LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
CALIFORNIA INSTITUTE OF TECHNOLOGY
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Technical Report **LIGO-T970112-00- D** 30 Sep 97

Physics Environment Monitoring

Final Design Document

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Distribution:

PEM FD Review Committee

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1 INTRODUCTION

1.1. Purpose

The purpose of this document is to describe the final design for the Physics Environment Monitoring (PEM) subsystem.

1.2. Scope

This document describes the proposed sensing and excitation elements which will make up the PEM. These follow the requirements defined in the PEM DRD document (1.4.1.1). Most of the PEM subsystems characteristics were presented in a preliminary form in PEM PDD (1.4.1.8). The Recommended Action Items from the PEM PDR (1.4.1.12) were also taken in consideration.

1.3. Definitions and Acronyms

- ADC - Analog to Digital Converter
- BLDG - building: 5 in WA and 3 in LA
- BT - Beam Tube
- BTM - Beam Tube Module (2Km)
- BS - Beam Splitter
- BW - beam Width
- CDS - Control and Data Systems
- DAQ - Data Acquisition System
- DRD - Design Requirement Document
- ETM - End Test Mass
- FMCS - Facility Monitoring and Control System
- ICD - Interface Control Document
- IFO - LIGO interferometer
- IOO - Input/Output Optics
- ISC - IFO Sensing and Control
- ISOLATABLE VOLUMES - in WA: 4/LVEA+(1/VEA*4VEA)=8; in LA: 3+1*2=5
- ITM - Input Test Mass
- LA - Louisiana (Livingston) site
- LVEA - Laser Vacuum Equipment Area
- PD - PhotoDiode
- PDD - Prelimnary Design Document
- PDR - Prelimnary Design Review
- PEM - Physics Environment Monitoring
- PSL - PreStabilised Laser
- RF - Radio Frequency
- RH - Relative Humidity
- RGA - Residual Gas Analyzer
- RMS - Root Mean Square
- SEI - Seismic Isolation

- SUS - Suspension Control
- T - Temperature
- TM - Test Mass
- TBA/D - To Be Analyzed/Determined
- VEA - Vacuum Equipment Area
- WA - Washington State (Hanford) site

1.4. Applicable Documents

1.4.1. LIGO Documents

1.4.1.1 PEM DRD LIGO-T960127-02-D

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

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

1.4.1.4 PEM system 1994: LIGO- T960029-00-H

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

1.4.1.6 PEM DRR Report and Action Items LIGO-E960126-A-D

1.4.1.7 Assignment of PEM DRR Action Items: LIGO-L960751-00-D

1.4.1.8 PEM PDD, LIGO-T970086-00-D

1.4.1.9 Input Optics PDD, LIGO-T970144-00-D

1.4.1.10 PEM FD Mechanical Interface Drawings (see 3.6. for the list of drawings)

1.4.1.11 PEM CDS PD : T970165-00-C

1.4.1.12 PEM PDR Review Report and Action Items: M970137-01-D

2 GENERAL DESCRIPTION

The final design which responds to the performance requirements given in the PEM DRR are given. Many of the final design parameters may be found in the Preliminary Design Document (1.4.1.8). Here we will present the final version of the PEM design, which include some updated items with respect to the preliminary design (but in accordance to the Review recommendations). Most of the sensors and excitation systems design presented in this document is final. ***There are some components, indicated by "PRELIMINARY", which need some more definition; we propose to carry this out during the procurement/fabrication phase.*** The mechanical interfaces are described in this document and its accompanying drawings, while the electrical interfaces will be described in the companion CDS document ***(see 1.4.1.11 TBD).***

For the PEM components which will be purchased commercially, the final design documentation consists of citing the relevant items and their interface characteristics; for in-house designs, mechanical and electrical (via CDS) drawings are given. We give here our present best candidates for the sensors and excitation systems to be used in the PEM, and expect very few changes in the as-realized system.

The PEM subsystems which have manual adjustments, which can not be remotely controlled or readback by CDS and which are required for interferometer operation, will have lockouts as needed to ensure that they remain as set.

3 FINAL DESIGNS

The performance requirements of sensors required can be found in the PEM DRD (see 1.4.1.1). The prices given below are approximate and are given to aid in setting the scale.

3.1. PEM Sensors

3.1.1. Seismic Noise

3.1.1.1 Seismic Noise Requirements

For reference, we give the 'LIGO Standard Spectrum' definition, used in initial design work:

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

3.1.1.2 Low frequency 3 axis Seismometer

3.1.1.2.1 GURALP CMG-40T Seismometer

- manufacturer/distributor: GURALP/Digital Technology
- model: Transducer CMG-40T
- digitizer: CMG-DM16 with RS 232 interface
- standard velocity output: 800V/m/s; optional high gain output: 8000V/m/s
- noise level: $a < 10^{-10}g$
- maximum optional frequency range: 0.008 to 50 Hz
- unit price $12,186 with digitizer (no power supply)
- CMG-40T hand-held control unit $896 (one unit/site for initial and periodic adjustments)
- • Transducer mechanical and electrical interface parameters
- weight: 20 lb
- dimensions (inch): 6.5 x 6.6 diam
- mechanical resonance: > 400 Hz
- temperature sensitivity: < 0.6 V / 10 deg C on low gain channel
- operating range: -10 to 65^{0}C
- cable length to electronics: 1m standard;

- connector type: KPT06f-16-26S for the transducer
- interface to CDS for power: 12V, 50mA
- interface to CDS for output signal (optional): max ±10 V;
- • Electronics mechanical and electrical interface parameters
- weight: NA
- dimensions (inch): 4 x 6.6 diam
- operating range: -20 to 65^{0} C
- interface to CDS: power 12V, 120mA
- interface to CDS for output signal: RS 232/422 standard interfaces
- output cable length: 100/500 ft.

3.1.1.2.2 Implementation

3.1.1.2.2.1 Quantity:

- one per building: 5 in WA and 3 in LA
- spares: one per site

The seismometer will be placed directly on the concrete foundation of the building, in the inside of the vertex of the 4km antenna, in the area called “PEM STAY CLEAR ZONE”. A barrier will be erected around the stay-clear zone (shared with the tiltmeter and other fixed PEM LVEA sensors) to prevent excess excitation or collisions.

3.1.1.2.2.2 Corner Station

- See “PEM Sensor Locations at WA site: D970210” on page 36
- See “PEM Stay Clear Zone Instrumentation, Corner Station: D970287” on page 36 for seismometer location and fence location within the “PEM Stay Clear Zone”
- LA design similar; See “PEM Sensor Locations at LA site: D970298” on page 36 and "PEM Stay Clear Zone Instrumentation, Corner Station: D970287".

3.1.1.2.2.3 Mid and End Stations

- See “PEM Sensor Locations at WA site: D970210” on page 36
- See “PEM Stay Clear Zone Instrumentation, Mid and End Stations: D970286” on page 36 for seismometer location and fence location within the “PEM Stay Clear Zone”
- LA design similar; See “PEM Sensor Locations at LA site: D970298” on page 36 and "PEM Stay Clear Zone Instrumentation, Mid and End Stations: D970286".

3.1.1.3 Low Frequency 2 Axis tiltmeter

3.1.1.3.1 Applied Geomechanics 500 series Tiltmeters

- manufacturer/distributor: Applied Geomechanics
- model: 520 Geodetic Tiltmeter
- resolution: <10nRad
- bandwidth: 0-10 Hz
- range (depends on the setting): $\pm 1400 \mu rad$ for setting 1
- temperature control monitor (build in): 10mV/deg.C; -40 to 100^{0} C range
- price for model 520 Platform Tiltmeter with micrometer legs: $8000

- • Transducer mechanical and electrical interface parameters

- weight: 10 lb
- dimensions (inch): 9.1 x 9.1 x 5.0
- mechanical resonance: NA
- temperature sensitivity: 0.11% per deg.C typical
- operating range: -25 to 70^{0} C
- cable length to electronics: 3m standard to Switch Box
- connector type: 15-pin quarter turn
- interface to CDS for power: none (through the switch box)
- interface to CDS for output signal: none (through the switch box)

- • Switch Box mechanical and electrical interface parameters

- weight: 4 lb
- dimensions (inch): 9 x 8 x 5.5
- operating range: -25 to 70^{0} C
- interface to CDS for power: 11-15VDC and -11 to -15VDC max 20mA each
- interface to CDS for output signal: up to ±8 VDC single ended (16 diff) at high gain
- output cable: shielded twisted pair to an ADC channel
- terminal strip connection for power and signal
- output impedance: 270 Ohm, short and surge protected

3.1.1.3.2 Implementation

3.1.1.3.2.1 Quantity:

- one per building: 5 in WA and 3 in LA;
- no spares

The tiltmeter will be placed directly on the concrete foundation of the building, on the inside of the vertex of the 4 Km antenna, in the area called “PEM STAY CLEAR ZONE”. A barrier will be erected around the stay-clear zone (shared with the seismometer) to prevent excess excitation or collisions (see 3.1.1.2.2).

3.1.1.3.2.2 Corner Station

- See “PEM Sensor Locations at WA site: D970210” on page 36
- See “PEM Stay Clear Zone Instrumentation, Corner Station: D970287” on page 36 for tiltmeter location and fence location within the “PEM Stay Clear Zone”
- LA design similar; See “PEM Sensor Locations at LA site: D970298” on page 36 and "PEM Stay Clear Zone Instrumentation, Corner Station: D970287".

3.1.1.3.2.3 Mid and End Stations

- See “PEM Sensor Locations at WA site: D970210” on page 36
- See “PEM Stay Clear Zone Instrumentation, Mid and End Stations: D970286” on page 36 for tiltmeter location and fence location within the “PEM Stay Clear Zone”
- LA design similar; See “PEM Sensor Locations at LA site: D970298” on page 36 and "PEM Stay Clear Zone Instrumentation, Mid and End Stations: D970286".

3.1.1.4 High frequency 1 axis PZT accelerometer

3.1.1.4.1 ISOTRON Accelerometer

- manufacturer/distributor: Endevco Meggitt Aerospace
- model: ISOTRON Accelerometer 7754-1000
- multi-channel signal conditioner power supply ISOTON model 2793M1 (16 channels)
- range $\pm 5g$
- voltage sensitivity 1000mV/g
- maximum Voltage: $\pm 5V$
- bandwidth 1Hz-1kHz
- residual equivalent g-rms noise for narrow band at 10 Hz: $5 \times 10^{-7} g_{rms}/\sqrt{Hz}$
- power requirement: +18-24VDC max 20mA
- unit Transducer price for large quantities: $745
- 16 channels signal conditioner and power supply: $1400
- Triaxial accelerometer mounting block; See "Triaxial Accelerometer Mounting Block: D970274" on page 36. Estimated cost: $150.

- Transducer mechanical and electrical interface parameters

- weight: 115 grams
- dimensions (inch): 1.16 x 1 diam.
- mechanical resonance: 9 kHz
- temperature sensitivity: NA
- operating range: -55 to 85^0 C
- cable length to signal conditioner: 3m, model 3061-129 for each accelerometer. Maximum custom made cable length: 250', with connectors 10-32 UNF-2B and BNC. The cost of a 20m cable with connectors: about $60.
- connector type: 10-32 UNF-2B
- interface to CDS for power: none (through the signal conditioner)
- interface to CDS for output signal: none (through the signal conditioner)

- Triaxial Mounting Block

- dimensions (inch): 1.2 x 1.2 x 1.1 without accelerometers
- weight: NA, approx 70 grams mount only
- anodized Al alloy, electrically isolated

- Signal Conditioner mechanical and electrical interface parameters

- 16 channels power supply and signal conditioner
- weight: 4 lb
- dimensions (inch): 19 inch rack mounting 1.73x19x9.45
- operating range: 0 to 50^0 C
- input connectors: BNC
- interface to CDS for power: 117 AC
- interface to CDS for output signal: 10 V pk-pk (3.535 Vrms), 2mA pk-pk or greater
- output connectors: BNC (strongly preferred for high frequencies) and 25-pin D connector
- output cable: BNC RG59 or shielded twisted pair to an ADC channel
- output impedance: 10 ohm

3.1.1.4.2 Implementation

3.1.1.4.2.1 Quantity:

Number of accelerometers at different locations:

1. WA 4Km IFO: 6x(4 TM)+3x(8 other locations: BS, HAM, PSL) = 48
2. WA 2Km IFO: (11 tanks + 1 PSL) x 3= 36
3. LA 4Km IFO: (11 tanks + 1 PSL) x 3 = 36
4. WA: 3 accelerometers every 500m on one BTM: 15

- •• TOTAL installed accelerometers

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

All points where an accelerometer can be mounted use the **Triaxial Mounting Block** (see drawing "Triaxial Accelerometer Mounting Block: D970274"). The Triaxial Accelerometer Mount Assembly can be mounted directly, or, using as interface the **PEM Mounting Plates** (See 3.5.), to the indicated locations. The mount will be held with screws. The PEM mounting plates have provisions for the mounting of other sensors and excitation systems.

The accelerometers are used in several applications:

3.1.1.4.2.2 PSL/IOO

The triaxial accelerometer assembly will be attached to the surface of the optical table carrying the PSL/IOO optics, close to the output optics. See "PEM Sensor Locations at WA site: D970210" on page 36 and "PEM Sensor Locations at LA site: D970298" for "PEM Accelerometers" location.

3.1.1.4.2.3 ITM and ETM of the 4kM IFO WA site only

The WA BSCs with Test Masses (ITM and ETM) each carry 6 accelerometers, and the objective is to sense all six degrees of freedom. These signals will not bear a simple relation to the actual stack excitation for frequencies higher than the resonances of the frame (the first resonance is expected to be at ~46 Hz), but will cover, with reasonable assurance, all excitation paths. A modal analysis will be performed to determine the best use of the 6 accelerometers and the interpretation of their signals. Refer to "PEM Sensor Locations at WA site: D970210" for "PEM Accelerometers" location, and to "PEM Sensors Assembly BSC and HAM (Plate type I): D970271" for assembly drawing.

Two *PEM mounting plates type I* (see 3.5.1.), with one triaxial block each, will be attached to the underside of the 4 ends of the seismic stack support beams (using tapped holes in the stack support beam, close to the bellows interface) for each of the BSCs with TM (4km WA IFO only). Thus, there are 4x6=24 possible emplacements for accelerometers, populated as desired for a given measurement.

3.1.1.4.2.4 HAM, BSC, ETM (2Km WA, and LA), ITM (2Km WA, and LA)

One *PEM mounting plate type I* (with one triaxial accelerometer assembly) will be attached to one of the seismic stack support beams (using a tapped hole in the stack support beam), close to the bellows interface (same as in 3.1.1.4.2.3.). See "PEM Sensor Locations at WA site: D970210" on page 36 and "PEM Sensor Locations at LA site: D970298" for “PEM Accelerometers” location, and "PEM Sensors Assembly BSC and HAM (Plate type I): D970271" for assembly drawing.

3.1.1.4.2.5 Beam Tube (one 2km BTM in WA)

The accelerometers monitoring the beam tube will be mounted together as a $x - y - z$ triplet in the Triaxial Mounting Block. A *PEM mounting plate type II* (see 3.5.2.), containing one accelerometer triaxial assembly, will be mounted with clamps to the wall of the Beam Tube reinforcing rings, after bakeout. Refer to "PEM Sensor Locations at WA site: D970210" for “PEM Accelerometers” location, and to "BT Sensors Assembly (plate type II): D970273" for the assembly drawing.

3.1.1.4.2.6 PEM Cart

The accelerometers associated with the PEM cart will be mounted together as a $x - y - z$ triplet in the Triaxial Mounting Block. A supply of mounting plates type I, II and III (see 3.5.) will be available, which can be attached to the surface of interest; all mounting plates will have a tapped hole pattern matching the Triaxial Accelerometer Mounting Block and other sensors and excitation systems.

3.1.2. Acoustic Noise

3.1.2.1 Acoustic Noise Requirements

- The required acoustic power pressure sensitivity near the tanks is $p(f) < 2 \times 10^{-9} atm/\sqrt{Hz}$.
- Frequency range: 10Hz -8kHz

3.1.2.2 Microphones

We choose a model with traceable sensitivity designed for measurement applications:

3.1.2.2.1 Bruel&Kjaer

- Model: measuring microphone 4130 ($431)
- polarization voltage: 28V
- free field 1/2 inch
- sensitivity: 10mV/Pa
- Frequency range: 6.5Hz to 8 kHz
- dynamic range: 26dBA to 142dBA with preamplifier 2642 ($446, freq. range 20Hz-20kHz, attenuation 2dB, noise A-weighted typical less than 3.5 microV)
- dynamic range: 22dBA to 142dBA with preamplifier 2669 ($575)
- power supply: B&K 2 channels model 2810 ($860), gain up to 40dB, battery or DC 28V
- 2m cables standard. Extension cables (AO 0175,-6,-7) of 3,10 and 30m available
- estimated price/channel $1500 including holder and cables

3.1.2.2.2 Implementation

3.1.2.2.2.1 Quantity:

One per VE chamber, one near each PSL/external IOO, two per cart per site, and *one every 500m of the one 2km BT module* ***(5 on one BTM, not in PDD, see 3.1.2.2.2.4)*** *in WA only*:

- •• total microphones:
- 22+2+2+5=31 in WA
- 11+1+2=14 in LA

The microphone will be purchased with the corresponding preamplifier and, a stand, microphone clip and an adaptor which converts the pipe-thread clip to a 1/4-20 tapped hole. The microphone will be mounted in its clip. The PEM mounting plate type I and II (see 3.5.) will have provision for mounting the acoustic microphones with the preamplifier and clip attached, using studio type soft mounts.

3.1.2.2.2.2 HAM/BSC

The seismic support beam of the chamber in question will have tapped holes near the bellows, for mounting the PEM mounting plate type I (see 3.5.1.) with the microphone in its clip with a headless 1/4-20 screw. Refer to "PEM Sensor Locations at WA site: D970210" and "PEM Sensor Locations at LA site: D970298" for “PEM Microphone” locations. Refer to Drawing "PEM Sensors Assembly BSC and HAM (Plate type I): D970271" for “Microphone Assembly” location.

3.1.2.2.2.3 PSL/IOO

The microphones will be mounted to holes in the optical table, using a headless 1/4-20 screw. Refer to "PEM Sensor Locations at WA site: D970210" and "PEM Sensor Locations at LA site: D970298" for “PEM Microphone” locations. See “Microphone Assembly for PSL: D970292” on page 36 for assembly.

3.1.2.2.2.4 Beam Tube (not in PD)

We propose to instrument with microphones the 2km BT at the WA locations, in the same places scheduled to receive triaxial accelerometer mounts and T and RH sensors. (Tests performed by Rai Weiss on the Hanford BTs show that the dominant source of BT vibrational excitation is acoustic.)

The microphone will be mounted to the PEM Mounting Plate type II (see 3.5.2.) which also carries the temperature, humidity and triaxial accelerometer assembly (see 3.1.1.4.2.5). Refer to "PEM Sensor Locations at WA site: D970210" for “PEM Microphone” locations. See “BT Sensors Assembly (plate type II): D970273” on page 36 for assembly.

3.1.2.2.2.5 Cart

The cart microphones will be mounted in its clip as above. A microphone stand with boom and 2-foot gooseneck will be acquired to support the microphone. Also, the PEM mounting plates type I and II (from the cart inventory) will have provisions to accept the microphone assembly.

3.1.3. Magnetic Field

3.1.3.1 Magnetic Field Requirements

For requirements discussion, see the PEM DRR document. The sources of magnetic field fluctuations can be divided into external and internal to LIGO. Measurements of the average magnetic fields in quiet environments are in the range of:

- 10^{-12} and $10^{-14} T / \sqrt{Hz}$ at 100 Hz (for normal weather conditions).
- There will be two types of magnetometers:
- triaxial commercial magnetometer to be used in most of the LIGO proposed locations,
- very sensitive, custom made, one axis coil magnetometer, to be used in various places for extremely low magnetic field measurements.

Filters are necessary to eliminate the AC 60Hz and its harmonic noises, as well as to compensate the continuous earth magnetic field.

3.1.3.2 Magnetic Field Sensors

3.1.3.2.1 3 Axis Magnetometer

- manufacturer/distributor: Bartington/GMW
- transducer model: MAG-03MCES100-L7 Environmentally sealed, low noise
- power supply model MAG-03PSU
- range: $\pm 70 \mu T$);$\pm 10 V$ full scale at the DAQ module input)
- bandwidth: 0 to 4.5 kHz
- noise at full bandwidth: less than 2nT
- internal noise: better than $7 pT_{rms} / \sqrt{Hz}$
- unit price with cylindrical probe: $3930.
- power supply: $920
- tripod mount and support $500
- cables MAG-03MCES5m: $280 and up (depend on the length add ~$7/m)
- 60 Hz and multiple notch filters (built in-house CDS)
- Transducer mechanical and electrical interface parameters
- weight: 100 grams
- dimensions: 202mm in length, 25mm diameter
- bracket 55x55x36 mm (MAG-03-MT) $210
- tripod mounting and support $300
- operating range: -40 to 85^0 C
- cable length to electronics: 3, model MAG-03MCES 5-600 m, 10 pin connector/cable environmentally sealed
- connector type: Amphenol GB 62GB51T10-7P, see cable model
- interface to CDS for power: none (through the PSU module)
- interface to CDS for output signal: none (through the PSU module)
- PSU module mechanical and electrical interface parameters
- power supply and signal conditioner
- weight: 0.5 kg
- dimensions (mm): 133 x 84 x 46
- operating range: NA room temperature
- input connectors: RM15TRD10P plug (see cable assembly from transducer)
- interface to CDS for power: 9-18 VDC via mains adaptor (10 h battery included)
- interface to CDS for output signal: $\pm 10 V$ analog output
- analog output connectors: 3 BNC

3.1.3.2.2 Implementation of the Bartington Magnetometer

3.1.3.2.2.1 Quantity:

- one for each chamber with a core optics (RM, BS, 2xITM and 2xETM): 6 in WA only.
- one remote magnetometer per site, outside the LVEA: 1 in WA and 1 in LA.
- one per PEM cart: 1 in WA and 1 in LA.
    - •• Total Bartington Magnetometers:
    - WA: 8
    - LA: 2

3.1.3.2.2.2 BSC/HAM

The magnetometer sensor will be mounted on an aluminum pedestal at the height of the test mass, and within 50cm of the wall of the Vacuum Chamber in question. Refer to "PEM Sensor Locations at WA site: D970210" for “PEM Magnetometer” locations. See drawing "Magnetometer Mounting Assembly: D970282" for the assembly stand. The power supply/signal conditioner should be mounted on the CDS DAQ rack which holds the ADCs for the magnetometer (as determined by CDS).

3.1.3.2.2.3 Remote

The magnetometer will be mounted in an underground fiberglass junction box, far from evident sources of sources of 60 Hz and multiples (only DC power will be supplied). The sensor (MAG-03MC) can tolerate temperatures of -40 deg C to +85 deg C; thus, it is expected that the box can be left without environmental control. The electronics will be placed within the nearest appropriate building (within the allowed 600m cable length). The power supply/signal conditioner should be mounted on the CDS DAQ rack which holds the ADCs for the magnetometer (as determined by CDS). Refer to "PEM Sensor Locations at WA site: D970210" and to "PEM Sensor Locations at LA site: D970298" for Remote Magnetometer Locations. See “Remote Magnetometer Sensor Box: D970295” on page 36 for the assembly drawing. Estimated price for the box is $200.

3.1.3.2.2.4 Cart

The magnetometer to be part of the PEM cart, will have the same type of hardware as the BSC/HAM magnetometers (see 3.1.3.2.2.2), but it will be part of the moveable PEM Instrumentation Cart (see 3.3.2.).

3.1.3.2.3 Custom Made Coil Magnetometer ***(PRELIMINARY)***

Based on the experience acquired in building the field sensitive magnetometer (R. Weiss, S. Chatterji and S. Veach), a simple coil magnetometer design exists. The coil magnetometer prototype is under construction at MIT and it will be used for the first field measurements at both LIGO locations. The data will be used as magnetic map references at the sites and to study correlated events. Some 60Hz and harmonics filters are to be designed as well.

Characteristics of the prototype device:

- •• Coil
- turns: 216 turns

- diameter: 1.5 meter
- gauge: 21 awg (heavy insulation)
- frame: PVC and nylon
- resistance: 43 Ohm
- inductance: 200 millihenry
- wire mass: approx 8 lbs.
- total mass: approx 20 lbs.

- • Low Noise Preamplifier:

- input referred noise:1.5 nV/rt(Hz) @ 100 Hz
- response range: 0.1 Hz to 10kHz (1 Hz to 1kHz optimal)

- • System:

- total sensitivity:1e-10 gauss/rt(Hz) @ 1kHz (1/f frequency dependence)

3.1.3.2.4 Implementation of the Custom Made Magnetometer on the Cart ***(PRELIMINARY)***

The magnetometer sensor will be mounted on an fiberglass or carbon fiber composite pedestal of adjustable height and position. The sensor and its hardware will occupy a floor space of max. 2m x 0.5m. A couple of long cables between the sensor head and the electronics will be provided, both for independent and/or coupled with DAQ card operation.

The custom made magnetometer will be part of the PEM Instrumentation Cart (see 3.3.2.).

3.1.4. Thunderstorm Monitor

3.1.4.1 Commercial data source

The 'National Lightning Detection Network' will provide real-time data on ground-cloud lightning strikes. Data can be retrieved as an ASCII stream with time, place, intensity, and multiplicity of lightning strikes, effectively in real-time.

The service provides the following information:

- Lightning location (about 1/2mile precision)
- Lightning time (precision better than 1msec)
- Lightning current in the main core

- Costs (includes government discounts) from Global Atmospheric Inc.

1. US coverage data access fee:$17,137 /year
2. communications fee: $636/year
3. Enhanced Data Stream (ASCII Output): $4k licence
4. Installations, training $3926
5. software: $2451

3.1.4.2 Implementation

Quantity: One for the two sites; data shared using internet or equivalent.

A satellite receiving dish is required (roof mounted) with cabling to a dedicated PC.

3.1.5. Radio Frequency Monitoring

3.1.5.1 RF Noise Monitoring Requirements

- Sensitivity better than -130dBm/m^2/kHz
- Bandwidth 30kHz to 300 MHz for broadband monitoring
- At least 4 simultaneously monitored frequencies with BW of about 10% or larger

3.1.5.2 Multi-channel Antenna/Receiver

The objective is to be able to monitor the background away from frequencies of transmitters. Ideally, the receiver should have a relatively wide bandwidth to improve the noise performance. Lightning and other broadband sources of EM interference are targeted.

3.1.5.2.1 Low Cost Broadband Receiver

Commercial receivers with narrow- and broad-band outputs will be used for the coverage of the proposed RF band. Four receivers will be used in parallel with the frequencies selected to be representative of quiet inter-signal bands.

- manufacturer: AOR
- model: AOR AR5000: $2000
  - frequency coverage: 10kHz to 2600MHz
  - bandwidths: 3, 6, 15, 30, 110, 220kHz, 10.7MHz
  - search and scan
  - SA7000 wide range antenna 30kHz-2GHz: $200 (for portable unit)
  - DA3000 Wide Band ‘Discone’ (25-2000MHz): $150 (roof)
  - dipole antenna DX-ULTRA 800’ (AlphaDelta): $120 (roof)
  - optional rackmount for two units RM500x2: $110
  - RS232 control
  - CDS-built baseband-to-arms converter

3.1.5.2.2 Implementation

Quantity: four per LVEA (fixed location) and one moveable/site: 5 in WA and 5 in LA

The four fixed units will be attached to one of the CDS DAQ racks, using the two-units rackmount. Those units will be connected to the roof antennas, using a fanout active low noise circuit. The moveable receiver with its antenna SA7000 will be implemented at a location to be monitored. This unit can work independently for quick evaluations of RF noises, or can be connected to the CDS ADCs and to a CDS port via RS232 for commands and data transfers.

3.1.6. Narrowband RF Receivers

3.1.7. Requirements

The narrowband RF receivers, placed near the dark ports of each IFOs, will be monitoring the RF signals in the LIGO modulation frequencies ranges. The present requirements are derived from the IO PDD (see 1.4.1.8). The output is in the form of the RMS level at the selected frequency in a 10 kHz BW and with 0.3 msec response time.

- Resonant Sideband Frequencies (modulation index $\Gamma = 0.47$ TBD):
  - 4km IFO: 24.493MHz
  - 2km IFO: 29.496MHz
- Nonresonant Sideband Frequencies (modulation index $\Gamma = 0.055$ TBD):
  - 4km IFO: 61.232MHz
  - 2km IFO: 68.800MHz
- Bandwidth for each frequency: less than 10kHz (TBD)

3.1.7.1 Narrowband RF Receiver and Antenna (Custom Made CDS)

To be built in-house. See CDS PEM DRD for details. The data are transferred to the CDS ADC via shielded twisted pair cable. (An alternative is to use commercial receivers as described above in 3.1.5.2.1.)

3.1.7.2 Implementation

Quantity: 2 in WA and 1 in LA to monitor the Resonant Sideband Frequencies only.

The antenna for the narrowband receiver will be attached to the optics table carrying the antisymmetric diode using standard optics mounts (near HAM 4 and 10 in WA and HAM 4 in LA). The receiver will be located on the ISC rack.

3.1.8. Charged Particle Detector

Preliminary calculations presented in PEM DRD (1.4.1.1), and subsequently continued (to be published), were focussed on the possibility to induce significant signals into the LIGO test masses, generated by secondary cosmic muons produced in high energy cosmic nuclei interactions with the atmosphere. The two possible ways to excite the test masses are via *ionization energy losses of bundles of muons* originated from the same primary interaction, or via *catastrophic energy release* (few mechanisms are possible) into the test masses. Those calculations were performed for the real size masses to be used in both the initial and advanced LIGO IFOs. They are based on very limited statistics of very high energy cosmic events, so the incertitudes in those calculations are quite big.

Calculations done for the initial LIGO showed that the probability to produce significant signals in test masses at both LIGO sites, due to ionization losses of bundles of muons, is negligible. Catastrophic energy losses which might affect individual test masses may occur at a rate less than 10,000 per year per site. But this is a more serious problem, because it can be accidentally in coincidence with other noises in the LIGO IFOs.

Due to the poor statistics available for high energy cosmic ray fluxes and possible accidental correlations with other noise sources, we choose (in consonance with the PEM-PDR review board, see 1.4.1.12) to implement the PEM with cosmic muon monitors.

3.1.8.1 Charged Particle Detector Requirements

- dynamic range: 1-10000 particles/slab of Scintillator:
- time resolution: better than 0.01 msec

3.1.8.2 Scintilator Detector and PMT Design Parameters

To be built in-house from standard components and designs:

- Scintillator (Bicron BC 412 or equivalent) sensitivity: min 50 Photoelectrons/cm for Minimum Ionizing Particles
- scintillator size: 50 x 50 x 2.5(or 1.25) cubic cm
- 4 x 2 inch Hamamatsu PMT model R3234-01 or equivalent, with base and magnetic shield
- 4 x custom made clear UVT lucite light guide from scintillator to PMTs
- the Scintillator, light guides and PMTs are mounted in a light-tight PVC box of dimensions 0.75 x 1.5 x 0.5 cubic meters
- range: 1-10000 particles/slab of Scintillator: propose two sets of PMTs driven at different gains (HV) in order to extend the dynamic range. The low gain PMTs can serve for the trigger.
- resolution: better than 0.01ms
- two LEDs (HP3000 or equivalent) will be mounted for calibration
- commercial 4 channels of charge/shaping amplifier, gain 1-100 (EG&G 4890 or equivalent separate charge preamp+shaping amp.). The analog signal after a charge preamp/shaping amplifier: max 10V compatible with the CDS ADCs
- NIM modules: LeCroy 821 discriminator, LeCroy Fan-in/Fan-out 429A, EG&G constant fraction discriminator, counter EG&G 770, NIM bin EG&G 4001A, LeCroy quad majority logic unit coincidence 365AL (Note: equivalent modules might be used as well).
- 2 channel of HV power supply 3kV, (EG&G 556 (NIM) or 556H or equivalent)
- estimated costs per detector: $10000

3.1.8.3 Implementation

Quantity: one per site.

The Scintillator and PMTs will be mounted into a light tight box (PVC box) which will be placed in the same stay-clear as the low-frequency seismometers and tiltmeters (see 3.1.1.4.2.5). Estimated box dimensions are (in cm): 150 x 75 x 50. The PVC box will be manufactured using the same technology used for MACRO Scintillator boxes.

3.1.9. Power Line Fluctuations

3.1.9.1 Technical Power Requirements

- 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.

3.1.9.2 FMCS Current monitors

The Civil-construction-installed current monitors will be integrated into the PEM system. This will be our source of continuous monitoring of the 60 Hz line for current and phase changes and low harmonic content.

At the present time, Parsons is implementing current sensors which will be able to provide a current signal of 0-100mA from sensors monitoring the HV lines. A request has been put in to deliver those signals to CDS for continuous sampling (nominal 600 Hz BW) and post-analysis for current consumption and harmonic content. This particular system will monitor mainly the power consumption of the LIGO laboratory by measuring the current at the high voltage line.

In addition, we propose to add 2-3 voltage/current monitors for the low voltage lines in each building, also to be acquired continuously by CDS (also nominal 600 Hz BW).

Quantity: one current-voltage pair for entire building, one for the chiller plant, one for utility buses

3.1.9.3 Power Line Monitor

3.1.9.3.1 Dranetz Handheld Power Analysis system

The unit can be programed to record only events occurred above a given threshold, which will reduce considerably the amount of data stored and transmitted to CDS. Its primary function is to detect and capture fast events (spikes).

- manufacturer/distributor: Dranetz
- model: Power Platform 4300
- 4 channels (three phases+neutral) monitoring
- RMS Voltage and RMS Current monitoring 2% accuracy
- frequency measurement
- spikes: max 300% full scale accuracy 10% for transients of 1microsec min.
- optional total harmonic distortion for voltage and current
- spectrum analysis
- price: $5000+ (depends on options)
- Electrical interface to CDS: via RS 232 optional adapter

3.1.9.4 Implementation

Quantity: 2 technical power monitors at WA and 1 at LA

Spares: none

- The power line monitor is a portable self-contained unit, with IEE488 or RS232 interface to the Data Acquisition system.

3.1.10. Residual Gas Monitor (RGA)

3.1.10.1 RGA Requirements

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

- sensitivity: measurement the pressure of the residual gas in the 4Km beam tubes: the sensitivity should be of the order of $10^{-14} torr$, 1-100 amu. This sensitivity of the system is intended be able to determine the contribution of gas bursts and other coherent residual gas fluctuations, leaks, etc. and to measure the composition of the residual gas.

- timing resolution on a single mass number $\Delta t_{res} \leq 10ms$. This is sufficient to stamp the time dependence of the pressure and bursts measurements.
- dynamic range: 10^9
- estimated data rate per RGA: 1x16 bit, 2048 sample rate on threshold crossing, 20Hz sample rate for continuous monitoring below threshold.
- availability requirement: one RGA head and controller per building required to be operational and in recent calibration.
- calibration: calibrated leaks to be installed with each RGA head

3.1.10.2 BALZERS RGA

- manufacturer/distributor: Balzers
- requirements: meets PEM DRD
- model: QMG 422-3 Quadrupole Mass Spectrometer
- Head assembly: QMA 430 vacuum annealed head + EP422 Ion Counter Preamp + QMH400-5 RF generator tuned to the QMA head: $35k
- Control Unit (controller): QMS422-C: $25k
- total RGA: $60k

3.1.10.3 Implementation

3.1.10.3.0.1 Quantity:

- RGA *head assemblies* installation: 9 in WA and 5 in LA (ports + 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.
- the "RGA cart" controller will consist of an independent movable "cart" which will have the RGA controller and a dedicated labtop. The data can be download to the nearest CDS port, as necessary.
- Spares: one head per site

The RGA consists of a sensor head and readout electronics. The readout electronics are self-contained rack mounted and will be mounted in roll-around carts for use with multiple heads in different places. The heads are mounted on existing ports of the Vacuum Equipment and the Beam Tube as described in the PEM ICD. Each isolatable volume (given in the PEM DRD) will carry an RGA. The RGA should in general be mounted as close as possible to contamination-sensitive optics, although not in direct line-of-sight. RGAs to be installed on existing ports on the Vacuum Equipment and Beam Tube; the Vacuum Equipment ports are to be identified by PSI nomenclature. Leaks and RGAs to be installed with metal valves allowing calibration without corruption of the Vacuum Equipment or Beam Tube by dead volumes or trace gases.

3.1.11. Vacuum Contamination Monitor

The requirements are listed in 3.2.1.9 and APPENDIX 1 of PEM DRD (1.4.1.1). The Contamination Monitor Final Design will be finalized at a later date, based on all information available at the time; a study of contamination is underway at the time of the Final Design Review. The baseline plan, in the event that no new information becomes available in the timely way, is described below.

3.1.11.1 Baseline Contamination Monitor Design *(PRELIMINARY)*

A monitor of deposited material, a 'crystal deposition monitor', will be placed with an RGA head on a port of each chamber carrying a core optic. The two instruments will be in an isolatable volume. The deposition monitor will be periodically polled to track any contamination. After some perceptible deposit is accumulated on the crystal monitor surface, the volume will be isolated and the deposition monitor will be heated to cause the contaminants to be outgassed. The RGA will analyze the outgassed material to determine its composition.

The following estimated costs are from the initial Cost Book PEM estimates (1.4.1.4) in 1994 dollars.

- manufacturer: Leybold model IC/4 PLUS or equivalent:
- crystal head assembly $3794
- electronics for crystal head: $9243
- RS 232 interface
- resolution 0.0058 Angstrom/Sec/Measurement
- maximum frequency 1.5MHZ

The Contamination Monitor Final Design is deferred to the second Final Design Review,

3.1.11.2 Implementation

Quantity:

- 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.
- one set of ***control electronics and PC*** per building, or 5 in WA and 3 in LA; intermittent data/control transfer to/from PC

The crystal head sensors are mounted on existing Vacuum Equipment ports, nearby RGA sensor heads (see 3.1.10.3), as per the PEM ICD document; their placement should be as close as possible to contamination-sensitive optics. The readout electronics are self-contained rack mounted and will be mounted in roll-around carts for use with multiple heads in different places.

3.1.12. Weather monitor

The thermometers and hygrometers are stand-alone sensors; the other weather sensors may be purchased with and with data converted by 'weather stations'. The instruments proposed below have sufficient provisions to monitor the weather parameters in a wide range. Since the PEM PDR we simplified the weather monitor system, by using fewer components and optimizing the weather station arrangements.

3.1.12.1 RH and Temperature Detectors

3.1.12.1.1 RH and Temperature transmitter (HX-93) for BT monitoring

- manufacturer/distributor: Omega
- model: HX 93

  - RH range and accuracy: 3-95%; ±2 %
  - Temperature range and accuracy: -20 to 75^0 C; ±0.6^0 C
  - Output 0-1VDC or 4-20 mA for each channel
  - RH temperature compensation
  - power requirements: unregulated 24 VDC
  - price: $210; calibration kit: $65 (not required for each transmitter)

3.1.12.1.2 Temperature Sensor and Transmitter (TX 92A-1) for outside T monitoring

- manufacturer/distributor: Omega
- model PRTXA-1 assembly ($189):
  - transmitter model: TX 92-1 with RTD probe ($99 if purchased without protection)
  - Resistance Temperature Detector (RTD) PR-12 probe 12” long
  - cast iron protection
  - T range and accuracy: $-40^o to 60^o C$; ±2 %
  - Output 0-1VDC or 4-20 mA
  - power requirements: unregulated 24 VDC
  - mounted to sense air temperature

3.1.12.2 Weather Stations

A ‘weather station’ will be used to convert the anemometer and precipitation monitor data to a convenient form. The other capabilities (temperature and RH IN and OUT) will be used as well.

3.1.12.2.1 Weather Station for buildings

- manufacturer/distributor: Cole Parmer
- model: GL-99800-20 indoor/outdoor monitoring system
- Sensors:

1. Indoor Temperature
   - range -40 to 127^o F
   - accuracy: ±1^o F
2. Outdoor Temperature
   - range -40 to 127^o F
   - accuracy: ±1^o F
3. Relative Humidity (in and out),
   - range 0-99%
   - accuracy: 3% at mid range
4. Wind (speed and direction): Anemometer
   - range: direction 0 - 360^0; speed 0 - 150 mph (or in kmh)
   - accuracy: direction ±5^0; speed better than ±2 %
5. Air Pressure (Barometer)
   - range: 28 to 32 in. Hg; selectable in mbar
   - accuracy: ±0.1 in.Hg
6. Rain fall
   - rain collector 99800-50(inch) or 51(mm)
   - range: daily up to 999.8mm, accumulated up to 9999mm
   - accuracy: ±2 %

7. Dew point
8. Wind chill.

- fulfill requirements
- RS 232 interface
- cost:
  - base unit: $395
  - rain collector: $75
  - outdoor T/RH/Dew-point sensor: $125
  - cables: $40
  - PC software: $165

3.1.12.3 Sensor Implementation

3.1.12.3.1 Quantity:

- •• Thermometers:

- one every 500m on one 2Km BTM: total 5 in WA. (HX 93)
- inside buildings temperature: 5 in WA and 3 in LA (part of C-P 20)
- outside temperature on four walls of building: 20 in WA + 12 in LA (TX 92A-1 temperature sensors)
- one/building external air temperature sensor 5 WA +3 LA (part of C-P 20)
- for BT thermometer implementation, see Hygrometers below
- spares: 5 TX 92A-1 per site

- •• Hygrometers (RH)/Thermometer Assemblies OMEGA HX 93

- one every 500m on one 2Km BTM: total 5 in WA.
- inside building humidity: 5 in WA and 3 in LA (part of C-P 20)
- outside humidity: 1 in WA and 1 in LA (part of C-P 20)
- cart: 5 per site

- •• Anemometers:

- one per building: 5 in WA and 3 in LA (part of C-P 20)

- •• Precipitation sensors:

- one per site: 1 in WA and 1 in LA (part of C-P 20 options)

- •• Barometers:

- one per building: 5 in WA and 3 in LA (built-in C-P 20)

3.1.12.3.2 Inside Buildings

The temperature and humidity sensors in the buildings are to be placed in the LVEA or VEA in places corresponding to the Facilities HVAC system zones, as indicated in the PEM ICD. They will be mounted to the walls of the facility on a bracket giving a suitable sample of air.

3.1.12.3.3 Outside Buildings

1. The thermometers which monitor the outside environment will be contained in protective enclosures to reduce the influence of sun and precipitation on the sensing element. Four TX 92

will be placed such that they take a representative sample of the temperature on the given building (LVEA/VEA) four exterior walls. The T sensor, part of the C-P 20 weather station, will be used for external air temperature monitoring.

2. The hygrometer will be placed with one of the external thermometers (part of the C-P 20).
3. The anemometer and precipitation sensors will be mounted on top of the LVEA building, at a point which will be representative of the free wind velocity on the surface of the building (the observation deck may be appropriate). They are parts of C-P 20 weather station.

3.1.12.3.4 Beam tube

The combined hygrometer-thermometer HX 93 will be attached to the bracket attached to the beam tube used for the triaxial accelerometer assembly and microphone (see 3.1.1.4.2).

3.1.12.3.5 Cart

The cart will have all the hardware and five HX 93 temperature/RH sensors.

3.1.12.4 Summary of the Weather Monitor Implementation

Table 2 shows THE implementation of the weather sensors and stations. Note that the C-P 20 unit

Table 1: Proposed Weather Sensors Configuration

Model	*Location*	*Total WA+LA*	*T Out*	*T In*	*RH Out*	*RH In*	*Wind*	*Press*	*Rain*	*Cart Spares*
C-P 20	Corner Bldg	1+1	1+1	1+1	1+1	1+1	1+1	1+1	1+1	
C-P 20	Mid, End Bldg	4+2	4+2	4+2	opt	4+2	4+2	4+2	opt	
HX-93	*WA BT*	*5+0*		*5+0*		*5+0*				5+5
TX92A	3/Bldg	20+12	20+12							5+5
Total	**Channels**	**:**	25+15	13+8	1+1	13+8	5+3	5+3	1+1	

comes with built-in pressure sensors, which explains why we have more than 1 barometer per site (see Mid and Corner Bldg).

3.1.13. Dust Monitoring

3.1.13.1 Requirements

- capable of measuring to class 1 (in a 10 minute time period, 0.3 micron particles).
- remote data collection

3.1.13.2 Dust Particle Detectors for Fixed Clean Rooms

- Met One Model 227B: $3150
- Particle size min 0.3 microns

- storage capability
- Power: DC 6-10V or AC adapter
- sample/hold time: 1sec to 24 hours
- RS 232/485 interface

3.1.13.3 Implementation

Quantity:

- 1 per OSB optics lab (fixed cleanroom corner station) (1WA and 1 in LA)
- 1 per OSB Vacuum Equip. Preparation room (fixed, corner station) (1WA + 1LA)
- 2 per LVEA at corner station(2 in WA and 2 in LA)
- 1 per VEA mid and end stations (4 in WA and 2 in LA)
- 1 per Mid & End-Station optics lab (4 in WA and 2 in LA)
- 1 per portable cleanroom (3 corner+2 mid+2 end=7 in WA, 3+1=4 in LA)
- 1 per PSL/IOO (2WA + 1LA)
- spares: none (units can be used interchangeably)

All dust particle monitors will be potentially portable. All will be mounted with Velcro or equivalent and use flexible cabling.

3.1.13.3.1 Clean Rooms

The sensors associated with the temporary clean rooms will be attached to the interior of the clean room frame when the clean rooms are implemented; they will be attached to nearby Vacuum Equipment external chamber walls when the clean rooms are not installed. In the permanent clean rooms, there will be a standard placement on a wall using Velcro; a flexible cable will allow implementation elsewhere in the room.

3.1.13.3.1.1 OSB Optics Labs and Vacuum Equipment Preparation Rooms

Exact locations of the dust monitors will be determined after these rooms are completed.

3.1.13.3.1.2 Portable Clean Rooms

Exact locations of the dust monitors will be determined after these rooms are completed.

3.1.13.3.2 LVEA and VEA

Sensors will be mounted on rack 1Y10 and 2Y1 of the LVEA. For the VEA locations, refer to CDS.

3.1.13.3.3 PSL

The sensor associated with the PSL will be mounted close to the output optics, inside and on the structure forming the walls of the dust/beam cover for the optical table. See “PEM Sensor Locations at WA site: D970210” on page 36 and "PEM Sensor Locations at LA site: D970298".

3.2. PEM Excitation System Final Design

NOTE: All the excitation systems are part of the PEM moveable carts and not permanently installed.

3.2.1. Seismic Excitation System

3.2.1.1 PZT Excitation System *(PRELIMINARY)*

The PZT 'shaker' will be built in-house. A multi-layer PZT stack is firmly attached to the object to be shaken at one end (e.g., the seismic support beam) and to a reaction (proof) mass on the other end (of 1 kg order of magnitude). The size of the shaker will be order of 10x10x10 cm. Piezo shakers are called out for normal use near the TMs due to the test mass magnetic field sensitivity.

- •• PZT shaker table

- Manufacturer: Piezo Systems Inc.
- table top diameter: 3.0 inch OD
- 1/4-28 tapped holes on base plate and table top
- Input 30VDC
- frequency range: DC to 200Hz
- weight 5 lbs.
- max AC voltage: 15Vrms
- axial deflection/no load: 0.22µm(rms)/Vrms
- max displacement with 150lb load: 4.5µm(rms) at 15Vrms
- price $4500

- •• Shake Table Driver (compatible with the general purpose generator (3.2.5.)

- Manufacturer: Piezo Systems Inc.
- AC power: 115V, 60Hz
- Freq. Range 0-200Hz
- max input $\pm 10V$
- output: 30VDC and 0-15Vrms(AC) and 2A maximum
- Price $3250
- The signal source could be either a general purpose oscillator (3.2.5.) or the CDS DAQ/Diagnostics system.
- ***Note: Due to the high cost, we are looking into the possibility to manufacture a custom made driver in-house***

- •• Quantity:

- 12 WA, 12 LA 'shakers' and their drivers
- spares: none

3.2.1.2 Electromagnetic Excitation System

To allow larger forces at low frequencies, a limited number of electromagnetic shakers will be available.

- •• B&K Vibration Exciter 4809

  - Force rating 45 Newton (10lbf) sine peak
  - Freq. Range 10Hz - 20kHz
  - weight 8.3kg
  - Fastening Threads: 4x5/16" for M5 base and 10-32UNF inserts(1).

  - Driver: Power Amp B&K 2706 (75VA; max 5A)
  - Price Shaker $4532, Driver: $3487
  - Quantity: 4 WA, 4 LA
- signal generators shared with other excitation systems (3.2.5.)

3.2.1.3 Implementation

The PZT shaker will be housed in a box with through holes, to be attached as needed to the seismic support beam (via tapped holes, using the PEM mounting plate type I, See "PEM PZT Excitation System (plate type I w/PZT): D970281" on page 36) or other object to be shaken.

The electromagnetic shaker/PEM Mounting Plate type III assembly will be attached to the object to be shaken using through and/or tapped holes in the mounting plate and jigs as needed. See "PEM ElectroMagnetic Excitation System (plate type III): TBD" on page 36.

3.2.2. Acoustic Noise Generator

3.2.2.1 Acoustic Noise generator (one system/cart)

- One BOSE Satellite System (subwoofer and two tweeters 16Hz-20kHz) $1000
- one or several portable localized sources of sound, like 'tweeters' and sound guns
- one pulse generator shared with the mechanical excitation system 3.2.5.
- wideband audio amplifier Carver or similar ($1000)

3.2.2.2 Implementation

Quantity:

- one per site for the PEM carts
- spares: none

The loudspeakers will be purchased with a stand which will allow placement at heights up to 1.5m and placed close to sensitive elements. Small sealed speakers (<20x20x20 cm) will be used. The localized sources of sound will be built in-house, and will consist of electromagnetic or piezoelectric tweeters and squawkers built into hermetic boxes with a well defined point for sound to be emitted.

3.2.3. Magnetic Field Generator *(PRELIMINARY)*

3.2.3.1 Custom Made Magnetic Exciter

  - Design Philosophy

Final design parameters for a coil mounted near the TM VE chambers, having the coil axis pointed to the TM, can be derived from the following formula:

$$B = \frac{\mu_0 \mu}{2\pi(R^2 + x^2)^{3/2}} \quad \text{where}$$

B is the magnetic field at the test mass location
$\mu_0 = 4\pi \times 10^{-7}$ is the permeability of the free space in units of Tesla Meters/Amps
$\mu = NIA = NI\pi R^2$ = dipole moment of the coil equivalent magnetic dipole
I= current in the coil
N= turns in the coil
R= Coil Radius
x = distance between the coil center and the test mass (x is perpendicular to the coil plane)

If $x \gg R$, then $$B \approx \frac{\mu_0 \mu}{2\pi x^3}$$

So, a simple coil can create magnetic field with an intensity inverse proportional with the cube of the axial distance from the coil center to the test mass. As for example, we will list bellow the magnetic excitation system design parameters for a two coil configuration to be mounted at about 2 meters from the test mass position:

- Small Coil Parameters

- R = 0.1 m
- x = 2.0 m
- N = 5 turns of insulated Cu $1mm^2$
- mounted coil dimensions: ring diam IO=0.17m, OD=0.25m, length=0.10m
- B range: $10^{-12} < B < 10^{-9}$ T for a current $10^{-3} < I < 1$ A

- Large Coil Parameters

- R = 0.5 m
- x = 2.0 m
- N = 51 turns urns of insulated Cu $1mm^2$
- mounted coil dimensions: ring diam IO=0.9m, OD=1.1m, length=0.30m
- B range: $10^{-9} < B < 10^{-5}$ T for a current $10^{-3} < I < 10$ A

- Current Supply:

- audio amplifier (used in common with shakers and loudspeakers); or direct drive from function generator

3.2.3.2 Implementation

Quantity:

- One per cart
- spares: none

The radiating coil will be supported by an aluminum stand of adjustable height, allowing placement at the height of a sensitive component (e.g., test mass) and close to the Vacuum Equipment chamber in question.

3.2.3.3 Calibration of the Magnetic Field at the test masses location

The B-field in proximity of the test masses and induced from by the magnetic exciter (3.2.3.1) can not be directly deduced from the measurement of the field external to the TM chambers. Prior to the installation of the test masses, we are proposing to calibrate the magnetic field gradients at the test masses locations by using the following equipment:

- Magnetic exciter, mounted at about 2m from the test mass location
- One magnetometer mounted at about 2m from the coil plane, outside the TM tanks
- One magnetometer probe mounted at the TM location inside the tank.

The test mass location will be mapped using several source positions and strength of the magnetic field. The residual magnetic field inside the tanks will be also studied.

3.2.4. RF generator

3.2.4.1 RF generator

3.2.4.1.1 HP Model HP ESG 1000A

- freq. range 0.25-1000MHz
- output level +13 to -137dBm
- amplitude and frequency modulation
- base unit $7000
- matched antenna HP 11966x: $2500-5000 (or shared with the Broadband RF receivers, see 3.1.5.2)

3.2.4.2 Implementation

Quantity:

- one per site: portable unit or part of the PEM cart

The antenna will be purchased with a stand which allows convenient placement. The RF generator and amplifier are rack-mounted in the PEM Cart.

3.2.5. General Purpose Signal Generators

3.2.5.1 Stanford Research Systems Signal Generator

- Model SRS DS 335:
- Quantity: 3 pieces at WA and 3 at LA
    - multiple wave shapes
    - maximum frequency: 3.1 MHz for sine and square pulses
    - GPIB and RS 232 interfaces
    - Output amplitude: 0.05 - 10V into 50 Ohms
- This generator will be used for
    - the PZT Excitation System (3.2.1.1)
    - the electromagnetic excitation system (3.2.1.2)
    - as part of the Acoustic Noise Generator (3.2.2.1)
- Price
    - Function Generator: $995
    - RS232 and GPIB: $395
    - Double or Single Rackmout: $85

3.2.5.2 Implementation

Quantity

- 3 per site: portable units, part of the PEM or PEM/DAQ cart as needed
- spares: none

3.3. PEM Carts

The PEM carts carry the moveable parts of the PEM system. In general, these moveable elements are to be used for temporary measurements/evaluations of various LIGO subsystems. The carts carry all the PEM excitation systems as well as a variety of sensors. In the previous sections, we presented the sensors and the excitation systems which will be part of the PEM carts. Here, we will summarize the different type of PEM carts, their equipment and purpose.

In general, all PEM carts will have provision to be connected to the PEM DAQ cart and/or directly to the CDS backbone at any point in the vicinity of the Vacuum Equipment in any of the buildings. The carts may be operated manually without connection to the CDS backbone if data to/from the CDS backbone is not needed (e.g., a signal generator, amplifier, and shaker can be used stand-alone).

The PEM carts will have wheels, and hooks for crane attachment.

3.3.1. PEM DAQ cart

The base of the PEM DAQ cart includes a standard 19 inch rack mount. The equipment is of general use with various PEM cart subsystems. See “PEM DAQ Cart layout D970293” on page 36.

3.3.1.1 19 inch Rack

- manufacturer: Knurr
- model number: MR 18336
- price: $1098 Rack only

3.3.1.2 VME crate

- CPU unit
- Hard Disk (CDS)
- ADC/DAC
- RS 232 or RS 485 or GPIB interfaces
- Timing as needed
- laptop PC for display and independent control
- estimated CDS price $70000

3.3.1.3 Other electronics permanently mounted on the DAQ Cart

- DC power suppliers (3)
- Signal Generators (3)
- Signal conditioner for accelerometers (16 channels)
- 3 x (1 to 4) Fan-Out (BNC): 4 outputs for each of the 3 inputs (CDS or commercial)
- AC Power strip

- Storage space
- small tools, components, cables, fixtures, etc.
- Cables
  - cables for ADC/DAC
  - cables for the PEM DAQ cart and for the CDS ports
- estimated price without signal generators (counted separately): $3000

3.3.2. PEM Instrumentation Cart

This cart will be instrumented with one or more excitation subsystems, as needed. The excitation systems may be driven manually or remotely, using the CDS ports. Some of the excitation systems requires additional sensors, as listed bellow.

3.3.2.1 Permanent equipment

- Storage (cabinets/drawers) for minor equipment, tools and cables.
- Set of tools, cables and minor equipment
- Built in light
- Rechargeable flashlight
- AC extension cords
- Work table and chair
- Table for moveable equipment (such as the electronics or signal conditioners)
- estimated price $2000
- tie-down straps to hold equipment in place

3.3.2.2 Temporary Equipment

3.3.2.2.1 Seismic Excitation

3.3.2.2.1.1 PZT Excitation System

- PZT shakers (12)
- Signal drivers for PZT tables
- 15 cables for driver out to shaker input
- 15 cables for Fan-Out to driver input: BNC both ends
- 4 cables from the signal generators to fanout (BNC)
- 5 spare BNC cables

Note: The PEM mount plates of the PZT shaker (type I) are permanently mounted on the tanks.

3.3.2.2.1.2 Electromagnetic Excitation System

- Vibration Exciter (electromagnetic shaker: 4)
- signal drivers for the electromagnetic shaker (4)
- PEM mount plates of type II (for the electromagnetic shakers: 4)
- 5 cables for driver out to shaker input
- 4 cables for Fan-Out or signal generator to driver input: BNC both ends
- mounting plates for the Electromagnetic Shakers (type III)

3.3.2.2.1.3 Seismic Sensors: Accelerometers

- 3 triaxial mount accelerometers (3x3)
- 15 cables for accelerometer (10-32)-signal conditioner BNC connection

3.3.2.2.1.4 Example of Seismic Excitation System Implementation

Figure1 shows the implementation of the mechanical excitation system, using the PEM DAQ cart

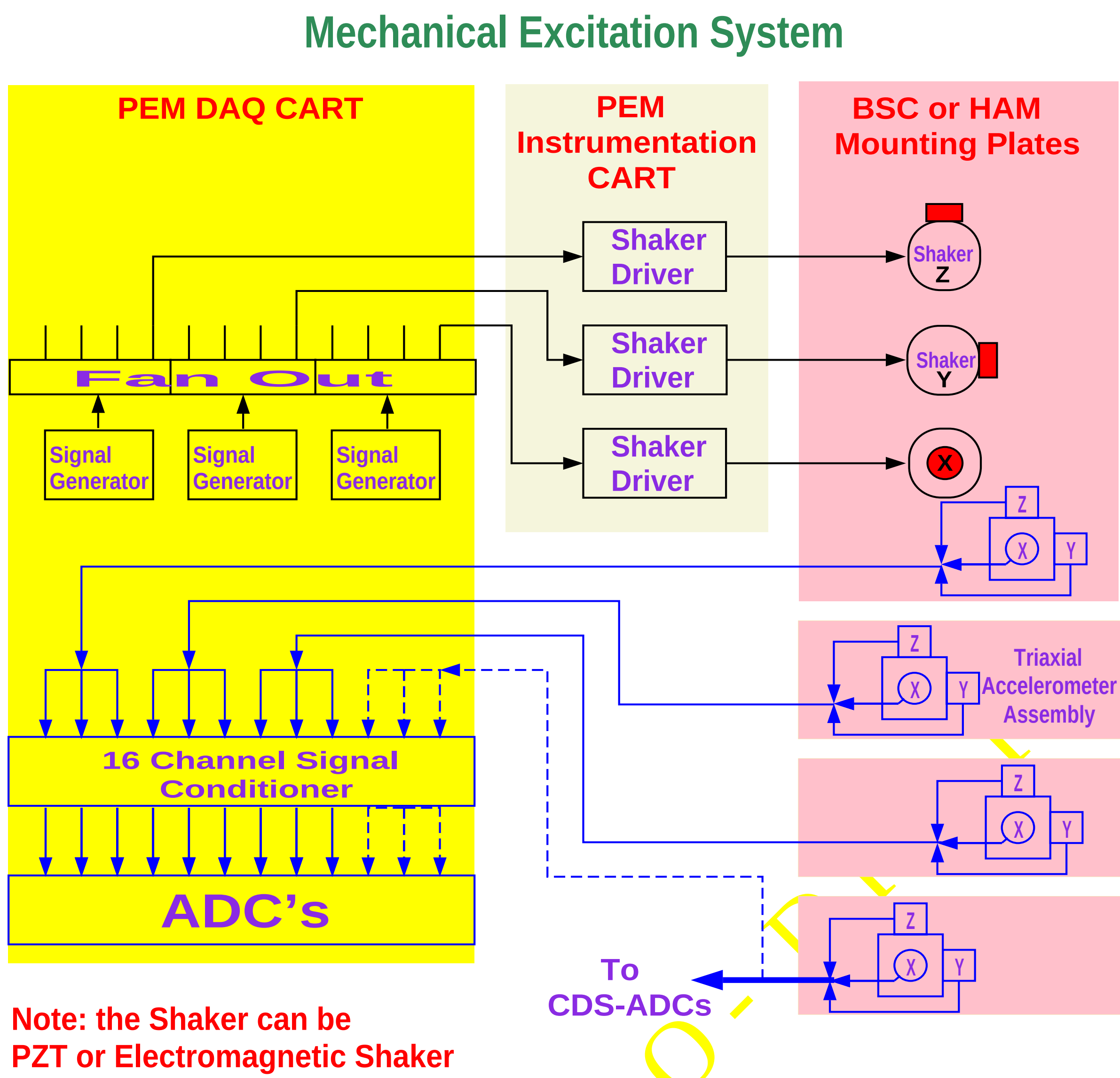

Figure 1: Implementation of the Mechanical Excitation System

and the PEM Instrumentation cart. The example shown is for the case when one tank is excited using three PZT or Electromagnetic Shakers, and a complete set of triaxial accelerometers (three from the PEM cart and one permanently mounted and connected to the main CDS DAQ). The three signal generators and the three 1:4 FanOuts offers a variety of scenarios for tanks excitations.

3.3.2.2.2 Acoustic Excitation System

- microphones with preamplifier and power supply
- signal amplifier
- loudspeakers
- stands for microphones
- cables

3.3.2.2.2.1 Example of Implementation of the Acoustic Excitation System

Figure2 shows the Acoustic Excitation system with an additional Acoustic Sensor using the PEM

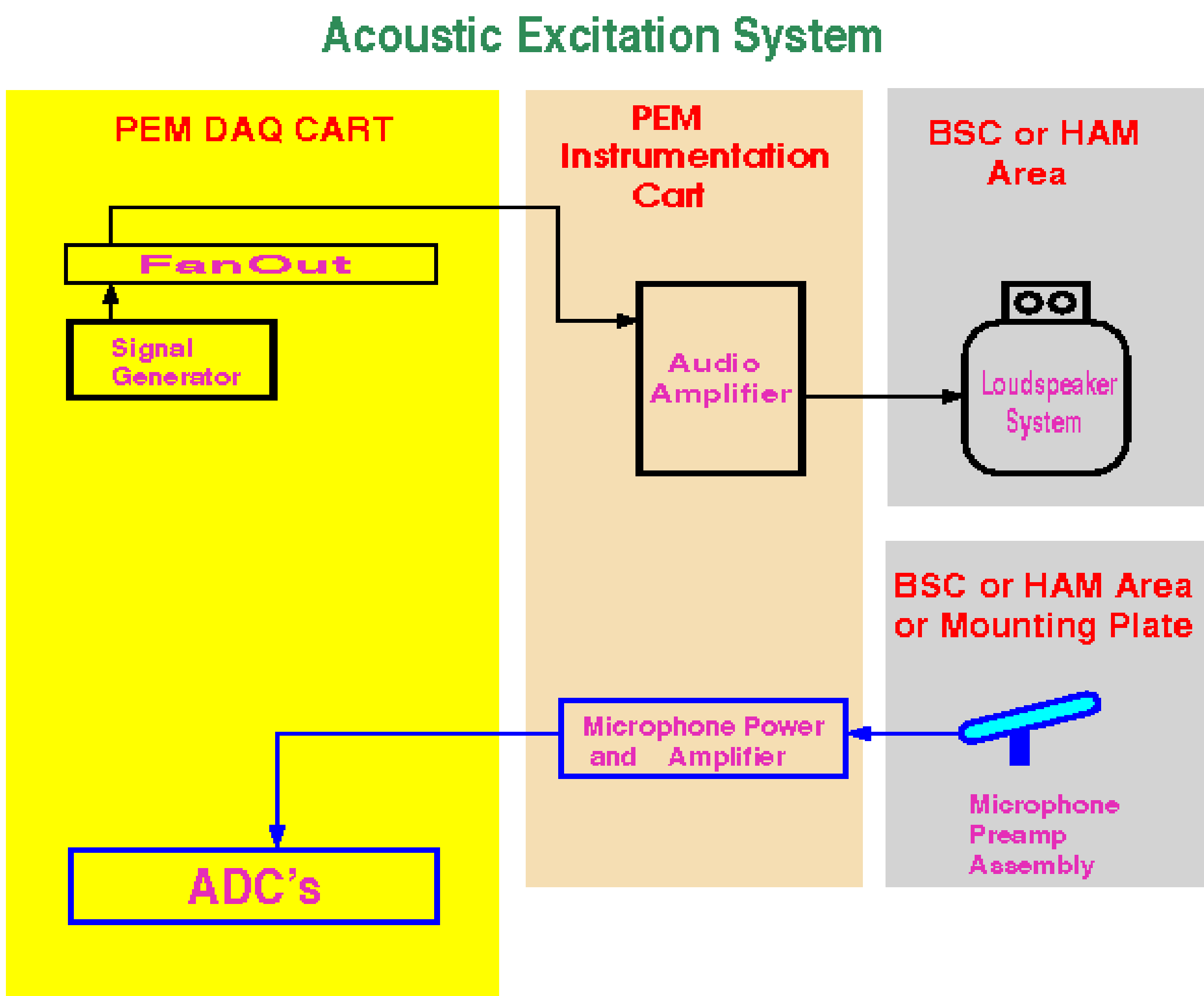

Figure 2: Acoustic Excitation System Implementation

DAQ cart and the PEM Instrumentation Cart. The loudspeaker system can be placed on its stands, near the tank area, while the acoustic microphone may be mounted on its stand-alone support, or on the PEM plates attached to the tanks.

3.3.2.2.3 Magnetic Excitation System

- Custom made excitation coil
- signal source and amplifier
- stand with adjusting screw for precise positioning of the coils
- signal conditioner/interface to PEM DAQ cart and CDS port
- cables

3.3.2.2.3.1 Example of Implementation of the Magnetic Excitation System

The custom made excitation coils will be mounted near the TM tanks oriented to supply force in the desired direction. The triaxial Bartington Magnetometers (permanent mounted or the cart magnetometer) and the custom made sensitive coil will be used to monitor the magnetic field during those tests. The excitation coil can be driven with DC or AC using a signal generator. Figure 3

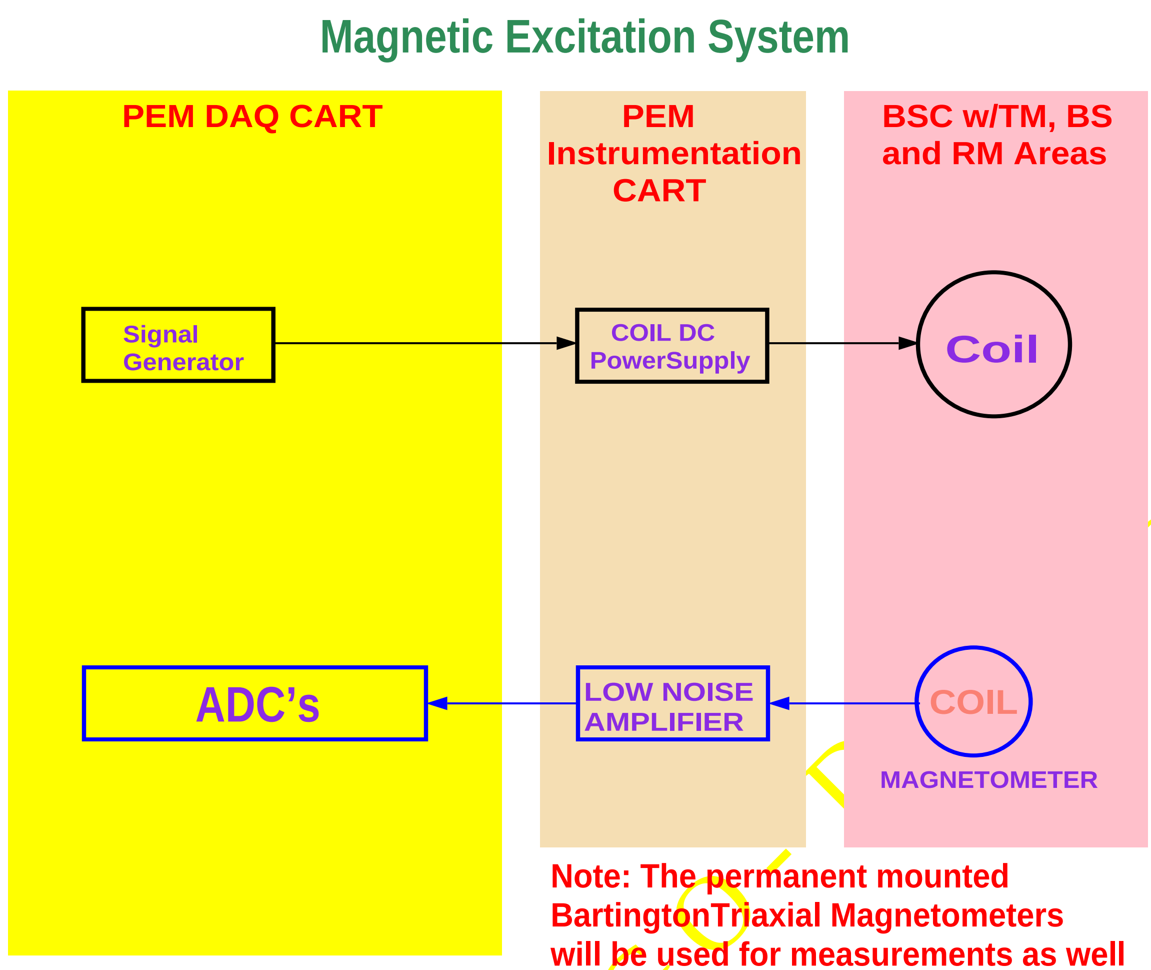

Figure 3: Implementation of the Magnetic Excitation System

shows the propose implementation of the magnetic excitation system.

3.3.2.2.4 Other sensors and miscellaneous equipment as needed

- Custom Made Sensitive Coil (movable sensor+stand and signal conditioner)
- Bartington Triaxial Magnetometer (transducer + cable + power supply)
- temperature/RH sensors HX 93
- cables for various sensors or excitation systems
- connectors
- tools
- oscilloscope
- extension cord
- hardware for excitation system mounting (screws, bolts, etc.)

3.3.3. RGA cart

This is a dedicated cart for RGA measurements. It can be moved at the RGA head locations as needed. It requires AC 117V and an CDS port. See “PEM RGA Cart Layout: D970294” on page 36.

- Equipment
  - RGA controller
  - labtop
  - cables and miscellaneous small tools
  - work table and chair
  - light
  - estimated price $3500 without the RGA controller

3.4. PEM Storage Space for Carts and Portable equipment

At each site, it is required to have a dedicated place to store the carts, their permanent and moveable equipment as well as the moveable PEM subsystems (such as the RF receiver and its hardware), and the spares of the PEM subsystems. The storage location should permit the PEM carts to be configured with the desired instruments and sensors.

A 12’ x 15’ section is set aside at each corner station. It will contain one cabinet 20” x’ 40” X 72”, and 20” x 40” desk, a chair and the PEM carts. See “PEM Sensor Locations at WA site: D970210” on page 36 and "PEM Sensor Locations at LA site: D970298".

3.5. PEM Mounting Plates

PEM mounting plates are designed to interface some of the sensing equipment and excitation systems with the LIGO detector. There will be at least two types of mounting plates, to accommodate various configurations and mounting procedures.

We give below full list of sensors and excitation systems for which the mounting plates have provisions. In general, only a part of the sensors and/or excitation systems will be mounted simultaneously, in order to perform dedicated tests.

3.5.1. HAM and BSC mounting plate (type I)

See "PEM Sensors Assembly BSC and HAM (Plate type I): D970271" on page 36 and See "PEM PZT Excitation System (plate type I w/PZT): D970281" on page 36: $750/piece

3.5.1.1 Sensors:

- One Triaxial Accelerometer Mounting block (two possible locations)
- One Acoustic microphone (two locations)
- Provision for Thermometer or RH or Thermometer/RH combination sensors in two locations, not implemented with sensors at the present time. These locations might be used to mount the cart contingent of temperature/RH sensors on the tanks.

3.5.1.2 Excitation Equipment

- Emplacements for three orthogonally-oriented PZT Shakers

3.5.1.3 Implementation

The implementation of the Type I plate follows the accelerometer implementation schedule (see and 3.1.1.4.2.4). As discussed in section 3.2., for some tests we will want to have shakers in all the 4 corners of the tanks. Using 12 PZT shakers, the permanent PEM mounting plate type I and three additional PEM mounting plates type I (from the PEM cart inventory) we can perform tests with all degrees of freedom driven and monitored.

- Permanent Mounting plates: WA 24 x 4, LA 12 x 4
- Plates for the PEM cart: WA 4, LA 4

3.5.2. BTM Mounting Plate (type II)

See "BT Sensors Assembly (plate type II): D970273" on page 36: $300/piece

3.5.2.1 Sensors:

- One Triaxial Accelerometer Mounting block (See "Triaxial Accelerometer Mounting Block: D970274" on page 36)
- One acoustic microphone
- One Thermometer/RH combination sensor

3.5.2.2 Implementation

One 2-km WA BTM is scheduled to receive sensors (see 3.1.1.4.2.5). The mounting plate type III will be attached to the BT reinforcement rings, using clamps. The cart plate can be used to mount sensors at any other BT location.

- Five for WA
- One per cart WA 1, LA 1

3.5.3. HAM and BSC mounting plate (type III)

See "PEM ElectroMagnetic Excitation System (plate type III): TBD" on page 36: $300/piece

3.5.3.1 Sensors:

- Four Triaxial Accelerometer Mounting blocks (See "Triaxial Accelerometer Mounting Block: D970274" on page 36)
- Two acoustic microphones

3.5.3.2 Excitation Equipment

- Electromagnetic Shakers in any one of three orthogonal orientations.

3.5.3.3 Implementation

The Type III plates will be mounted whenever an electromagnetic excitation program will be planned. It will not have permanent mounted plates on the tanks, and all the supply of type III plates will be kept together with the electromagnetic excitation system (see and 3.1.1.4.2.4).

- Plates for the PEM cart: WA 3, LA 3

3.6. List of Drawings

This is a summary of the mechanical drawings for the mechanical interfaces of the PEM (see 1.4.1.10)

3.6.1. PEM Sensor Locations at WA site: D970210

3.6.2. PEM Sensor Locations at LA site: D970298

3.6.3. PEM Stay Clear Zone Instrumentation, Corner Station: D970287

3.6.4. PEM Stay Clear Zone Instrumentation, Mid and End Stations: D970286

3.6.5. Microphone Assembly for PSL: D970292

3.6.6. PEM Sensors Assembly BSC and HAM (Plate type I): D970271

3.6.7. Triaxial Accelerometer Mounting Block: D970274

3.6.8. BT Sensors Assembly (plate type II): D970273

3.6.9. Magnetometer Mounting Assembly: D970282

3.6.10. PEM PZT Excitation System (plate type I w/PZT): D970281

3.6.11. PEM ElectroMagnetic Excitation System (plate type III): *TBD*

3.6.12. Remote Magnetometer Sensor Box: D970295

3.6.13. PEM DAQ Cart layout D970293

3.6.14. PEM Instrumentation Cart Layout: D970299

3.6.15. PEM RGA Cart Layout: D970294

APPENDIX 1 SUMMARY TABLES

Table 2: Initial PEM System characteristics and estimated costs. (For carts see table 3)

	Detector	*Sensitivity*	*Range*	*Nr WA LA*	*Cost (k$) Unit*	*Total*
Seismic Noise	3 axis seismometer	10^{-10} m @1Hz	1 - 10Hz	1/bldg: 5 + 3	14	112
	2 axis tiltmeter	10^{-9} rad@1Hz	1 - 10Hz	1/bldg: 5 + 3	10	80
	1 axis accelerometer	10^{-11} m @100Hz	10Hz-800 Hz	see3.1.1.4.2.1 99+36	1.1	149
Acoustic Noise	B&K Micro-phone	2×10^{-9} atm. @100Hz	6.5 -8kHz	see 3.1.2.2.2.1 29+12	1.5	62
Magnetic Field	3 axis magnetometer	10^{-11} T @100Hz	DC - 4.5kHz	see 3.1.3.2.2.1 7 + 1	6.5 with DAQ	52
Thunderstorm Monitor	Thunderstorm satelite service			1+0 RS232	28 first year 18/year	
RF Interference	Broadband Receivers	0.01mV/m	10kHz to 1.3GHz	1/bldg 4 + 4	2.5	20
RF Interference TBD	Narrowband Receiver (CDS)	0.01mV/m	TBD 25-35MHz	1/dark port 2 + 1	2.5	8
Cosmic Muons	Scintilator Detector	$\frac{10^{-6} \cdot \mu}{s \cdot m^2}$	100Mev 1ms res.	1 / site 1 + 1	10	20
Power Line	Line Monitor	see 3.1.9.	up to 2kHz	2 + 1	6.	18
Residual Gas	RGA Head RGA controller	$P \leq 10^{-14}$ torr	1-100 amu	9 + 5 6 + 4	35 25	490 250
Contamination TBD	Crystal Head controller	monolayer/ week	see 3.1.11.	8 + 5 5 + 3	4 10	52 80
Weather Moni-tor	Weather Station T and T/RH	see 3.1.12.	see 3.1.12.	5+3 (RS232) 25 + 12	0.8 0.24	7 9
Dust Monitor	Dust Part. Det.	see 3.1.13.1	see 3.1.13.1	21+13 (RS 232)	3.2	109
TOTAL	**COST**	**for full**	**PEM**	**(no carts)**		**1546**
Other costs:	**Mechanical:**	**plates ($140k)**	**carts, etc (24k)**	**(without CDS)**		**164**
TOTAL	**COST**	**for full**	**PEM with**	**carts**		**2370**

CDS costs for various custom made components are not included. The unit prices include signal conditioner and/or power suppliers if needed.

Table 3 present the PEM cart components, characteristics and estimated cost. The cart estimated cost does not include the optional batteries. Note that some components from the carts require

Table 3: The PEM Carts instrumentation (one per site).

	Equipment	*Sensitivity*	*Range*	*Chan (units)*	*Unit Total (k$)*
	Sensing	**equipment**	**for**	**carts**	
Seismic Noise	3x3 axis accel-erometer	$10^{-11} m$ @100Hz	10 - 800 Hz	9	1.1 10
Acoustic Noise	Electret Micro-phones	$2 \cdot 10^{-9} atm$ @100Hz	~1kHz	2	1.2 3
Magnetic Field	3 axis magne-tometer	$10^{-11} T$ @100Hz	DC - 1kHz	3 (1)	6 6
	Custom Made magnetometer	$\sim 10^{-14}$ T @100Hz	DC - 4.5kHz	3 see 3.1.3.2.4	3 3
RF Interference	Broadband RF Receiver	0.01mV/m	10kHz to 1.3GHz	1 RS232	2.5 3
Contam +RGA	Contr.head control RGA	$P \le 10^{-14}$ torr	1-100 amu	1 RS232	50 50 TBD
Weather Mon	T and RH	see text	see text	10 (5)	0.2 1
	Excitation	**equipment**	**for**	**carts**	
Signal Generator	SRS DS 335	SRS	3.1MHz	3 (3) RS232	1.5 5
Seismic Noise	PZT shakers	PIEZO	<200Hz	NONE (12)	8(TBD) 96
	E-M Shaker	B&K 52N	10hz-20kHz	NONE (3)	8(TBD) 32
Acoustic Noise	Loudspeaker	Generator	20-1000Hz	NONE (1)	2 2
Magnetic Field	Custom design	coils	DC-1kHz	NONE (1)	2 TBD 2
RF noise	RF Generator	HP+antenna	< 1.3GHz	1 (1) RS 232	13 13
DAQ cart: TOTAL	parts and	components,	DAQ/CDS	(estimated)	90
Other carts, TOTAL	tools, parts and	miscellaneous		(estimated)	14
TOTAL	**COST**	**per**	**CART,**	**per site:**	**330**

more definitions or decisions for CDS custom made components, which might reduce the costs.