-AIR PURGE ROUGHING & ION PUMPS, UTILITY
F	25cm OD TUBE***	6	CONFLAT**, WITH BLIND FLANGE	ELECTRICAL FEEDTHROUGHS
G	20cm OD TUBE***	22	CONFLAT**, WITH BLIND FLANGE	OBSERVATION, BEAM PICK-OFFS
H	3.8cm OD TUBE	1	CONFLAT**, WITH BLIND FLANGE	ANNULUS PUMPOUT (NOT SHOWN)

*DUAL O-RING DESIGN, WITH CAPABILITY OF REPLACING INBOARD O-RING WITH METAL SEAL. THESE FLANGES EACH INCLUDE AN ANNULAR CHANNEL BETWEEN O-RINGS, MANIFOLDED TO A SINGLE PUMPOUT PORT ON EACH CHAMBER, WITH CONFLAT** SEAL.
**REGISTERED TRADEMARK, VARIAN VACUUM PRODUCTS; COMPATIBLE ALTERNATES ARE ACCEPTABLE.
***THESE FLANGES ARE TANGENT TO LOCAL VACUUM WALL, WITH MINIMUM NECK LENGTH.



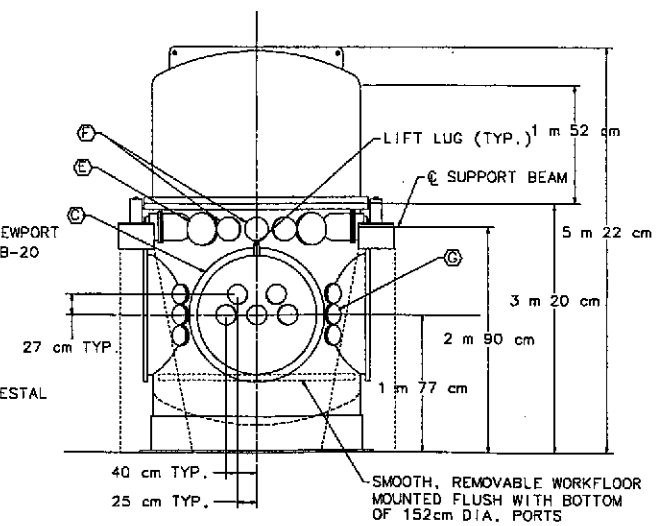


Figure 8.

LIGO PROJECT
J. WORLE
BEAM SPLITTER CHAMBER (BSC)
1101009

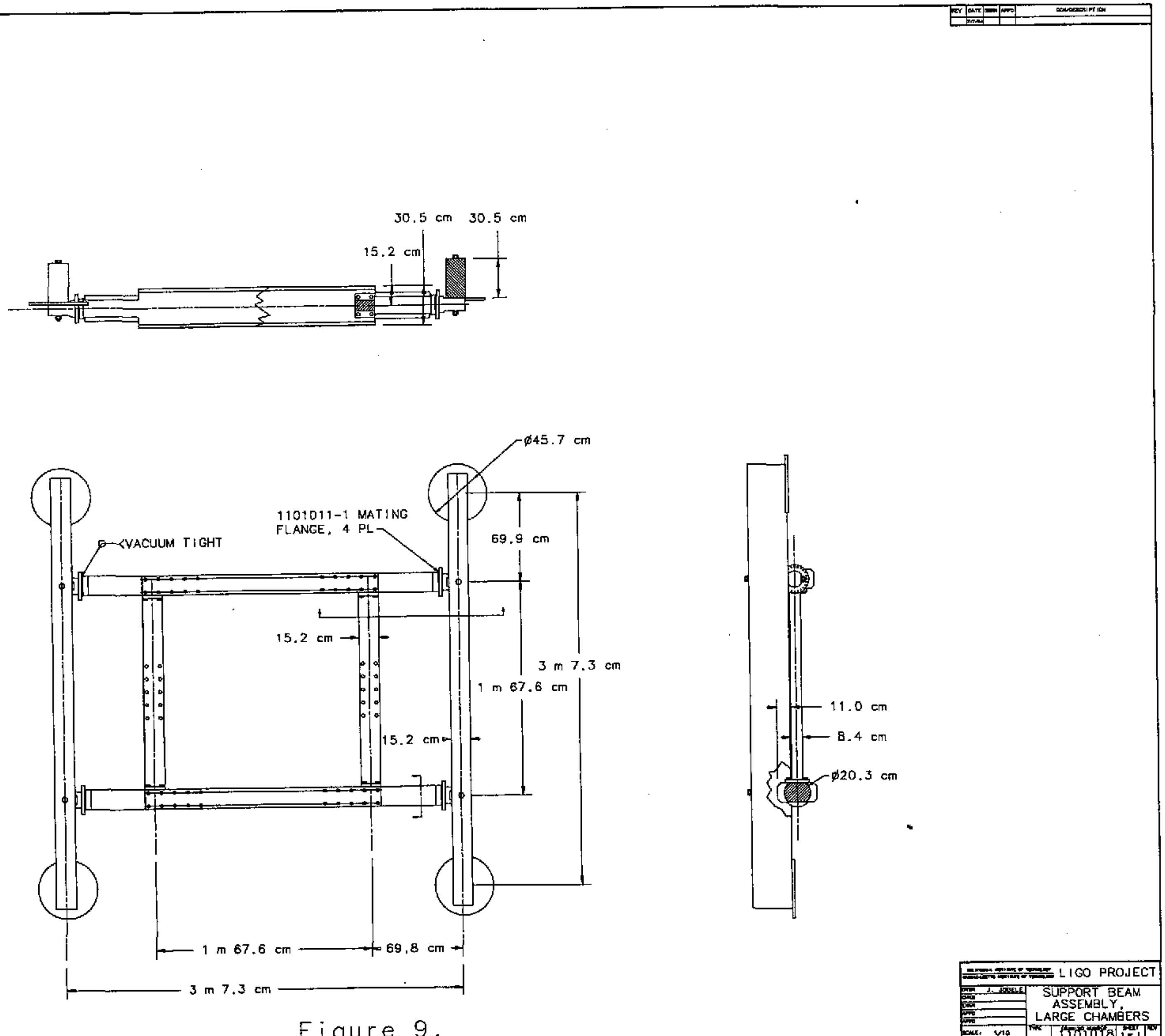

30.5 cm
30.5 cm
15.2 cm
ø45.7 cm
1101011-1 MATING
FLANGE, 4 PL
VACUUM TIGHT
69.9 cm
15.2 cm
3 m 7.3 cm
1 m 67.6 cm
15.2 cm
11.0 cm
8.4 cm
ø20.3 cm
1 m 67.6 cm
69.8 cm
3 m 7.3 cm
LIGO PROJECT
SUPPORT BEAM
ASSEMBLY,
LARGE CHAMBERS
1101018

Figure 9.

NOTES:

1. BELLOWS SPRING RATE: AXIAL <500 LB/IN.
2. RATED PRESSURE DIFFERENTIAL (EXTERNAL) ≥ 40 PSI AT 300 DEGREES F
3. DESIGN LIFE OF BELLOWS, AT ±0.59" AXIAL STROKE, ±0.84" LATERAL STROKE, AND ±11 MINUTES ROTATIONAL STROKE: 2000 CYCLES
4. ALL LINEAR DIMENSIONS ARE IN INCHES
5. TOLERANCES, UNLESS OTHERWISE SPECIFIED: LINEAR, ±0.1 INCH
   ANGULAR, ±1 DEGREE

*REGISTERED TRADEMARK, VARIAN ASSOCIATES, INC.

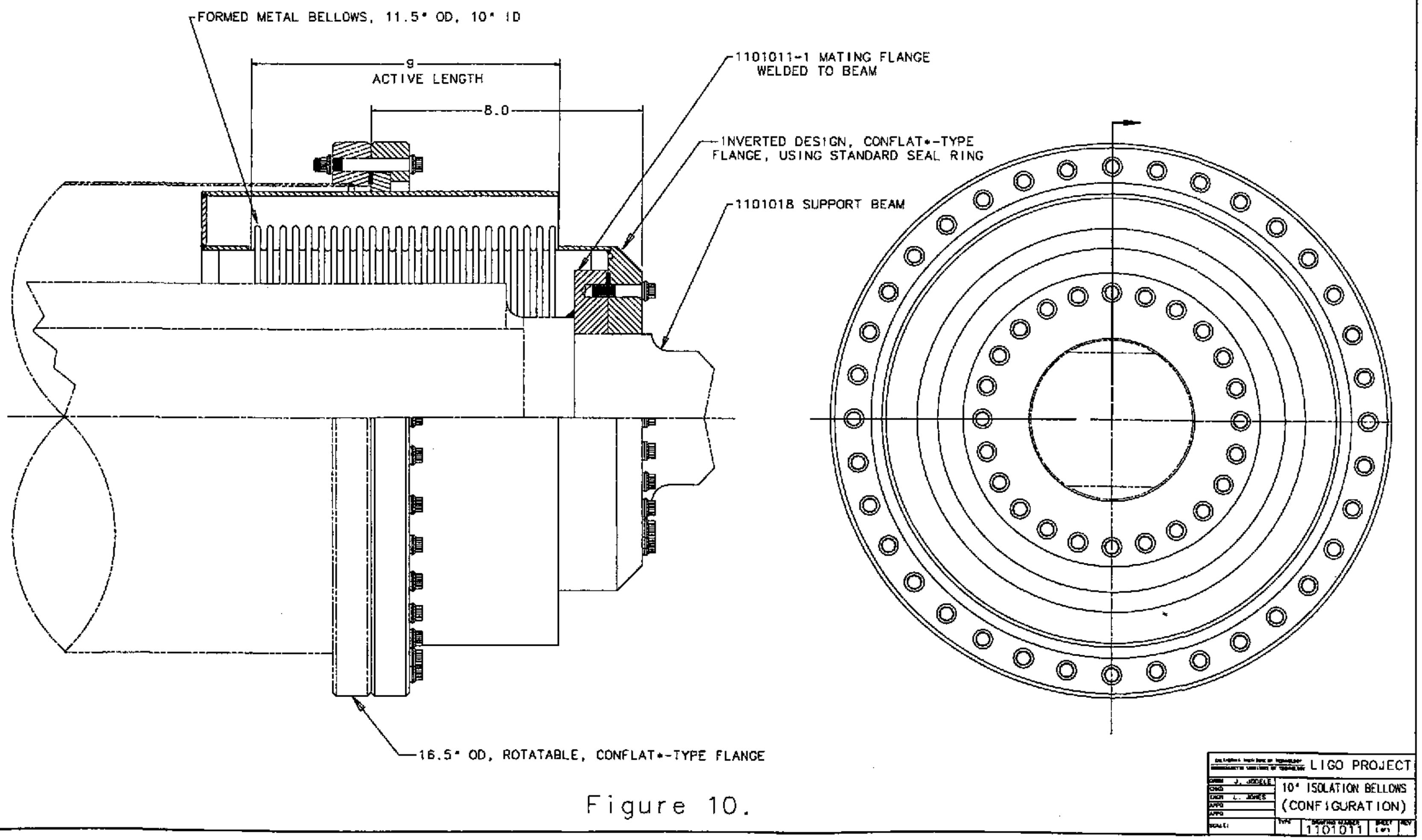


Figure 10.

NOTES:
1. HEADS ARE ASME F&D.
3. INCLUDE CENTERING PINS ON NOZZLE FLANGES WHERE APPROPRIATE.
3. VIEWPORT (ITEM Ⓕ) MEASUREMENTS REFER TO INTERSECTION OF VIEWPORT AXIS WITH OUTER SURFACE OF VACUUM WALL.

4. TOLERANCES, UNLESS OTHERWISE SPECIFIED: LINEAR, ±0.25 CM
ANGULAR, ± 1 DEGREE

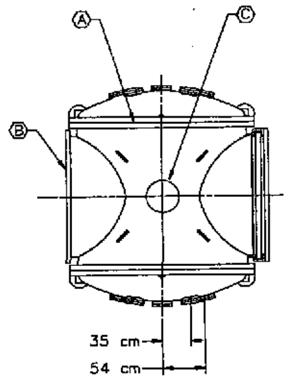
5. NOZZLE SCHEDULE PER TABLE BELOW:

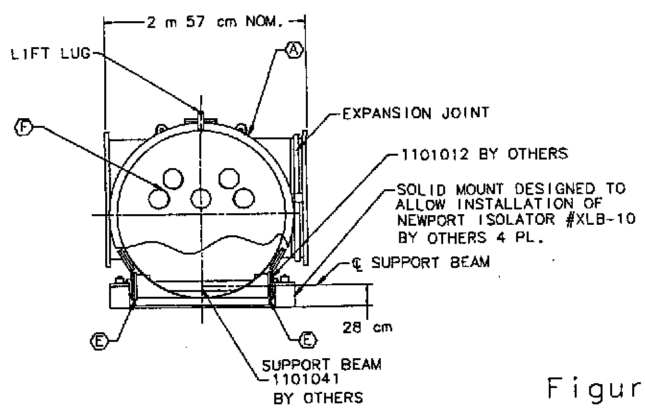
ITEM	SIZE	QUANTITY	FLANGE TYPE	PURPOSE
Ⓐ	213cm ID TUBE	2	O/O-O/METAL*	MAJOR ACCESS
Ⓑ	152cm ID TUBE	2	O/O-O/METAL*	LASER BEAM
Ⓒ	35cm TUBE	1	CONFLAT**, WITH BLIND FLANGE	ION PUMP/AIR SHOWERS, BACK-TO-AIR PURGE
Ⓓ	25cm OD TUBE	8	CONFLAT**, WITH BLIND FLANGE	ELECTRICAL FEEDTHROUGHS, UTILITY
Ⓔ	30cm OD TUBE	4	CONFLAT**	SUPPORT BEAMS
Ⓕ	20cm OD TUBE***	10	CONFLAT**, WITH BLIND FLANGE	OBSERVATION, PICKOFFS
Ⓖ	3.8cm TUBE	1	CONFLAT**, WITH BLIND FLANGE	ANNULUS PUMPOUT (NOT SHOWN)

* DUAL O-RING DESIGN, WITH CAPABILITY OF REPLACING INBOARD O-RING WITH METAL SEAL. THESE FLANGES EACH INCLUDE AN ANNULAR CHANNEL BETWEEN O-RINGS, MANIFOLDED TO A SINGLE PUMPOUT PORT ON EACH CHAMBER, WITH CONFLAT** SEAL.

** REGISTERED TRADEMARK, VARIAN VACUUM PRODUCTS; COMPATIBLE ALTERNATIVES ARE ACCEPTIBLE

*** THESE FLANGES ARE TANGENT TO LOCAL VACUUM WALL, WITH MINIMUM NECK LENGTH





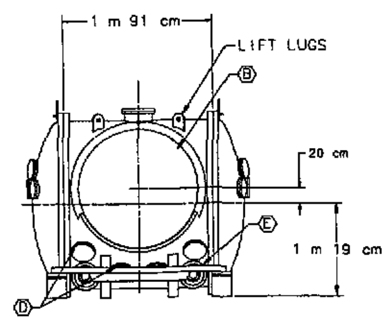


Figure 11.

LIGO PROJECT

HORIZONTAL AXIS MODULE (HAM)

1101010

NOTES:
1. BELLOWS SPRING RATE: AXIAL <120LB/IN
2. RATED PRESSURE DIFFERENTIAL (EXTERNAL) ≥ 40 PSI AT 300 DEGREES F
3. DESIGN LIFE OF BELLOWS, AT ± 0.59" AXIAL STROKE, ± 0.84" LATERAL STROKE, AND AT ± 17 MINUTES ROTATIONAL STROKE: 2000 CYCLES
4. ALL LINEAR DIMENSIONS ARE IN INCHES
5. TOLERANCES, UNLESS OTHERWISE SPECIFIED: LINEAR, ± 0.1 INCH
   ANGULAR, ± 1 DEGREE

*REGISTERED TRADEMARK, VARIAN ASSOCIATES, INC.

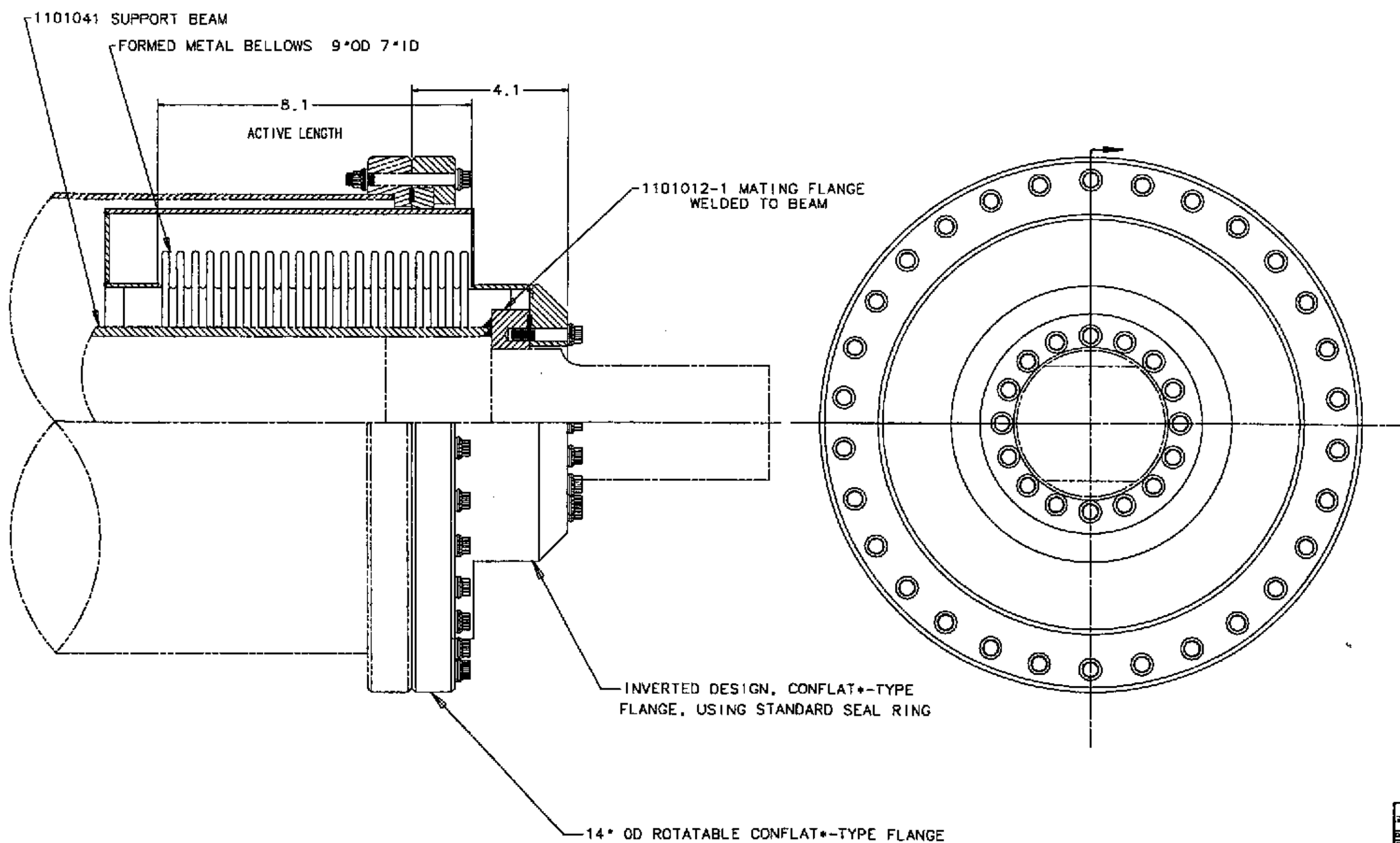
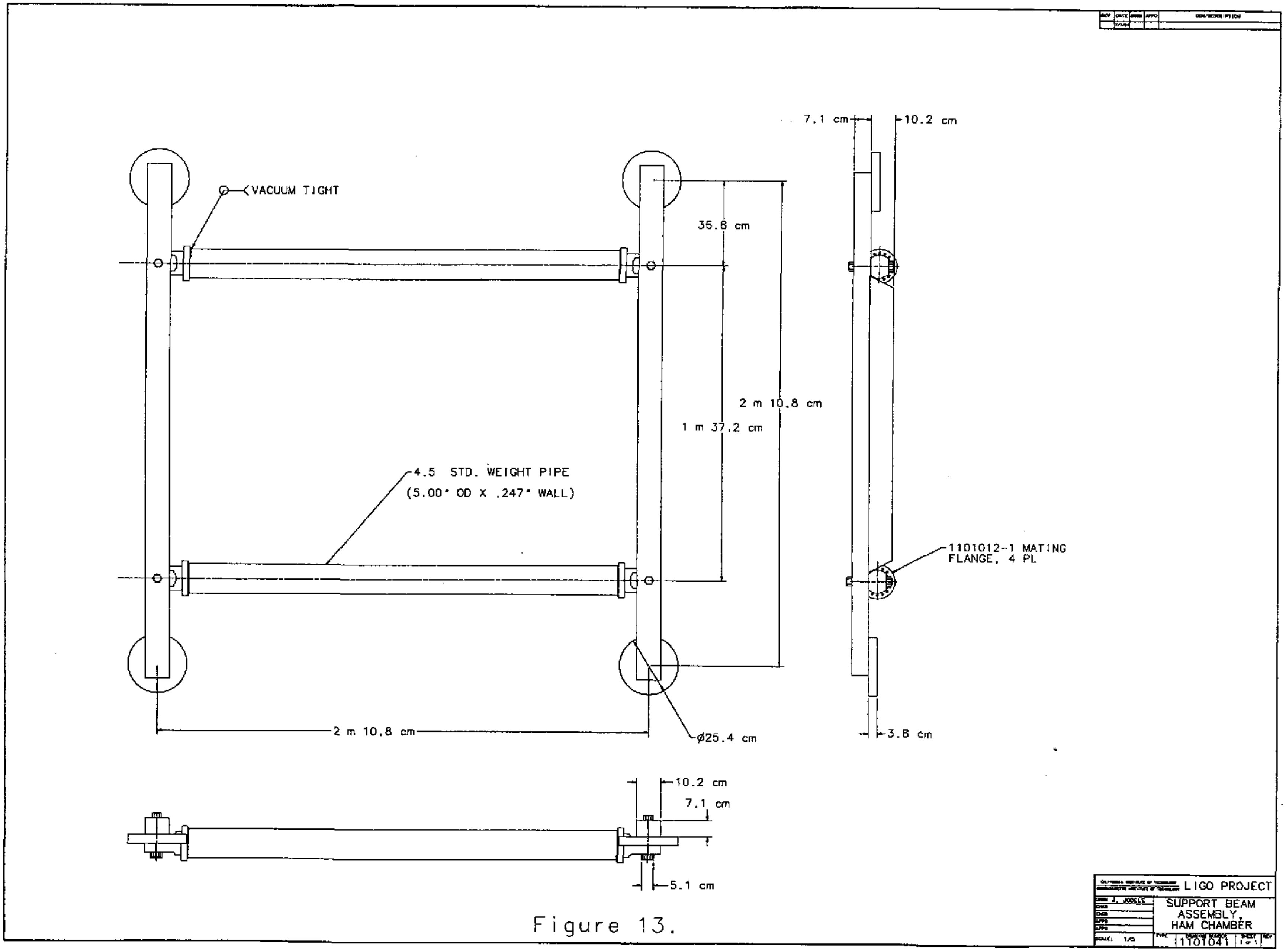


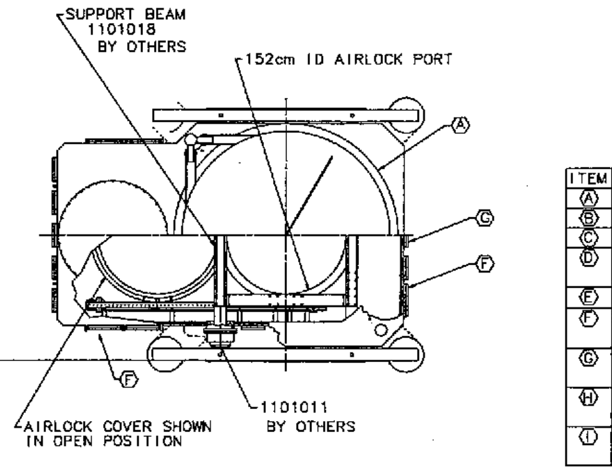
Figure 12.

LIGO PROJECT
7" ISOLATION BELLOWS (CONFIGURATION)
SCALE: FULL
1101012



VACUUM TIGHT
7.1 cm
10.2 cm
36.6 cm
2 m 10.8 cm
1 m 37.2 cm
4.5 STD. WEIGHT PIPE
(5.00" OD X .247" WALL)
1101012-1 MATING FLANGE, 4 PL
2 m 10.8 cm
ø25.4 cm
3.8 cm
10.2 cm
7.1 cm
5.1 cm
LIGO PROJECT
SUPPORT BEAM ASSEMBLY, HAM CHAMBER
1101041

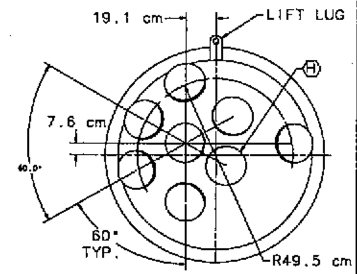
Figure 13.



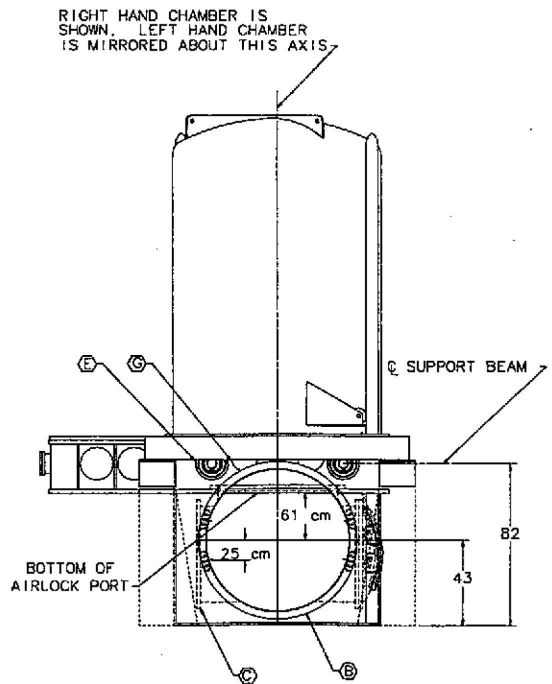
NOTES:
1. HEADS ARE ASME F&D.
2. INCLUDE CENTERING PINS ON NOZZLE FLANGES WHERE APPROPRIATE.
3. VIEWPORT (ITEM Ⓗ) MEASUREMENTS REFER TO INTERSECTION OF VIEWPORT AXIS WITH OUTER SURFACE OF VACUUM WALL.
4. TOLERANCES, UNLESS OTHERWISE SPECIFIED: LINEAR, ±0.25 CM
ANGULAR, ± 1 DEGREE
5. NOZZLE SCHEDULE PER TABLE BELOW:

ITEM	SIZE	QUANTITY	FLANGE TYPE	PURPOSE
Ⓐ	264cm ID TUBE	1	O/O-O/METAL*	MAJOR ACCESS
Ⓑ	183cm ID TUBE	2	METAL SEAL	LASER BEAM
Ⓒ	122cm ID TUBE	1	O/O-O/METAL*	LASER BEAM
Ⓓ	122cm ID TUBE	1	O/O-O/METAL*, WITH BLIND FLANGE	EMERGENCY ACCESS (MINIMIZE NECK LENGTH)
Ⓔ	35cm OD TUBE	4	CONFLAT**	SUPPORT BEAMS
Ⓕ	35cm OD TUBE	6	CONFLAT**, WITH BLIND FLANGE	ELECTRICAL FEEDTHROUGHS ROUGHING & ION PUMPS, UTILITY
Ⓖ	25cm OD TUBE	12	CONFLAT**, WITH BLIND FLANGE	ELECTRICAL FEEDTHROUGHS, BACK-TO-AIR PURGE
Ⓗ	20cm OD TUBE***	12	CONFLAT**, WITH BLIND FLANGE	OBSERVATION, BEAM PICKOFFS
Ⓘ	3.8cm OD TUBE	1	CONFLAT**, WITH BLIND FLANGE	ANNULUS PUMPOUT (NOT SHOWN)

*DUAL O-RING DESIGN, WITH CAPABILITY OF REPLACING INBOARD O-RING WITH METAL SEAL. THESE FLANGES EACH INCLUDE AN ANNULAR CHANNEL BETWEEN O-RINGS, MANIFOLDED TO A SINGLE PUMPOUT PORT ON EACH CHAMBER, WITH CONFLAT** SEAL.
**REGISTERED TRADEMARK, VARIAN VACUUM PRODUCTS
COMPATIBLE ALTERNATIVES ARE ACCEPTABLE
***THESE FLANGES ARE TANGENT TO LOCAL VACUUM WALL, WITH MINIMUM NECK LENGTH



122cm BLIND FLANGE DETAILS
SEE NOTE 3.



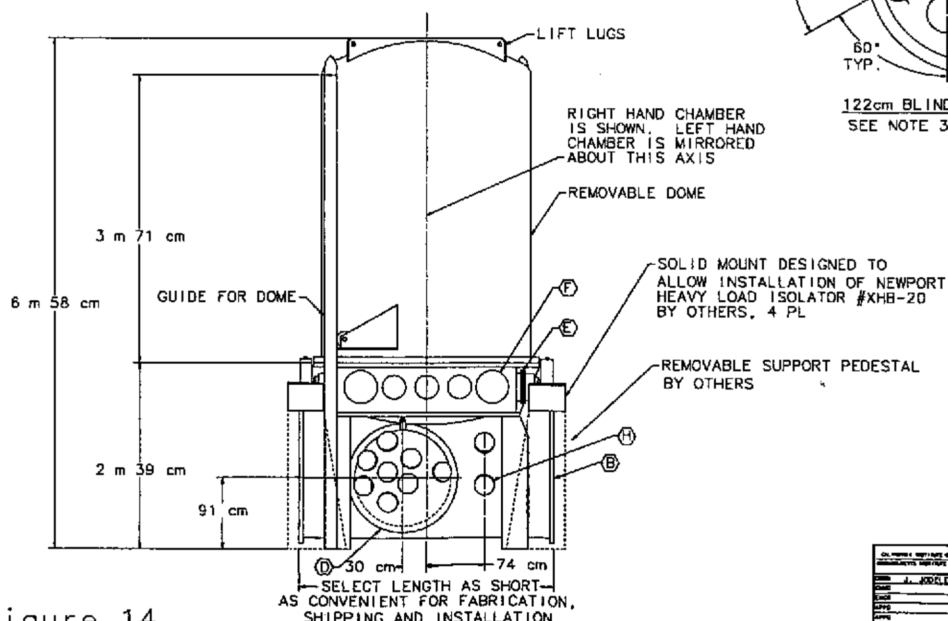


Figure 14.

LIGO PROJECT	
TEST MASS CHAMBER (TMC)	
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