LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
CALIFORNIA INSTITUTE OF TECHNOLOGY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Technical Report **LIGO-T960127-01-** **D** 2 Dec 96

Physics Environment Monitoring

Design Requirements Document

A Marin, D. Shoemaker, R. Weiss

Version 1.1

This is an internal working note
of the LIGO Project.

California Institute of Technology
LIGO Project - MS 51-33
Pasadena CA 91125
Phone (818) 395-2129
Fax (818) 304-9834
E-mail: info@ligo.caltech.edu

Massachusetts Institute of Technology
LIGO Project - MS 20B-145
Cambridge, MA 01239
Phone (617) 253-4824
Fax (617) 253-7014
E-mail: info@ligo.mit.edu

WWW: http://www.ligo.caltech.edu/

1 INTRODUCTION

1.1. Purpose

The purpose of this document is to describe the design requirements for the Physics Environment Monitoring (PEM) subsystem. The present version of this document incorporates the recommendations of the PEM DRR (1.4.1.17).

1.2. Scope

This document describes the philosophy and roles of the PEM subsystem, the environment to be monitored, sensors, requirements, and the quantity and placement of sensors.

1.3. Definitions and Acronyms

- BS - Beam Splitter
- BSC - Beam Splitter Chamber
- BT - Beam Tube
- BTM - Beam Tube Module (2 km Each)
- CDS - Control and Data Systems
- ETM - End Test Mass
- FMCS - Facility Monitor and Control System
- IFO - LIGO interferometer
- ITM - Input Test Mass
- LVEA - Laser Vacuum Equipment Area
- PSL - PreStabilised Laser
- PEM - Physics Environment Monitoring
- RGA - Residual Gas Analyzer
- RM - Recycling Mirror
- SRD - LIGO Science Requirements Document
- SEI - Seismic Isolation
- SUS - Suspension Control
- SYS - Detector Systems Engineering
- TM - Test Mass
- TBA/D - To Be Analyzed/Determined
- VEA - Vacuum Equipment Area

1.4. Applicable Documents

1.4.1. LIGO Documents

1.4.1.1 LIGO Science Requirements Document: LIGO-E950018-02-E

1.4.1.2 Detector Subsystems Requirements Document: LIGO-T950112-04-D

1.4.1.3 Vibration and Acoustic requirements for the LVEA and VEA of the LIGO Facilities. (revision): LIGO-T950113-04-O

1.4.1.4 LIGO EMI Control Plan and Procedures: LIGO-E960036-02-E

1.4.1.5 Ground Noise Meas. in MIT Buildings 20 and N9: LIGO-T960039-00-R

1.4.1.6 Test Mass Suspension and Control Concept for Initial LIGO Receivers: LIGO-T920003-A-D. See also: Magnet Size Considerations; Interference and Coil Power Dissipation: LIGO-T960126-01-I

1.4.1.7 Frequency, Intensity and Oscillator Noise in the LIGO: LIGO T960019-00D

1.4.1.8 ASC documents: Conceptual Design: T960134-00-D; DRD: T952007-03-I; See also Environmental Input to Alignment Noise: T960103-00-D

1.4.1.9 LIGO-Parsons DCCD vol 1 for Livingston: LIGO-C961574-00-O

1.4.1.10 Derivation of CDS Rack Acoustic Noise Specifications: LIGO-T960083-A-E

1.4.1.11 R. Weiss (Limits on RFI in LIGO; 3/8/89). See also T952009-00-E (PEM in LIGO)

1.4.1.12 Cosmic Muons: M. Burka Memo 3/89 in T960029-00-H (PEM 1994); A. Marin, R. Weiss 1996 Memo TBP.

1.4.1.13 Issues and Considerations on Beam Tube Bake LIGO-T960124-00; see also: Beam Tube Qualification Test, LIGO-T960125.

1.4.1.14 Ambient Ground Vibration Measurement at Hanford: LIGO-C950572-02-01

1.4.1.15 DAQ System DRR: LIGO-T960009-00-C

1.4.1.16 Derivation of CDS Rack Acoustic Noise Specifications, Al Lazzarini T960083

1.4.1.17 PEM DRR Review Report E960126-A-D and Assignment of AI L960751-00-D

1.4.1.18 A. Gillespie, Ph.D. Physics Thesis, Caltech, 1995; LIGO P950006-00-I

1.4.2. Non-LIGO Documents

1.4.2.1 D.C. Agnew: Strainmeters and Tiltmeters, Rev. of Geophys. Res., 24 (1986) 579; also F. Wyat, J. Berger: Investigation of Tilt measurements using Shallow Borehole Tiltmeters, ibid, 85 (1980), 4351

1.4.2.2 H. Volland: Atmospheric Electrodynamics, Vol.I and Ref., CRC Press, 1995

1.4.2.3 N. Christensen, Ph.D. Physics Thesis, MIT, 1990

1.4.2.4 M. Gordon, BS Physics, MIT, 1973

1.4.2.5 Reference Data for Radio Engineers, fourth edition, ITT, NY, 1956

1.4.2.6 Handbook of Geophysics and Space Environment, AF Cambridge Res. Lab, USAF, 1965, page 8-11

1.4.2.7 Physical Review D: Review of Particles Properties, vol. 50, page. 1269 (1994)

2 GENERAL DESCRIPTION

2.1. Specification Tree

This document is part of an overall LIGO detector requirement specification tree. This particular document is circled in Fig. 1.

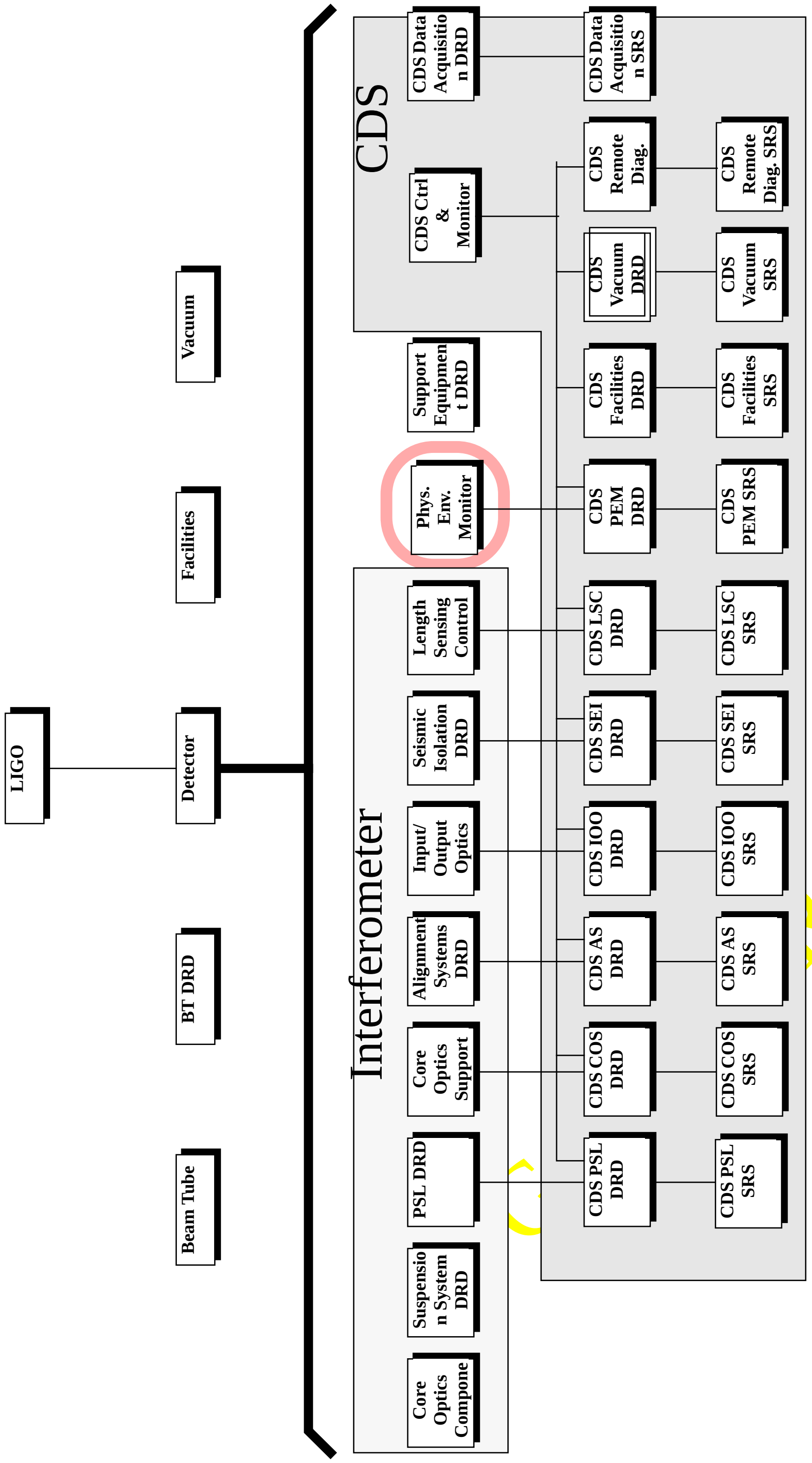


Figure 1: LIGO Specification Tree

2.2. Product Perspective

PEM is designed to measure disturbances in the physical environment which might affect the interferometers and that could produce spurious signals in the gravitational wave record. The PEM is intended to function as an independent monitoring and calibration system to allow on-line and off-line analysis. During the IFO operation, the data taken by the system is acquired and archived along with the interferometer signals and should be easily accessed by analysis routines. The PEM system shall be able to perform its sensing functions without requiring any other IFO subsystem to be operational.

A design goal of the PEM is to employ sensors with sufficient sensitivity to measure the fluctuating environmental variables to the naturally occurring ambient levels. Such a design criterion anticipates the needs for initial, enhanced and advanced interferometers. The design requirement is to be able to measure the environmental impact on the initial interferometer.

The principal role of the PEM is to execute the functions listed in 2.3 related to improving detection confidence and reduction in the environmental noise in the gravitational wave observations. Another set of functions are related to detector diagnostics and detector development, as follows:

1. Monitoring the physical variables in the vacuum system that could influence the performance of the detectors. (This function is distinct from the monitor and control to maintain the health and safety of the vacuum system which is provided by a self contained facility system.)
2. Monitoring the perturbations to the environment induced by the support equipment in the buildings, the buildings themselves and those due to meteorological conditions which may affect detector performance. (This function is distinct from the monitor and control to maintain the health and safety of the buildings provided by the FMCS.)
3. Measuring the transfer functions from environmental input to interferometer response.

The PEM will monitor the vacuum system and the facilities with the sensitivity, bandwidth and timing resolution to be useful for the scientific data analysis, a capability not intended for the FMCS.

The PEM also serves as part of the initial diagnostics and characterization of the interferometer during installation, performing the diagnostic tests that stimulate the detector at places where the environment influences the noise budget and determine the detector transfer function to the environmental perturbation. The stimulation is carried out at levels to achieve high signal to noise measurements but within the dynamic range of the detector. Examples of such tests are the stimulation of the external points of support of the seismic isolation system to determine the seismic isolation or the measurement of the response of a test mass to a spatially and temporally varying magnetic field.

The number and placement of the sensing and excitation systems is intended to be a minimum set which will allow an initial determination of the need and use of the information of an environmental input. The system will be modified according to the experience gained from initial data.

An important concept for the PEM system is a **portable (moveable) PEM cart** (see 3.1). The intent of this system is to perform stimulation and monitoring functions at different locations in the detector during initial detector shakedown and diagnostics without having to purchase permanent equipment for each test location. The PEM cart will be one of the first PEM elements to be implemented at the sites, *even before the IFO installation is complete*, in order to monitor various environmental parameters from the early stages of the LIGO IFO construction. Local data collection will be used for these pre-CDS measurements.

There is enough uncertainty in the actual needs and learning to be done that we choose to stage the implementation of the PEM. A limited installation, sufficient to determine the utility of the various sensing/excitation systems, will be made initially. In particular, a single 2km Beam Tube module will be instrumented. However, the CDS infrastructure (data acquisition system, control and monitoring system) should be ***extensible*** enough to accommodate the number of channels and data rates required for instrumenting all BT modules in the event that it is later determined to be of sufficient merit. For this reason we also give the anticipated numbers of elements for a ‘full implementation’ of the PEM.

2.3. Product Functions

The PEM system main functions are summarized as follows:

1. To monitor and record the time and amplitude of disturbances in the physical environment of the interferometers that could produce spurious signals in the gravitational wave record. The data can be used as a primary *veto* in the data analysis of the gravitational wave signal from one site and to reduce the numbers of candidate events in subsequent coincidence analysis between records from interferometers at different sites.
2. To set limits on or measure the correlation of disturbances in the environment and the data at each site.
3. To provide data for the linear regression calculations of the cross correlated noises.
4. To provide continuous environmental disturbance records for direct correlations between sites and with the gravity wave records in specialized gravitational wave searches such as those for periodic sources and stochastic backgrounds.
5. To aid future interferometer subsystem development by determining sensitivities to external disturbances.
6. To provide diagnostic information on the performance of the interferometers and the LIGO facilities.

In addition to these functions described in previous documents concerning the PEM we are proposing to add the following *new functions*:

7. To measure the transfer functions between the environmental perturbations and the detector
8. To provide stimulation and calibration of the detector noise where environmentally driven.

2.3.1. Modes of Operation

The PEM subsystem elements can operate in several different modes; not all elements are capable of all modes, and different elements can be in different modes simultaneously.

2.3.1.1 Detection mode: Continuous acquisition of PEM sensor data.

2.3.1.2 Threshold mode: Acquisition of one or more sensor outputs at an accelerated rate or with additional data due to the crossing of a threshold in the triggered sensor or by some other event (within the PEM, detector, on-line data analysis, etc.).

2.3.1.3 Diagnostic/Calibration mode. Some of those tests are performed periodically as part of a scheduled or exploratory research and/or calibration program. The functions of this mode are to:

- enable measurements of the interferometer sensitivity to environmental input
- support diagnosis of other subsystems
- provide diagnostic capability to determine the performance of the PEM
- enable implementation of calibration procedures within the PEM (e.g., determination of the sensor sensitivities)

2.3.1.4 Stand-alone mode. The PEM cart can be used without any reference to the rest of the detector, for both early tests (even before the CDS infrastructure is in place, via the carts stand-alone data acquisition system) and for later measurements where any connection with the outside world could compromise the data.

2.4. Environment

This section describes the environment which the PEM must sense and information on the interferometer sensitivity to the environment.

The PEM sensitivity requirement will be to measure the environmental level at which the initial interferometer is sensitive; the PEM goal will be to measure the background environmental level (if the cost impact is small, improved sensitivity is justifiable). The following exceptions are considered:

- If the environmental level at which the initial IFO is sensitive can not be readily established with reasonable confidence, then the requirement should be to measure the expected environmental level.
- If the measurement of the expected environmental level is beyond the capability of the commercial equipment, then either (1) the capability of the best commercially available instrument shall be deemed acceptable, or (2) if warranted on a cost and schedule basis, the level at which the initial IFO is sensitive must be established by test, analysis or simulation.

2.4.1. LIGO detector performance (see 1.4.1.1, 1.4.1.2)

The required ***initial detector*** performance is:

- $x\ (100\ \mathrm{Hz}) = 2.0 \times 10^{-19}\ \mathrm{m} / \mathrm{Hz}^{1/2}$
- $x\ (10\ \mathrm{kHz}) = 4.0 \times 10^{-18}\ \mathrm{m} / \mathrm{Hz}^{1/2}$

For reference, we give the ***ultimate detector*** performance as limited by the facilities:

- $x\ (100\ \mathrm{Hz}) = 2.0 \times 10^{-21}\ \mathrm{m} / \mathrm{Hz}^{1/2}$
- $x\ (10\ \mathrm{kHz}) = 2.0 \times 10^{-21}\ \mathrm{m} / \mathrm{Hz}^{1/2}$

2.4.2. Seismic Noise

Fig. 2 shows a straight-line approximation to the measured seismic noise at the two LIGO sites. See also 1.4.1.14. The facility will add some locally generated noise due to coupling to wind, HVAC, and anthropogenic activity. To specify the PEM, we wish to know the lower limit of the noise, which is given by the minimum of the curves in Figure 2. For reference, we also give the ‘LIGO Standard Spectrum’ definition, used in initial design work:

- $x(f) < 10^{-9}[f/(Hz)]^{-3} m/\sqrt{Hz}$ for $0.1Hz \le f < 1Hz$
- $x(f) < 10^{-9} m/\sqrt{Hz}$ for $1Hz \le f \le 10Hz$
- $x(f) < 10^{-7}[f/(Hz)]^{-2} m/\sqrt{Hz}$ above 10 Hz

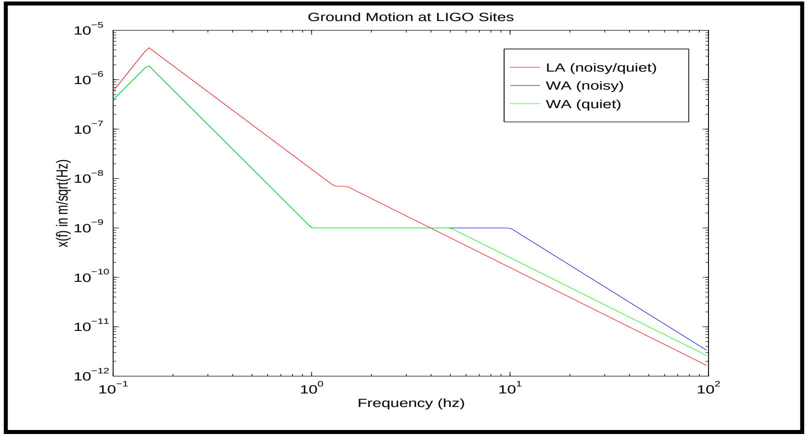


Figure 2: Ground noise at LIGO site

2.4.3. Acoustic Noise

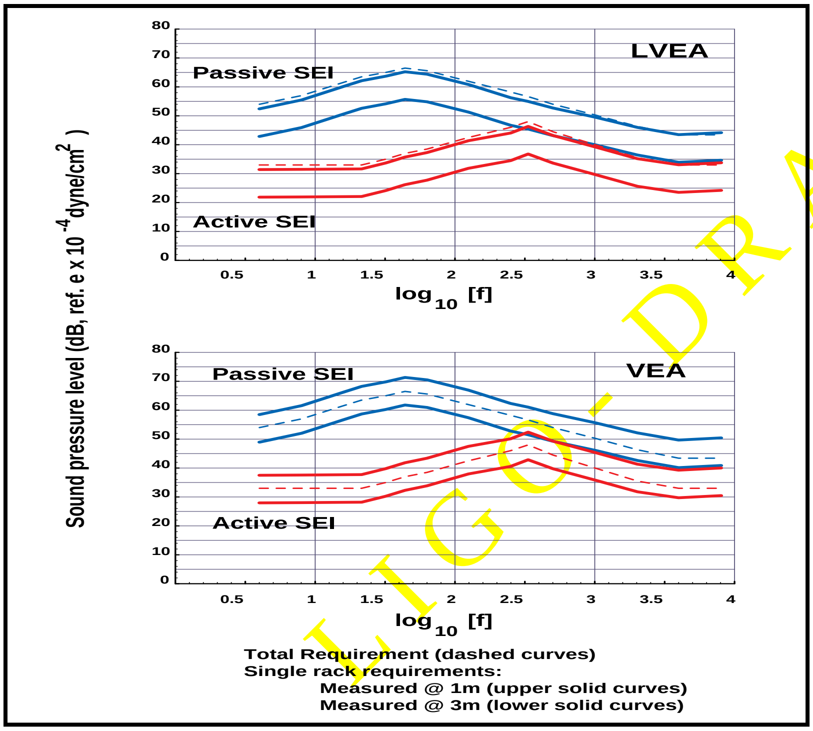


Figure 3: Sound Pressure Requirements (see 1.4.1.10)

The required acoustic noise levels in the LVEA are given in 1.4.1.10. Fig. 3 shows the Sound Pressure Level (SPL) requirements as calculated in this document. For our purposes, the maximum SPL near the tanks, corresponds in terms of acoustic power pressure to $p(f) < 2 \times 10^{-9} atm / \sqrt{Hz}$ (see 1.4.1.10 and 1.4.1.3). This required pressure sensitivity will be also enough to measure the sound pressure variations which may change the force exerted by the Vacuum Equipment on the LVEA slab, and due to the finite stiffness of the slab thus also the flatness of the slab. This causes both translations and tilts of the suspended components. Initial calculations, documented in 1.4.1.8, indicate that this may dominate the excitation at some frequencies. More detailed models of the LVEA slab, and of the sound pressure spectrum in the building are to be integrated into the model.

2.4.4. Magnetic Field Fluctuations

The sources of magnetic field fluctuations can be divided into external and internal to LIGO. Measurements of the average magnetic fields in quiet environments (see 1.4.2.3 and references) indicate that the typical range of such magnetic fields fluctuations are of the order of 10^{-14} to $10^{-15} T / \sqrt{Hz}$ for frequencies around 100Hz. Other measurements, quoted by the SUS DRD and 1.4.2.3, indicate values of the magnetic field in between 10^{-12} and $10^{-14} T / \sqrt{Hz}$ at 100 Hz (for normal weather conditions).

In Fig. 4 • we present a set of natural magnetic field measurements. On the same plot are displayed the measured magnetic field at two MIT locations which represent our current best estimate of the stationary magnetic field background in a working laboratory. The data will be updated with measurements at the LIGO sites when possible. The following data are shown:

- Saipan during active thunderstorm period (see 1.4.2.3)
- Malta during moderate period (see 1.4.2.3)
- Malta over the fall (the most active season) (see 1.4.2.3)
- Northern Sweden (see 1.4.2.2)
- Kochi, Japan (see 1.4.2.2)
- MIT Building 20 (LIGO lab) (see 1.4.1.5)
- MIT Building 9 (see (1.4.1.5)

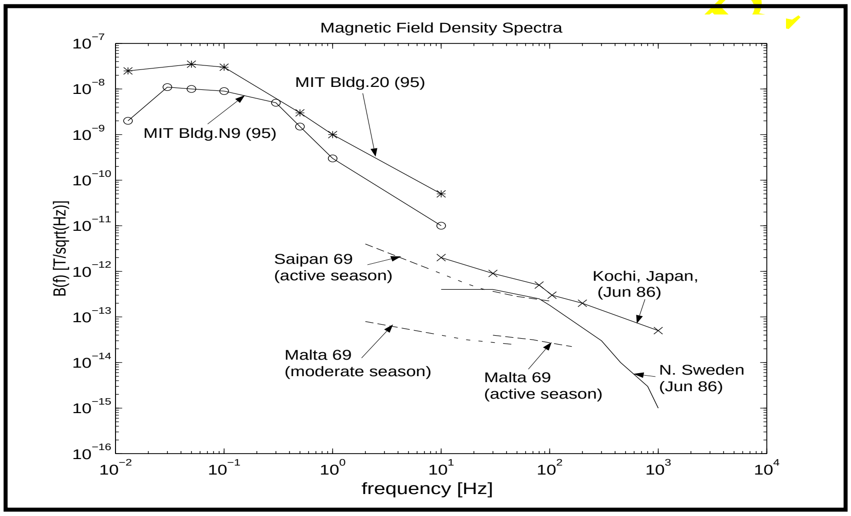


Figure 4: Plot of B(f) field (in T/Hz$^{1/2}$) vs. frequency (in Hz). See text.

An important external source is thunderstorms as well as the resonance cavity formed by the earth with its ionosphere, leading to significant signals in the vicinity of 25 kHz with an apparent strain pulse induced by thunderstorms on our masses of the same order of magnitude as the LIGO sensitivity. Lightning events also generate significant RF (see 2.4.5). Measurements made by Weiss and Gordon and documented in Christensen (1.4.2.3, 1.4.2.4) indicate the possibility that big lightning strikes may induce brief magnetic pulses at large distances, comparable with the LIGO site separation. Conservatively, we might expect to have magnetic bursts of about 10^{-11} T at both sites if a lightning strike with a current of at least 10^{5} A occurs at the mid-point between the two LIGO sites. The bursts might last 50-200μ s (see 1.4.2.3, 1.4.2.2).

Local sources are due principally to electronic systems (such as currents in conductors and electronics, laser and their control electronics, etc.), but can also be due to objects modulating the external field such as passing cars/trucks.

A 60 Hz magnetic field ambient of 10mG (10^{-6} T) is typical for industrial environment close to the power lines. For LIGO, it is expected that those lines will have (eddy current) shielding or be twisted to reduce the dipole contribution. Recent calculations (D. Coyne, B. Young, private communications, to be released as LIGO document) of the LVEA magnetic field for the “worst case” chamber location in the LVEA, predict the resultant magnetic field B(60Hz) centered in the chamber to be less than 1.5mG (without shielding, which should reduce the field by a factor of 3). This prediction is consistent with measurements done at the 40m prototype. Power line fluctuations might also induce magnetic field fluctuations (see 2.4.7). Those values largely exceed the natural magnetic field fluctuations as well as the recommended maximum magnetic field fluctuations (see 1.4.1.6) of 10^{-11} T/Hz$^{1/2}$, but occur at known frequency of the AC power and its harmonics.

The principal design problem for the magnetic sensor will be to obtain the dynamic range to measure the small naturally occurring fluctuations against the steady state but large fields at the power line frequency and its harmonics.

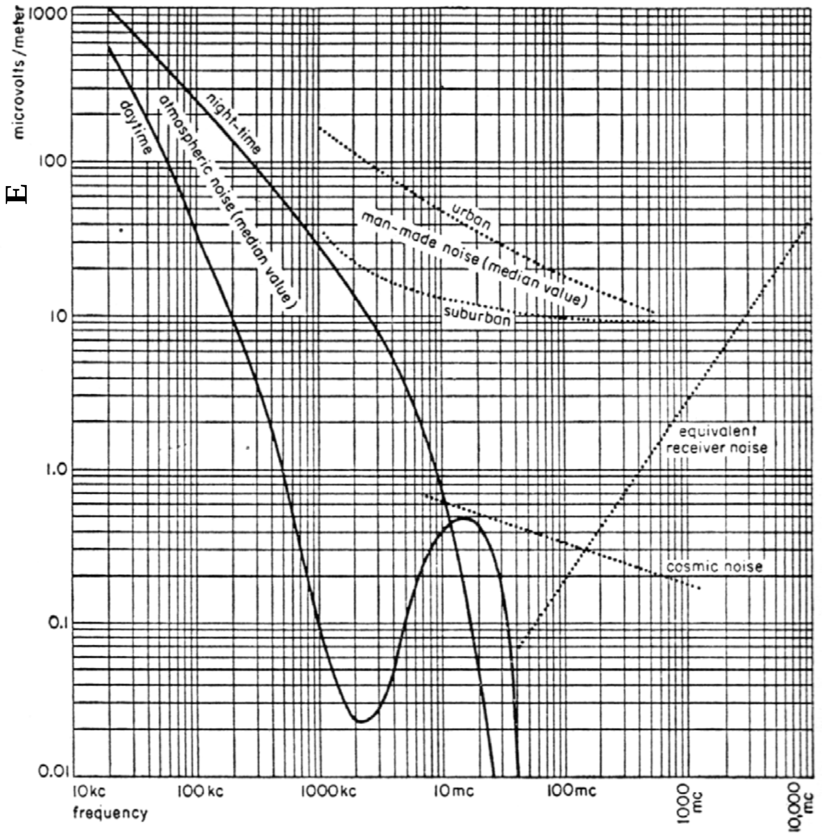
2.4.5. Radio Frequency Interference (see 1.4.1.4 and 1.4.1.11)

The principal sources of radio frequency interference can be divided into external and internal to LIGO. Continuous natural local RF noises might be of the order of 1mV/m at 10kHz to about $10\mu V/m$ above 10MHz (for typical values for suburban area, see fig. 5 from 1.4.2.5). Continuous human-generated local RF sources such as local radio and TV stations, transformers, power lines, power supplies are in accordance with FCC regulations. Measurements made at the Hanford location (see EMI 1.4.1.4) indicate RF signals up to 300 mV/m, generated by the local TV stations.

Thunderstorms and high altitude magnetic perturbations generate RF noise (see also 2.4.4 for thunderstorm generated noise). It is anticipated that those RF noises might be correlated at the two sites. Ref. 1.4.2.6 indicates that for typical lightnings produced at more than 1000Km, we might expect electric field bursts up to 100 mV/m, which means that we may have *correlated* events between LIGO sites due to electric field variations from lightning.

Internal/Local sources will be from local human-generated RF sources such as hand held transmitters, cellular telephones, cars, all kind of electric switches, electronics and power supplies, RF modulation systems, etc. These sources will probably dominate over external sources (see the

EMI Guidelines document for the list of sources and banned sources). For all electronic devices, EMI Guidelines recommends the maximum radiated field to be less than 100 mV/m at 1 m.



1. All curves assume a bandwidth of 10 kilocycles/second.
2. Refer to Fig. 3 for converting man-made-noise curves to bandwidths greater than 10 kilocycles. For all other curves, noise amplitude varies as the square root of bandwidth.
3. The curve of receiver noise shows the field intensities required to equal the receiver noise assuming
   a. The use of a half-wave-dipole antenna.
   b. A receiver noise level greater than the ideal receiver level by a factor varying from 2 decibels at 50 megacycles to 9 decibels at 1000 megacycles.
4. Transmission-line loss is not considered in the calculations.
5. For antennas having a gain with respect to a half-wave dipole, equivalent noise-field intensities are less than indicated above in proportion to the net gain of the antenna–transmission-line combination.

—Major sources of radio-frequency noise, showing amplitudes at various frequencies. For the U.S.A. and regions of similar latitude.

Figure 5: RF noise for US latitude

There is a large local contribution which must be removed to sense the smaller but possibly more significant contributions that would correlate between the sites and between interferometers at the same site. The important measurement will be to monitor changes around the ambient levels.

2.4.6. Cosmic Muons (see 1.4.1.12)

The passage of cosmic muons through the LIGO test masses might induce pendulum motions as well as excite the internal motions of the masses. Calculations show that the most likely source of noise induced by cosmic muons occur for very high energy showers.

- In order to be conservative, we will present here the displacement calculations for the advanced LIGO detector. Assuming the mirror dimensions for the advanced LIGO to be D=30cm and L=20cm, we find:
  - displacement spectral density due to a single horizontal muon with kinetic energy above 200MeV:
  $$x^{1\mu}(f) = (3.9 \times 10^{-22}/f^2)m/\sqrt{Hz}$$
  - the standard muon background produces (conservative, see 1.4.2.7 and ref):
  $$x(f) = (5.3 \times 10^{-22}/f^2)m/\sqrt{Hz}.$$
  - the expected rms displacement at 100Hz due to muon background is $x_{rms} = 5.3 \times 10^{-26} m$ in 1 Hz bandwidth, which is negligible in comparison with the advanced LIGO requirement.

Table 1: Force spectral density for initial and advanced LIGO pendulum

IFO	*Resonance* f_{0i}	α_i	*Q*	$F^2(f)[N^2/Hz]$ *(thermal)*	$F^2(f)[N^2/Hz]$ *(muons)*
Initial M=10.7 Kg	0.74 Hz (fundamental)	1	10^7	$6 \times 10^{-26}/f$	9.3×10^{-39}
	9421 Hz	0.50	10^7	$5 \times 10^{-18}/f$	9.3×10^{-39}
	29100 Hz	390.	10^7	$3.7 \times 10^{-14}/f$	9.3×10^{-39}
	29587 Hz	1.224	10^7	$1.2 \times 10^{-16}/f$	9.3×10^{-39}
	30792 Hz	0.087	10^7	$9.2 \times 10^{-18}/f$	9.3×10^{-39}
Advanced M=30 Kg	0.74 Hz (fundamental)	1	10^9	$1.7 \times 10^{-27}/f$	5.4×10^{-38}

- Table 1 shows few values for the force spectral density due to thermal noise:

$$F^2(f) = \frac{4k_B T\alpha_i M\omega_{0i}^2}{Q\omega}$$

where $\alpha_i \times M$ is the effective mass of the pendulum (see 1.4.2.4), and ω_{0i} is the resonant angular frequency of the test mass. The values used in Table 1 represents a very small, but representative sample of the calculated resonances and effective mass coefficients for the planned initial LIGO optical parameters developed by Kent Blackburn for the initial IFO. For our purposes, the important points are those with low both effective mass and resonant frequency. The effective masses and the internal mode resonance frequencies for the advanced LIGO IFO are not available at the present time: TBA.

- The average force spectral density due to the cosmic muon background (upper limit), to induce pendulum motions of the test masses and the excitation of its internal modes, is

$$F^2{}_{\mu}(f) = 2P_{dep}^2(dN/dt)$$

where P_{dep} is the momentum deposited by a muon into the test mass, and dN/dt is the horizontal muon flux through the test mass. We may conclude that the background muon induced noise due to the ionization process only is negligible with respect to the thermal forces (see Table 1 and 1.4.1.18).

- The displacement due to a **burst of muons** generated by a high energy cosmic proton or a nucleus interacting with the earth's atmosphere might be significant for very high energy primary cosmic rays. Previous calculations (see 1.4.1.12) indicate that in order to induce a mirror displacement equivalent to the LIGO advanced detector sensitivity, the necessary number of horizontal particles interacting with the mass is of the order of 1.5×10^5 particles. It was estimated that such a density of muons might be produced by horizontal primary cosmic protons with energy of the order of 10^{18} eV or higher. More recent calculations, based on full GEANT Monte Carlo simulations and data from literature, shows that for the initial LIGO IFO the rates of cosmic showers which might affect only one end of the IFOs test masses are of the order of one every few thousands years. The probability to have excitations due to cosmic muons at both ends or at the two sites is much smaller.

TBA: A simulation program will be written to study if a catastrophic loss of muon energy might affect the muon induced noise. The probability of such events is very small, and it is very unlikely to happen simultaneously in more than one test mass.

2.4.7. Power Line Fluctuations (see 1.4.1.9)

The instrumentation building power distribution system typical of that used for standards and research laboratories. Some of the guidelines for the power distribution and wiring of the LVEA are listed below (Hanford Final Design Rep, Vol I--DCCD doc, Parson 4/12/96 draft):

- Nominal Voltages: 120V and 480V
- Ranges: 2% for Uninterrupted Power; +4% and -8% for technical power
- 5% maximum Total Harmonic Content (THC)
- Frequency 60Hz; 1Hz fluctuation.
- Transients shall not exceed +10% of the specified voltage for a duration not exceeding 200 microseconds.

In order to reduce the incidence of power line transients and associated fluctuating magnetic fields, effort has been made to avoid electrically driven devices which cycle on off such as relay actuated fans in the HVAC system and pumps. Another measure that has been taken is to place rotating machinery (other than transient pump carts) 10 meters or more from the test mass chambers.

2.4.8. Residual Gas (vacuum) see 1.4.1.13

Average Pressure: The average pressure in the Beam Tubes for the initial pumping strategy is required to cause less than 1/2 the shot noise contribution ($h(f) \leq 5 \times 10^{-24}/\sqrt{Hz}$) to the initial interferometer noise, due to statistical fluctuations in the residual gas optical index. It is expected, based on QT tests, that the level will be much less (making less than a 1/10 contribution to shot noise, or a negligible level). The long-term goal for the performance of the system is to make less than 1/2 the quantum limit noise contribution for a 1 ton test mass for a search for periodic waves at 100 Hz ($h(f) \le 1.5 \times 10^{-25}/\sqrt{Hz}$). Note that the scaling law for this noise source is $h(f) \le 4.8 \times 10^{-21} R(x/H_2) \langle P(torr) \rangle_L^{1/2}$.

Gas Bursts: The initial sensitivity to bursts, $\Delta B \approx 100\,\mathrm{Hz}$ at 100Hz, is for the initial interferometer $h_{rms} = 1.5 \times 10^{-22}$ and for the advanced interferometer $h_{rms} = 1.5 \times 10^{-23}$. The allowed rates per IFO (triple coincidence, no templates), for an accidental coincidence rate of 0.1/year, coincidence window of ~10 msec, rate 1/minute translates to a rate/area (bellows and welds/beam tube module) of $1 \times 10^{-8} bursts/(cm^2 s)$. The Equivalent Hydrogen bursts in terms of pressure are $\Delta P = 3 \times 10^{-15} torr$ (initial interferometer) and $\Delta P = 2 \times 10^{-16} torr$ (advanced interferometer).

Leaks: The maximum air leak permitted per beam tube module end pumping (2200 liters/sec) is $Q_{air} \le 8 \times 10^{-9} torr \cdot liters/s$ (1/10 of the goal statistical phase noise).

2.4.9. Vacuum Contamination (see 1.4.1.13)

TBD; no requirement has been established, pending contamination measurements and interpretation. A trial requirement is that the vapor pressure of condensable gases with optical loss to ensure a deposition of less than 1 monolayer per month on optical components. See Appendix 1.

2.4.10. Meteorological conditions

Weather will influence the performance of the interferometers through acoustic, seismic, and electromagnetic paths due to changes in the wind, barometric pressure, humidity, precipitation, solar heating/cloud cover cooling, and lightning. In addition, it will be useful to monitor acoustic disturbances external to the buildings (airplanes, shooting, vehicles). The speed of propagation and typical sizes of disturbances indicate the need for monitoring at both the vertex station and the end (and mid) stations.

2.4.11. Clean Room Monitoring

Dust particle counters are required to monitor the air quality of the clean rooms. PEM will provide fixed and portable dust particle counters for the LVEA, VEA and optic room spaces.

3 REQUIREMENTS

3.1. Introduction

The PEM system derives its requirements from the ultimate LIGO detector performance (for the sensitivity and excitation levels) and availability. The requirements are grouped into sections corresponding to the main subsystem and detector techniques proposed for the PEM system. The main requirements and proposed performances are presented. As mentioned in section 2.4., the PEM sensor requirements are calculated at the sensor locations, and are derived from the standard LIGO requirements. We derive all noise requirements given below assuming that the related noise amplitude spectral density is held to 10% of the LIGO sensitivity *h(f)* at all in-band frequencies. The stimulation (excitation) systems are specified to give signals at the test points that provide a 10/1 (TBA) signal to noise over the existing background for most of the designed dynamic range.

The roles of the sensors for veto, diagnostics, and transfer functions will be defined later. This will be given in table form as the preliminary design advances, and laid out in a way to ease the extraction of the impact on availability of the detector. (TBD)

3.1.1. The PEM Moveable Cart

Some of the sensing equipment and sources of excitation are proposed to be part of dedicated *PEM moveable carts.* Physically, at each site there might be a couple of carts, each containing a part of the sensors and excitation sources listed bellow, or a single cart which can be instrumented as required. This carts can move from place to place in the LVEA, BT or mid-end stations to supply excitation and to temporarily place sensors. They communicates with the CDS backbone wherever installed for data acquisition, and can also use independent local data logging. This PEM carts allows the reduction of fixed excitation and sensing stations. The PEM carts will contain the following (the characteristics are listed in chapter 3.2):

3.1.1.1 Sensing Equipment for the PEM Carts

- 3 x 3 accelerometers
- 2 acoustic microphones
- magnetic field sensors
- RFI sensors
- RGA and contamination control electronics
- weather monitor

3.1.1.2 Sources of Excitation for the PEM Carts

- PZT and electromagnetic shaker excitation for the seismic noise above 10 Hz.
- acoustic noise generators
- magnetic field generators
- RFI generators

3.1.1.3 Remote control of the PEM Carts

- Remote commands to be interpreted by the PEM cart, TBD; telephone-line bandwidth modem link anticipated to suffice.

3.1.1.4 Special Requirements for the PEM Carts

- The PEM carts should be considered as the *first PEM subsystem to be implemented* at the sites. In the first stages, it can have its own data acquisition system for quick independent tests and evaluations of the environmental noises.
- The PEM cart can be placed anywhere on the LIGO site within one day to carry out a data collection plan. The required 24 hours are from the conception of measurement to equipment in place ready to perform measurements
- In order to increase even more the flexibility of this cart, the cart will also be battery operated and have both some storage capacity and communication as indicated in the next sec-

tion. This “independent” PEM cart will be extremely useful during the initial LIGO construction and operation.

3.1.2. Alternative PEM Data Links

For the PEM cart and measurements made on the BT locations where data ports are not available but where a connection to the CDS Control and Monitoring system is needed, a low power X-band radio link between the PEM cart or BT monitoring location to the vertex station can be considered. The radio antennas would be outside the BT tunnels.

3.2. Characteristics

The quantities of sensors given below are for the initial implementation of the PEM. When there are differences, the number and placement of sensors for a ‘full’ implementation are also given to aid in projecting future CDS requirements.

3.2.1. Performance Characteristics of the PEM Sensing System

3.2.1.1 Seismic Noise: Low Frequency $0.1 \le f \le 10$ Hz

Due to the nature of the seismic noise, and with the proper requirements for other vibration generators, we propose to have one 3-axis seismometer and one 2-axis tiltmeter per building.

3.2.1.1.1 Low frequency 3 axis seismometer

- sensitivity: $x(f) \le 3 \times 10^{-10} / f^2 [m/\sqrt{Hz}]$
- maximum noise level: $a < 10^{-10} g$
- dynamic range 100 dB
- frequency range DC to 10 Hz
- one per building: 5 in WA and 3 in LA

3.2.1.1.2 2 Axis tiltmeter

- sensitivity: $\theta(f) \le (2 \times 10^{-9} / f^2) rad/\sqrt{Hz}$
- maximum noise level: TBD
- dynamic range 100 dB
- bandwidth: 10 Hz
- one per building: 5 in WA and 3 in LA

3.2.1.2 Seismic Noise: High Frequency $10 \le f \le 200$ Hz

The PEM will

- monitor the motion (all degrees of freedom) of the TM tanks and to sample other important points in the interferometer
- monitor the beam tube mechanical excitation
- monitor the ground motion near seismic support piers in order to obtain the transfer function from floor to support beams. These accelerometers are part of the PEM portable excitation/diagnostic cart.

3.2.1.2.1 High frequency 1 axis PZT accelerometer

- sensitivity: $x(f) \le (10^{-8}/f^2) m/\sqrt{Hz}$
- maximum noise level: $a < 10^{-9} g$
- dynamic range 100 dB
- bandwidth: 200 Hz
- 3 x 3 accelerometers/site for the PEM cart: 9 in WA and 9 in LA
- number of accelerometers at different locations:

1. WA 4Km IFO: 6x(4 TM)+3x(8 other chambers: BS, HAM, PSL) = 48
2. WA 2Km IFO: (12 chambers) x 3= 36
3. LA 4Km IFO: (12 chambers) x 3 = 36
4. WA: 3 accelerometers every 500m on one BTM: 15

- TOTAL accelerometers at WA site: 9(cart)+48(4Km IFO)+36(2Km IFO)+15(BTM)=108
- TOTAL accelerometers at LA site: 9(cart)+36(IFO)=45

3.2.1.3 Acoustic Noise (see 2.4.3)

The acoustic noise is an important in the vicinity of the optics; one per tank is required.

3.2.1.3.1 Microphones

- sensitivity $p(f) \le 10^{-4}(N/m^2/\sqrt{Hz}) = 10^{-9} atm/\sqrt{Hz}$
- maximum noise level $p_{noise} < 10^{-10} atm$
- dynamic range 60 dB
- bandwidth: 10Hz - 1kHz, TBD
- one per tank, two near PSL/external IOO, two per cart per site: 14+2+2=18 in WA and 7+1+2=10 in LA

3.2.1.4 Magnetic Field (see 2.4.4)

This disturbance source also has a short scale length and thus requires instrumentation close to the test mass to be useful. The national thunderstorm activity network may also provide data. This correlation is important both for magnetic and RF signal produced by thunderstorms. In addition, in order to measure the natural magnetic field environment, a DC-powered magnetometer is proposed to be mounted outside of the LVEA at each site, to ensure freedom from locally-generated 60 Hz fields in the LVEA (the BT may provide a good site; to be resolved for PDR)

3.2.1.4.1 3 Axis Low Noise Flux Gate Magnetometer

- sensitivity $B(f) \le 2 \times 10^{-11}(T/\sqrt{Hz})$
- Internal Noise $n_{rms} \le 10^{-11} T_{rms}/\sqrt{Hz}$ at 1Hz
- dynamic range 100 dB, with 60,120 Hz filters
- bandwidth: 1k
- initial installation: total 8 in WA and 2 in LA as follows

1. one per cart: 1 in WA and 1 in LA
2. one for each chamber with a core optics (RM, BS, 2xITM and 2xETM): 6 in WA
3. one DC magnetometer per site, outside the LVEA: 1 in WA and 1 in LA.

- CDS extensibility to allow one/chamber with core optics in LA: additional 4 in LA

3.2.1.4.2 High Sensitivity Custom Made Coil (not in the initial installation TBD)

- sensitivity $B(f) \le 2 \times 10^{-12} T/\sqrt{Hz}$ at 1kHz
- Internal Noise $n_{rms} \le 10^{-12} T_{rms}/\sqrt{Hz}$ at 1Hz
- dynamic range 100 dB
- bandwidth: 1kHz
- built-in bucking coil for $n \cdot 60$ Hz compensating field
- CDS extensibility to allow (as in 3.2.1.4.1): 8 in WA and 6 in LA

3.2.1.5 Radio Frequency Interference (see 2.4.5)

3.2.1.5.1 Multi-channel Antenna/Receiver

- sensitivity $E \le 10(\mu V/m)$ TBD.
- dynamic range 120 dB
- bandwidth: 1.3GHz
- peak detection in 6 bands with msec timing
- estimated data rate per receiver: 6x16 bit, 2048 Hz sample rate
- one per site: 1 in WA and 1 in LA (moveable units)

3.2.1.5.2 Narrowband RF receivers

- one per RF modulation frequency
- antennas placed in close proximity to the antisymmetric photodiode
- data collected on TBD 1 db change in level
- 2 in WA and 1 in LA

3.2.1.6 Cosmic Muons (see 2.4.6)

The position of the muon detector should in the corner building near the TM tanks. The detector should be sensitive to short bursts of muons. At the present time, we are proposing to install only one detector at one site.

3.2.1.6.1 Scintillator Detector

- sensitivity $F(E > 100MeV) \le 10^{-4} \mu/s/m^2$
- 1msec timing resolution or better
- dynamic range: 60dB
- estimated data rate per detector: 1x16 bit 2048 Hz sample rate
- one in WA

3.2.1.7 Power Line Fluctuations (see 2.4.7)

3.2.1.7.1 Power Line Monitor

- sensitivity: fractional fluctuations in voltage:

  long period: $\Delta V/V|_{rms} \le 0.02$, for minutes;
  $\Delta V/V|_{rms} \le 0.01$ for 1sec to 1msec
  $\Delta V/V|_{rms} \le 0.05$ for less than 0.2 msec
- harmonic content: less than 0.05 for line harmonics to 2kHz

- dynamic range: 60dB
- estimated maximum data rate per power line monitor: 4x16 bit, 2048 Hz sample rate, at threshold crossing, 20Hz sample rate for continuous monitoring bellow threshold.

- initial installation: 2 technical power monitors at WA and 1 at LA to measure the power quality and perform cross-correlation analysis with the interferometer during commissioning in order to determine the factors and levels to which the interferometer is sensitive and establish the requirements for a complete power monitoring system for later installation.

- CDS extensibility to allow 1/building: additional 3 in WA and 2 in LA.

3.2.1.8 Residual Gas (vacuum) see 1.4.1.13.

3.2.1.8.1 Residual Gas monitor (RGA)

Requirements for **pressure measurement** in instrumentation chambers, associated tube and beam tube modules:

- measure the pressures of the residual gas in the 4Km beam tubes: the sensitivity should be of the order of $10^{-14} torr$ or less.
- The sensitivity of the system should be able to determine the contribution of gas bursts and other coherent residual gas fluctuations, leaks, etc.; to measure the composition of the residual gas (1-100amu, $10^{-14} torr$)
- to stamp the time dependence of the pressure and bursts measurements.
- sensitivity: partial pressures $P_p \le 10^{-14} torr$ for 1 - 100 amu
- dynamic range: 10^9
- timing resolution on a single mass number $\Delta t_{res} \le 10 ms$
- estimated data rate per RGA: 1x16 bit, 2048 sample rate on threshold crossing, 20Hz sample rate for continuous monitoring bellow threshold.

- initial RGA heads installation: 9 in WA and 5 in LA (ports and power required) as follows:

1. 7 isolatable volumes (4/LVEA in WA and 3/LVEA in LA) + 1 isolatable volume per VEA x 6 VEAs (4+2) = 13 total RGA heads (8 in WA and 5 in LA)
2. one RGA head in the midpoint of one BTM at WA site

- initial RGA controller installation: one/cart and one /building: 6 in WA and 4 in LA

- CDS extensibility to allow one RGA head/Km of BT: additional 7 in WA and 8 in LA.

3.2.1.9 Vacuum Contamination Monitor (see 1.4.1.13). TBD See Appendix 1

As an initial step, we will research the utility of one means of monitoring the contamination:

1. procure a crystal deposition monitor
2. study and establish if the crystal monitor is adequate
3. study how many crystal monitors are necessary after the experience during the commissioning of the IFO.

- initial installation (estimate, if method is successful):

1. one ***head*** per isolatable vacuum volume (excluding the beam tube), or 8 in WA and 5 in LA; the heads should be close to the RGA heads.
2. one set of ***control electronics and PC*** per building, or 5 in WA and 3 in LA; intermittent data/control transfer to/from PC

3.2.1.10 Weather monitor

We require a sensitivity and precision sufficient to correlate weather conditions with interferometer behavior, and to give warning of exceptional meteorological conditions.

Variations of the temperature, humidity and pressure will affect the alignment of LIGO components, and may induce additional spurious noises due to expansion or contraction of the beam tubes. Inside humidity measurements are useful in tracking problems in the electronics. Wind and precipitation are sources of local seismic noise. Pressure, temperature, humidity and wind variations might indicate the possibility of an approaching thunderstorm.

NOTE: The thermometers, hygrometers, barometers and anemometer might be combined in a weather station for the locations which require all those measurements. We are listing them separately in order to indicate their physical required parameters. ***Also, note that all the data rate are estimated at 2Hz which may be considered an upper limit. (TBD)***

3.2.1.10.1 Thermometers

- precision 1 deg C
- range: inside 0-50 deg. C; outside -20 to 70 deg. C
- estimated data rate: 1x16 bit sample rate 2Hz
- •• initial implementation: 30 in WA and 19 in LA as follows:

1. one every 500m on one 2Km BTM: total 5 in WA.
2. inside buildings temperature: 5 in WA and 3 in LA
3. outside temperature on four(TBD) building sides: 20 in WA and 16 in LA

- •• CDS extensibility to allow: one/500m on BT: 11 in WA and 16 in LA

3.2.1.10.2 Humidity Detectors

- precision 10%
- range 10-100% relative humidity
- estimated data rate: 1x16 bit sample rate 2Hz
- •• initial implementation: 11 in WA and 9 in LA as follows:

1. one every 500m on one 2Km BTM: total 5 in WA.
2. inside buildings humidity: 5 in WA and 3 in LA
3. outside humidity: 1 in WA and 1 in LA

- •• CDS extensibility to allow: one/500m (TBD) on BT: 11 in WA and 16 in LA

3.2.1.10.3 Precipitation

- precision 10%
- rate or accumulation

- estimated data rate: 1x16 bit sample rate 2Hz
- one per site: 1 in WA and 1 in LA

3.2.1.10.4 Wind monitors

- wind speed precision: 1mph
- wind direction precision: 5deg
- estimated data rate: 2x16 bit sample rate 2Hz
- one per building: 5 in WA and 3 in LA

3.2.1.10.5 Barometers

- pressure precision/resolution: 1mm Hg
- range: 650-850 mm Hg with max/min feature
- estimated data rate: 1x16 bit sample rate 2Hz
- one per site: 1 in WA and 1 in LA

3.2.1.11 Dust Particle Detectors

•• Dust particle counters are required to monitor the air quality of the clean rooms. PEM will provide fixed and portable dust particle counters for the LVEA and VEA spaces. The following quantities and locations are proposed:

- 1 per OSB optics lab (fixed cleanroom)
- 1 per OSB Vacuum Equip. Preparation room (fixed cleanroom)
- 2 per LVEA
- 1 per VEA
- 1 per Mid & End-Station optics lab
- 1 per portable cleanroom

•• The requirements are as follows:

- capable of measuring to class 1 in a 10 minute time period TBD
- remote data collection
- others TBD, consistent with present monitors used in MIT/CIT labs
- estimated data rate: 7x16 bit sample rate less than 1Hz (see above, TBD)

3.2.2. Performance Characteristics of the PEM Excitation System (TBD)

NOTE: All the excitation systems except the seismic PZT (3.2.2.1) are part of the PEM moveable cart and not permanently installed.

3.2.2.1 Fixed Seismic Excitation System TBD

We are proposing to design parts of the seismic fixed excitation system for the seismic group. The system will ensure the possibility to support the stack in such a way, that there will be some means to insert one of several portable exciters into the beam supports. If the Detector includes an active SEI system, PEM will use those means instead to excite the support point.

3.2.2.2 Acoustic Noise Generator

This consists of a conventional wide-bandwidth loudspeaker and also one or several portable localized sources of sound, like ‘tweeters’ and sound guns.

- dynamic range $10^{-5} \geq p(f) \geq 10^{-9} atm/\sqrt{Hz}$ bandwidth: 10Hz - 1kHz, TBD
- several per site for the PEM carts

3.2.2.3 Magnetic Field Generator (TBD)

The magnetic field generator should be able to produce fields and gradients in all directions near the location of the test masses and have sufficient strength to induce motions seen above the noise in the suspensions.

- Dynamic range: $10^{-12} \leq B \leq 10^{-5} T$
- Bursts duration: 10-300μs
- Built-in gradient monitor
- One per building (possible need for one coil per tank if not demountable)

3.2.2.4 RF generator

- dynamic range 120 dB
- bandwidth: 1.3GHz
- one per site: portable unit or part of the PEM cart (TBD)

3.2.3. Interface Definitions

3.2.3.1 Interfaces to other LIGO detector subsystems

Presently, the PEM system is designed as an independent system so far as the data is concerned, attached to different parts of the LIGO interferometer, or mounted near the LIGO detector. There are no signal or optical interfaces with the interferometer subsystems, to avoid corruption of either. PEM accepts and provides monitor and control inputs, used in acquisition, and eventually in control or on-line veto of the acquisition data taking. For the initial stage of the LIGO detector, it is proposed to have no hardware vetoes.

3.2.3.1.1 Mechanical Interfaces

- All the PEM low-frequency Seismometers and Tiltmeters should be mounted on the ground of the LVEA at a point representative of the seismic excitation of the SEI stack support piers.
- LVEA accelerometers should be mounted on the stack support columns, as close as possible to the bellows feedthrough.
- BT accelerometers should be mounted on the beam tube walls to sense the acceleration of the BT and baffle surfaces.
- Microphones for tanks to be mounted as close as possible to the bellows feedthrough
- Microphones for PSL/IOO should be mounted on the PSL/IOO table
- Magnetometers should be mounted as close as possible to the LIGO test masses, outside the tanks
- The cosmic ray monitor should be within 20m of the tanks containing the test masses
- The crystal heads for the contamination monitor and the RGA heads are mounted inside the vacuum tanks on existing flanges, in the VEs. TBD

3.2.3.1.2 Electrical Interfaces

In general, the PEM signal interfaces are directly to the CDS DAQ system.

- Power line monitors are connected at a point representative of the power in the LVEA

3.2.3.1.3 Stay Clear Zones

3.2.3.2 Interfaces external to LIGO detector subsystems

The Seismometers and Tiltmeters will need LVEA floor space with no strong local sources of heat or vibration. A rough guess is 1 m^2 per unit. This is generous, but is designed to isolate the system from local effects. The actual footprint of a sensor will be of the order of 0.01 m^2

3.2.4. Reliability TBD

A *figure of merit* for all the proposed PEM monitors and their coupling functions has to be developed, before or during the commissioning of the first IFO. Based on those calculated and measured figure of merit, we (with Systems Integration) will estimate the significance of every environmental effect on the IFOs. According to the DRR recommendations, this should be factored into a reliability table for each PEM subsystem/sensor and for PEM as a whole, including a determination of which sensors are needed for what types of searches (coalescence, periodic, stochastic, etc.). Also, an estimation will be made of the minimum number of each PEM subsystems which should be working in order to take data, as well as the weight of each PEM parameter in the veto signal.

4 QUALITY ASSURANCE PROVISIONS (TBD).

APPENDIX 1 THE RESIDUAL GAS AND VACUUM CONTAMINATION MONITORING (TBD)

Here we outline a possible combination of RGAs and Deposition monitors as a means to determine the rate and nature of contaminants on the optics. Due to the lack of information on the nature of contamination, we cannot yet specify a system which is sure to be useful. The system outlined below was included in the CostBook estimate and scope of the PEM, and may also contain a useful start for a design of a contamination monitor.

A gas burst monitor may become part of the monitoring system once LIGO is operating. One possibility is a low sensitivity blue or near ultraviolet interferometer or absorption spectrometer that samples the full 4km of each leg. This would require optical ports ~10 cm in diameter with an unobstructed path in each 4km arm. The location of the beam in the clear aperture is uncritical.

•• Requirements for **contamination monitors** in instrumentation chambers and associated tubes

- Capability to measure deposition of 1 monolayer/month on ambient temperature surface.
- Capability to perform qualitative desorption analysis to separate water from other adsorbed molecules
- Digital control and read interface to LIGO instrumentation system.

The vacuum contamination level is required to be such that the degradation of the interferometer components (the mirror surfaces) does not significantly impact the performance of the interferometer. The allowed in-vacuum components and the level of contaminants is to be determined via exposure tests now (mid-96) underway. From this research may come information which can be used to design a contamination monitoring system.

- The system functions: optical contamination and outgassing
- The proposed sensitivity: less than a monolayer/month of hydrocarbons deposition.
- The analytic capability is provided by:
    1. evaporation of absorbed layer vs. crystal oscillator sample collector temperature
    2. measurement of the evaporated layer by an RGA
- one Crystal Head and one RGA per isolatable vacuum volume
- one RGA mounted on one BTM for test purposes
- one control unit for Crystal head per bldg