Physics (Environmental) Monitor

Agenda/Organization of presentations

- Scope and 'Philosophy' (D. Shoemaker)
- Physical environment (A. Marin)
- Requirements and Conceptual Design (A. Marin)

A note on names:

- in Cost Book, 'Physics Monitor'
- habitual three letter acronym: PEM

PEM Functions

Functions:
- improve detection confidence by supplying veto information
- allow correlation/regression with disturbances to improve net S/N
- to provide diagnostic information for the initial commissioning and shakedown
- to aid the design of enhancements

Means:
- measurement of disturbances in the physical environment
- characterization of the coupling from disturbance to interferometer output
- (proposal:) supply sources of excitation to aid in characterization

Top-level requirements

The PEM should monitor and record the physical environment with:

sensitivity sufficient to measure the natural background
- covers all interferometers to be installed in lifetime of LIGO

bandwidth over range where influence on interferometer is anticipated
- GW signal range (30 Hz—10 kHz)
- low frequencies where upconversion or actuator dynamic range an issue
- radio frequencies where downconversion or saturation an issue

timing resolution sufficient to allow regression/correlation with GW signals
- for most signals with a direct correlation to interferometer: 10 μsec
- other timing as appropriate

sufficient completeness to give confidence in detection
- no probable path from environment to IFO left un-monitored

Approaches to implementation

'All probable paths':
- have some clear models for coupling (seismic noise)
- certainty of coupling at some level (beam tube excitation)
- feeling that a record should exist (temperature)

Possible partial implementations

-goal: save money and effort

-risk: insufficient confidence in apparent GW data

- start with one accelerometer, one microphone, etc.
  -model for work on prototype interferometers
  -measure couplings and develop monitors as needed
- select some aspects with known couplings for implementation
  -complete seismic noise sensing, e.g.,
  -others as need is perceived

Approaches to implementation cont.

- complete implementation on a one (WA 4km) interferometer
  - -recommended approach,
  - -allows commissioning and initial diagnostics with the most information
- portable instrument cart as further aid
  - -possible reduction/delay/scaling in BT wiring
  - -with independent power and data recording, can proceed CDS
  - -may be exploited more fully than in present documentation

Recommend full data acquisition backbone for all implementation plans.

- avoid disruption of observing if more complete system mandated

Interfaces

Interfaces to other interferometer subsystems
- wish to have confidence that there is no mixing of PEM and IFO signals
- thus, minimal signal interface

Interaction with other LIGO systems
- shadow the Facilities Monitoring/Control measurement system
- take over VacEq and BT monitoring after PSI and CBI finish installation

Data Acquisition
- instruments primarily with analog outputs (some configurable with digital)
- work with CDS to interface
- use DAQ backbone

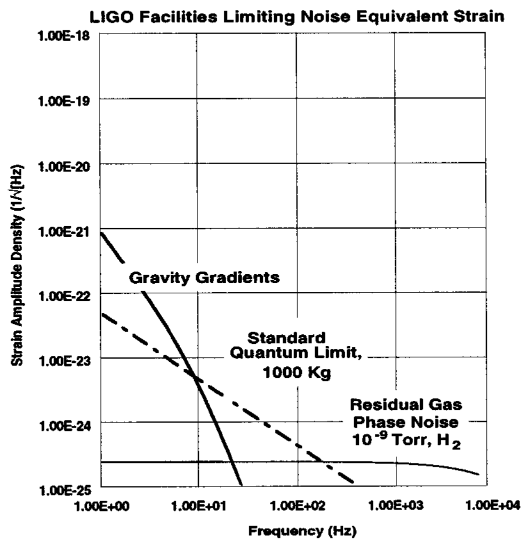
PEM for LIGO Ultimate Detector

››The anticipated detector performance as limited by facilities:

(from SRD)

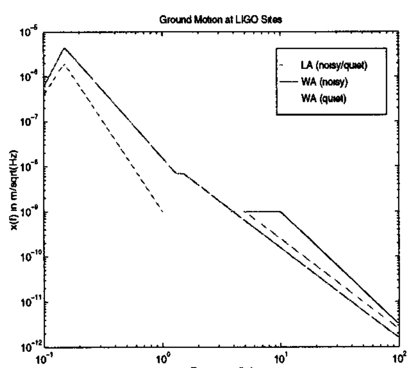
x(10 kHz) = 1.5 x 10^{-22} m / $Hz^{1/2}$

x(100 Hz) = 4.0 x 10^{-22} m / $Hz^{1/2}$



Seismic Noise

LIGO Standard Spectrum



Ground Noise at LIGO sites

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

$x(f) < 10^{-9} m/\sqrt{Hz}$ for $1 Hz \le f \le 10 Hz$

$x(f) < 10^{-7}[f/(Hz)]^{-2} m/\sqrt{Hz}$ above $10\ Hz$

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

›› Low Frequency 3 Axis Seismometer Requirements

- sensitivity: $x(f) \le 3 \times 10^{-10} / f^2 [m/\sqrt{Hz}]$
- minimum signal level: $a < 10^{-10} g$
- dynamic range 100 dB
- frequency range DC to 10 Hz
- estimated data rate per seismometer: 3x16 bit, 256 Hz sample rate
- one per building: 5 in WA and 3 in LA

—***GURALP CMG-40T Seismometer***

- standard velocity output: 800V/m/s
- optional high gain output: 8000V/m/s
- signal level: $a < 10^{-10} g$
- maximum optional frequency range: 0.008 to 50 Hz
- peak output: max 10V
- power requirements: 12V 60mA
- unit price $7930 in quantity of 8 without digitizer (no power supply)
- optional CMG-40T breakout box $683 in quantity of 8
- optional CMG-40T handheld control unit $896 in quantity of 8
- unit price with optional digitizer and software $13194 (no power supply)

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

››Low Frequency 2 Axis tiltmeter Requirements

- sensitivity: $\theta(f) \le (2 \times 10^{-9} / f^2) rad/\sqrt{Hz}$
- dynamic range: 100 dB
- bandwidth: 0-10 Hz
- estimated data rate per tiltmeter: 2x16
- bit, 256 Hz sample rate
- one per building: 5 in WA and 3 in LA

—***Applied Geomechanics 500 series Tiltmeters***

- manufacturer/distributor: Applied Geomechanics
- models considered: 520 Geodetic Tiltmeter
- resolution: 10nRad or better
- Output Voltage Range: up to ± 8VDC single ended (16 diff) at high gain
- bandwidth: 0-10 Hz
- temperature control monitor
- power requirements: 11-15VDC and -11 to -15VDC max 20mA each
- price for model 520 Platform Tiltmeter with micrometer legs: $8000
- price for model 520 Platform Tiltmeter with worm gear legs: $9176

Seismic Noise High Frequency $10 \le f \le 200\,\mathrm{Hz}$

Monitor all the possible movements (degree of freedom) of the tanks and the BT mechanical excitation monitor the ground motion near seismic support piers in order to obtain the transfer function from floor to support beams. They might be part of the PEM cart.

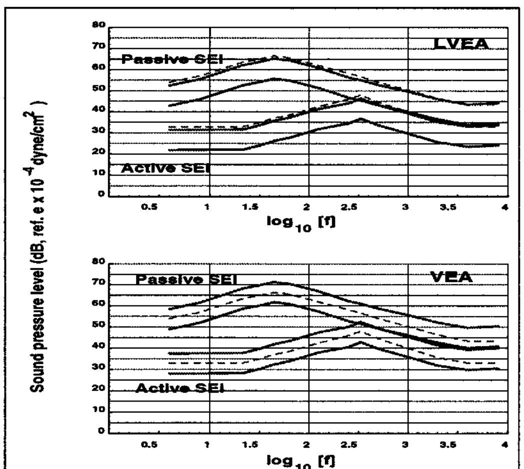
››High frequency 1 axis PZT accelerometer Requirements

- sensitivity: $x(f) \le (10^{-8}/f^2) m/\sqrt{Hz}$; minimum signal level: $a < 10^{-9} g$ TBD
- bandwidth: 10-200 Hz;
- dynamic range 100 dB
- estimated data rate per accelerometer: 1x16 bit, 256 Hz sample rate
- 6 accelerometers/tank to measure translation and rotation: 84 in WA and 42 in LA
- 3 accelerometers every 500m of beam tube to measure excitation: 48 in WA and 48 in LA
- 3 x 3 accelerometers/site for the PEM cart: 9 in WA and 9 in LA (not in the initial PEM)

—ISOTRON Accelerometer 7754-1000 (Endevco Meggitt Aerospace)

- voltage sensitivity 1000mV/g; maximum Voltage: $\pm 5V$ (range $\pm 5g$)
- bandwidth 1Hz-10kHz
- residual equivalent g-rms noise for broadband 0.1-100Hz typical: $10^{-5} g_{rms}$
- unit price for large quantities (more than 250): $745
- optional 16 channel ISOTRON 2793 Constant Power Supply/Amplifier: $1377.5 for large quantities (can drive 16 accelerometers: power requirement: +18-24VDC, 20mA)

Acoustic Noise



Total Requirement (dashed curves)
Single rack requirements:
Measured @ 1m (upper solid curves)
Measured @ 3m (lower solid curves)

The **required acoustic noise levels** in the LVEA are given in the above figure (as calculated by A. Lazzarini). For our purposes, the maximum SPL near the tanks, corresponds in terms of acoustic power pressure to $p(f) < 2 \times 10^{-9} atm/\sqrt{Hz}$.

Acoustic noise (continued)

››Acoustic Microphones Requirements (above 10Hz)

- sensitivity $p(f) \le 10^{-4} (N/m^2/\sqrt{Hz}) = 10^{-9} atm/\sqrt{Hz}$
- dynamic range 60 dB; bandwidth: 10Hz - 1kHz, TBD
- estimated data rate per microphone: 1x16 bit, Hz 2048 Hz sample rate
- one per tank and one near PSL laser: 14+2 in WA and 7+1 in LA + two per site for the PEM cart (not in the initial PEM)

—***Electret Condenser Capsule Microphones***

- unit price: $6 + electronics custom made unit: $100

››Infra Acoustic Detectors Requirements TBA (not in the initial PEM)

Sound pressure variations 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. The usefulness of those detectors was indicated by the ASC analysis of stack tilt as a function of atmospheric pressure change

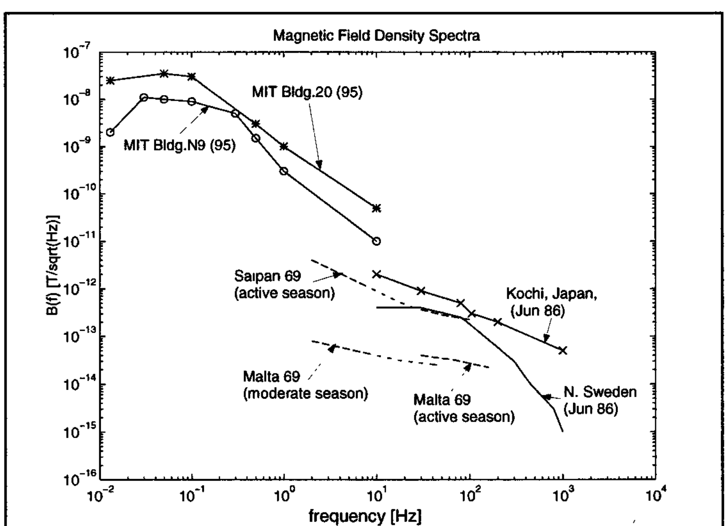
- Frequency Range: 0 - 10 Hz
- sensitivity $p(f) \le 10^{-4} (N/m^2/\sqrt{Hz}) = 10^{-9} atm/\sqrt{Hz}$

—***Low Pressure Low Frequency detector TBD***

- A sensor is yet to be selected.

Magnetic Field Fluctuations

››Quiet Magnetic Field: Average Values



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

Magnetic Field (continued 1)

››External source: **thunderstorms**:

- signals ~ **25 kHz** with an significant strain pulse + *significant RF.*
- Big lightning strikes (with currents of at least 10^5 A) at mid-point between the two LIGO sites, conservatively, might induce at both sites, magnetic bursts of about 10^{-11} T, with durations of 50-200μs (Weiss, Gordon).

››Local sources

- currents in conductors and electronics, laser and their control electronics, etc.; also due to objects modulating the external field such as passing cars/trucks.

—The 60 Hz magnetic field ambient.

- Calculations (Al Lazzarini) 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 and consistent with measurements at the 40m). Power line fluctuations might also induce magnetic field fluctuations. Those values largely exceed the natural magnetic field fluctuations as well as the recommended maximum magnetic field fluctuations 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.

Magnetic Field (continued 2)

››3 Axis Magnetometer Requirements

- sensitivity $B(f) \leq 2 \times 10^{-11} (T/\sqrt{Hz})$
- dynamic range 100 dB, with 60,120 Hz filters
- bandwidth: 1kHz
- estimated data rate per magnetometers: 3x16 bit, 2048 Hz sample rate
- one per tank: 14 in WA and 7 in LA
- one per site for the PEM cart: 1 in WA and 1 in LA (not in the initial PEM)

—Magnetometer Bartington/GMW MAG-03MCES100-L7

- range: $\pm 70\mu T$ and 10V full scale
- bandwidth: 0 to 4.5 kHz
- noise at full bandwidth: less than 2nT
- internal noise: better than $7pT_{rms}/\sqrt{Hz}$
- unit price with cylindrical probe: $2900. (Environmentally sealed with low noise option)
- Square probe equivalent version: $3830; unit power supply: $830
- cables $260 and up (depend on the length and type of probe)
- *TBD 60Hz and harmonics filters*
- *NOTE: There are some more sensitive 1 axis nanoteslameters such as model MAG-01H, which have 0.1nT noise, but costs $2450 for 1 axis only.*

Magnetic Field (continued 3)

››High Sensitivity Coil Magnetometer Requirements (not in the initial PEM)

- sensitivity $B(f) \le 2 \times 10^{-12} T/\sqrt{Hz}$ at 1kHz
- dynamic range 100 dB
- bandwidth: 1kHz
- build in bucking coil for 60n Hz compensating field
- estimated data rate per coil: 1x16 bit, 2048 Hz sample rate
- one per tank: 14 in WA and 7 in LA

—*Custom Made Coil*

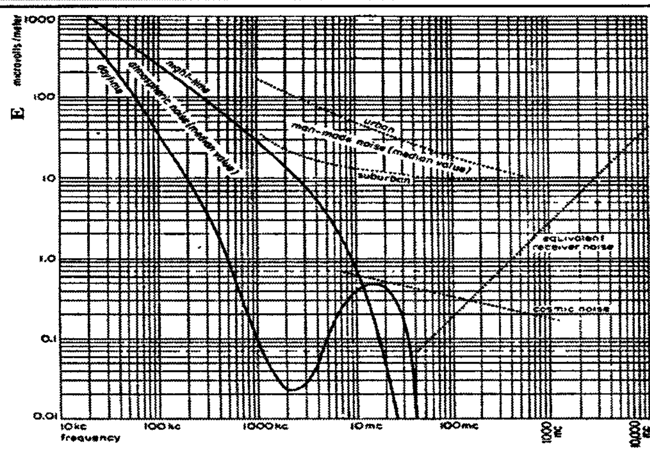
- in-house a coil magnetometer and amplifier: cost-effective and only way, to obtain the required sensitivity of $B(f) \le 2 \times 10^{-12} T/\sqrt{Hz}$
- dimensions of a BSC chamber, and thus somewhat unwieldy if a conventional design.
- bucking coil or other feedback at the amplifier input may be needed to avoid saturation of the amplifier by the 60 Hz and multiples.,
- number of turns: about 100000
- diameter: 3m TBD

RF Interference

››Sources of radio frequency interference

- Continuous natural local RF noises might be of the order of 1mV/m at 10kHz to about $10 \mu V/m$ above 10MHz.
- Continuous human-generated local RF sources such as local radio and TV stations, transformers, power lines, power supplies are in accordance with FCC regulations. At Hanford location: RF signals up to 300 mV/m, generated by a local TV stations.
- Thunderstorms and high altitude magnetic perturbations generate RF noise. Expect correlated electric field bursts up 100 mV/m.
- Other internal/Local human-generated RF sources: hand held transmitters, cell-phones, electric switches, electronics, power supplies, RF modulation, corset. Regulated by EMI Guidelines document which recommends the maximum radiated field to be less than 100 mV/m at 1 m.
- RFI monitors need more thought: 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 IFOs at the same site. The important measurement will be to monitor changes around the ambient levels.

RF Interference US latitude (continued 1)



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.

RF Interference (continued 2)

›› Radio Frequency Multi-channel Antenna/Receiver Requirements

- sensitivity $E \leq 10(\mu V/m)$ 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 building: 5 in WA and 3 in LA

—Hewlett Packard Signal Analyzer HP 8902A (many options available)

- RF power (with 11722 sensor): range 30dBm(1W) to -20dBm(10μW); bandwidth 0.1MHZ to 2.6GHz
- Tuned RF Level: range: 0 to -127dBm; bandwidth: 2.5MHz to 1.3GHz
- Optional Selective Power Measurements: Filter Bandwidth availability
- RF Frequency: resolution 1Hz; range 150kHz to 1.3MHz
- Amplitude and Frequency Modulation Measurement
- Phase Modulation, Audio, frequency and Distortion Capabilities
- Prices with options around $40000: (receiver only HP 8902A: $31500)

—Other Multichannel Receivers (less overall coverage and performance) TBD.

- HP 8901B almost same but: RF power amplitude range 30 to -20 dBm; 1band; Cost: $25000 with options
- HP 8901A same as 8901B but: RF power amplitude range 30 to 0 dBm; No audio frequency and distortion measurement capability; total cost: $20000 with options

Cosmic Muons

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.

››Mirror displacement for the advanced LIGO (D=30cm and L=20cm):

›› the standard muon background produces (conservative):

$$x(f) = (5.3 \times 10^{-22}/f^2) m/\sqrt{Hz}.$$

›› 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.

Cosmic Muons: Force spectral density

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}

- Force spectral density due to thermal noise: $F^2(f) = \frac{4k_B T \alpha_i M \omega_{0i}^2}{Q\omega}$

where $\alpha_i \times M$ = effective mass; and ω_{0i}= resonant angular frequency

- Average force spectral density due to cosmic muon background: $F^2_{\mu}(f) = 2P^2_{dep}(dN/dt)$

where P_{dep} is the momentum deposited; dN/dt = horizontal muon flux.

SO: background muon induced noise (ionization process only) is *negligible* with respect to the thermal forces.

Cosmic Muons: Muon Showers

›› The displacement due to a burst of muons generated by a high energy cosmic proton or nucleus interacting with the earth's atmosphere

– To induce a mirror displacement equivalent to the LIGO advanced detector sensitivity, we need ~ 1.5×10^5 particles. Such a density of muons might be produced by primary cosmic protons with energy of the order of 10^{18} eV or higher.

–TBD the probability of very high energy horizontal showers

››- 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.

Cosmic Muon Detector

››Charged Particle Detector Requirements

- sensitive to charged particles, in particular muons
- minimum sensitivity $F(E > 100MeV) \leq 10^{-4}\mu/s/m^2$
- 1msec timing resolution or better
- dynamic range: 60dB (option with no additional cost: up to 100dB)
- estimated data rate per detector: 1x16 bit 2048 Hz sample rate
- one per building: 5 in WA and 3 in LA

–Scintilator Detector and PMT

- We propose to assemble the detector in-house from standard components.
- Scintilator sensitivity: min 50 Photoelectrons/cm/Minimum Ionizing Particles
- recommended 2.5cm thickness scintilator
- range: 1-10000 particles/slab of Scintillator
- two sets of 2 inch PMTs driven at different gains (HV) in order to extend the dynamic range. The low gain PMTs can serve for the trigger generator.
- resolution: better than 0.01ms
- analog signal after a charge/shaping amplifier: 10V
- estimated costs per detector: $9000

Power Line Monitoring

››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) 100 meters or more from the test mass chambers.

Even with these precautions it is considered necessary to monitor the power in the buildings.

Power Line (continued)

››Power Line Fluctuations Requirements

- sensitivity: fractional fluctuations in voltage:
  1. long period: $\Delta V/V|_{rms} \leq 0.02$, for minutes;
  2. $\Delta V/V|_{rms} \leq 0.01$ for 1sec to 1msec
  3. $\Delta V/V|_{rms} \leq 0.05$ for spikes shorter than 0.2 msec
- harmonic content: less than 0.05 for line harmonics to 2kHz
- dynamic range: 60dB
- estimated data rate at threshold crossing/line: 4x16 bit, 2048 Hz sample rate
- one per building: 5 in WA and 3 in LA

—BMI 8800 Power Scope (Line Monitor)

- 4 channels (three phases+neutral) monitoring
- RMS Voltage and RMS Current monitoring: 2% long period resolution
- frequency measurement
- Spikes: less than 5% fractional voltage fluctuations in less than 0.1ms
- high frequency noise, total harmonic distortion and spectrum analysis
- price: $13495 + probes($355-545 each, in function of total current and bandwidth)
- optional temperature/humidity probes (up to 8): $1180 each (see Weather Monitor)
- **For monophase measurement only (numbers of units TBD), model number 8800-4 at a price of $8775 + probes can be an option. The 3-phase option is more cost effective. Less expensive units with less features are available: TBD**

Residual Gas Monitoring

››Average Pressure:

- The average pressure in the BT for the initial pumping: 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 ($h(f) \leq 1.5 \times 10^{-25} / \sqrt{Hz}$).

›› Gas Bursts: TBD

- The initial sensitivity to bursts, $\Delta B \approx 100$Hz at 100Hz, is for
  1. the initial interferometer $h_{rms} = 1.5 \times 10^{-22}$
  2. the advanced interferometer $h_{rms} = 1.5 \times 10^{-23}$.
- 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 $Q_{air} \leq 8 \times 10^{-9} torr \cdot liters/s$ (1/10 of the goal statistical phase noise).

Residual Gas Monitor (RGA)

››Residual Gas Monitor (RGA) Requirements

Requirements for pressure in instrumentation chambers, associated tube and BT modules:

- RGA able to determine: contribution of gas bursts, 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 $P_p \leq 10^{-14} torr$ for 1 - 100 amu
- dynamic range: 10^9
- timing resolution on a single mass number $\Delta t_{res} \leq 10 ms$
- estimated data rate per RGA: 1x16 bit, 2048 sample rate on threshold crossing
- one per building AND one per each Km of beamtube: 13 in WA and 11 in LA.
- TBD: 1 additional RGA for the WA corner building to instrument the second VEA. The cart RGA can be used for this purpose.

—BALZERS RGA

- manufacturer/distributor: Balzers
- model: BKM 18111 QMG421-3 without RGA head: $23000
- Head only QMA 430: $13000
- ion counter preamp and board: $5000
- network server BN882086: $2600
- total RGA: $43600

Vacuum Contamination Monitoring TBD

TBD; no final 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.

››The residual gas and vacuum contamination monitoring (TBD)

- possible combination of RGAs and Deposition monitors as a means to determine the rate and nature of contaminants on the optics. The system outlined below was included in the Cost Book 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.

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. Due to the lack of information on the nature of contamination, we cannot yet specify a system which is sure to be useful.

Contamination Monitor

›› Preliminary Requirements for **contamination monitors** in instrumentation chambers and associated tubes

- Capability to measure deposition of 1 monolayer/month on ambient T^o surface.
- Capability to perform qualitative desorption analysis to separate water from other absorbed molecules
- Digital control and read interface to LIGO instrumentation 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.T of the crystal oscillator sample collector and **2)** measurement of the evaporated layer by an RGA
- one Crystal Head per tank (14 in WA and 7 in LA)
- one RGA head per tank for contamination measurements (14 in WA and 7 in LA)
- one control unit for Crystal head and one control RGA per bldg (5 in WA and 3 in LA)

—Contamination Monitor and RGA:TBD (from the initial Cost Book PEM estimates)

- crystal head assembly: $3794
- RGA head assembly: $13000
- electronics for crystal head: $9243
- network server BN882086: $2600
- ion counter preamp and board: $5000
- RGA Balzers (see 4.1.12.2) system: $23000

Weather Monitoring

Not in the initial PEM but parts were included in facility monitoring system.

››Weather monitor Requirements

Thermometers

- precision 1deg. C; range: inside 0-50 deg. C; outside -20 to 70 deg. C
- estimated data rate: 1x16 bit sample rate 2Hz
- 4 in each building and every 500m on the Beam tube: 20+16 in WA and 12 + 16 in LA
- outside temperature on four building sides: 20 in WA and 16 in LA

Humidity Detectors

- precision 10%; range 10-100% relative humidity
- estimated data rate: 1x16 bit sample rate 2Hz
- inside humidity: 1 per building and one every 500m of BT: 5+16 in WA and 3+16 in LA
- outside humidity: one per site, LA and WA

Precipitation

- precision 10%
- rate or accumulation
- one per site

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

Weather Monitor Stations

››RH and Temperature Detectors

Omega; model: HX 93V

- RH range and accuracy: 3-95%; ±2% with temperature compensation
- Temperature range and accuracy: -20 to 75^0C; $\pm 0.6^0$C
- Output 0-1VDC for each channel; power requirements: unregulated 16-23VDC
- price: $210 + calibration kit: $65 (one/site) + optional power supply: $40

Low cost Hand held RH and temperature monitor for PEM cart

- model Omega RH 83: within requirements for RH and for Temperature (but max 50^0C)
- price: $99

››Weather Stations

Low Cost Weather Station: Cole Parmer H-99800-20 indoor/outdoor monitoring system

- Monitor: Temperature, RH, Wind speed and direction, Air Pressure, Precipitation
- fulfill requirements (except max. T=60degr C)
- cost: $570 (base unit with rain collector, outdoor T/RH sensor and cables) + optional PC software: $165

Advanced Weather Station: Cole Parmer H-99750-30 indoor/outdoor monitoring system

- Monitor: Temperature, RH, Wind speed and direction, Wind chill, Time, Air Pressure, Precipitation
- fulfill requirements (except max. T=60degr C)
- sophisticated computer interface
- cost: $2290 (base unit with rain collector, outdoor T/RH sensor and 50ft cables)

PEM Excitation System (new:TBD)

Characteristics of the PEM Excitation System

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

››Fixed Seismic Excitation System

- The excitation for each seismic beam support point is proposed to be part of the active SEI system. If the Detector eliminates the active SEI system, PEM will add PZT excitation in the spacers which replace the active SEI.
- For the PEM cart might be useful to have a set of 3 PZT shakers

››Acoustic Noise Generator Requirements

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

—*Acoustic Noise generator*

- This probably consists of a conventional wide-bandwidth loudspeaker and also one or several portable localized sources of sound, like 'tweeters' and sound guns.
- estimated for one system: TBD

PEM Excitation System (continued)

››Magnetic Field Generator (TBD) Requirements

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

- Dynamic range: $10^{-12} \leq B \leq 10^{-5} T$
- frequency range from DC-->10 kHz
- Built-in gradient monitor
- One per building (possible need for one coil per tank if not demountable)

—*Magnetic Field Generator TBD*

- Due to its requirements, it is estimated that this will be a custom made system.

››RF generator Requirements

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

—*HP RF generator TBD*

- model HP 8463A with option 002: $25000 with options
- satisfies parameters requirements

PEM Moveable Carts (new)

- can move from place to place in the LVEA, BT or mid-end stations to supply excitation and sensors.
- It communicates with the CDS backbone installed for DAQ.
- The PEM cart allows the reduction of fixed excitation and sensing stations.

The PEM cart will contain the following Sensing Equipment

- 3 x 3 accelerometers
- 3 acoustic microphones and (TBD)infrasonic microphones
- magnetic field sensors
- RFI sensors
- Limited Weather Monitors

Sources of Excitation for the PEM Cart

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

Special Requirements and Alternative Data Links for the PEM Cart

- Can have its own *DAQ* with some *storage capacity* (TBD) i
- The PEM/noise cart: placed anywhere there is power and data ports within 1 day.
- Options: *battery operated, low power X-band radio link* between cart or BT location to the vertex station is considered. The antennas would be outside the BT tunnels.
- *First PEM subsystem to be implemented* at the sites.

Interface to Other LIGO Systems

››Interfaces to other LIGO detector subsystems

1.The PEM system is an independent system, attached to parts of the IFO, or mounted near IFO.

2.There are no signal or optical interfaces with the IFO subsystems. PEM accepts and provides monitor and control inputs, used in DAQ, and eventually in control or on-line veto.

3.For the initial stage of the LIGO detector, it is proposed to have no hardware vetoes.

—Mechanical Interfaces

- Seismometers and Tiltmeters mounted on the ground of the LVEA at a point representative of the seismic excitation of the SEI stack support piers.
- LVEA accelerometers: on the stack support columns, close to the bellows feedthrough.
- BT accelerometers: on the BT walls and on the baffle surfaces.
- Microphones for tanks to be mounted as close as possible to the bellows feedthrough
- Microphones for PSL should be mounted on the PSL table
- Magnetometers: 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 contamination heads and the RGA heads: inside vacuum tanks on flanges

—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

—Interfaces external to LIGO detector subsystems

- Seismometers and Tiltmeters need LVEA floor space with no strong local sources of heat or vibration (max. 1 m^2 per unit), to isolate the system from local effects. The actual footprint of a sensor will be ~ 0.01 m^2

	Equipment	Sensitivity	Range	Smple rate Hz/ chan	Chan	DataRate KBytes/ sec	Unit Total k$
	Sensing	equipment	for	PEM	carts		
Seismic Noise	3 axis seismometer	$10^{-10}m$ @1Hz	1 - 10Hz	256	3	2	14
	2 axis tiltmeter	$10^{-9}rad$ @1Hz	1 - 10Hz	256	2	1	10
	6 axis accelerometer	$10^{-11}m$ @100Hz	10Hz-200 Hz	256	6	2	1.1 7
Acoustic Noise	Electret Microphones	$2 \cdot 10^{-9}atm$ @100Hz	~1kHz	2048	3	12	0.2 0.6
Infrasound Noise	TBD	$10^{-9}atm$	0-10Hz	256	1	1	2 TBD
Magnetic Field	3 axis magnetometer	$10^{-11}T$ @100Hz	DC - 1kHz	2048	1	4	3.5
RF Interference	Multichannel Receiver	0.01mV/m 6 channels	up to 1.3GHz	2048	6	24	36 TBD
Contam + RGA	Contr head control RGA	$P \leq 10^{-14}$ torr	1-100 amu	2048	1	4	51
	Excitation	equipment	for	PEM	carts		
Seismic Noise	PZT and e-m Shaker		above 10Hz		3		3 TBD
Acoustic Noise	Loudspeaker Generator		20-1000Hz		1		2
Infrasound Noise	TBD Generator		bellow 20Hz		1		2 TBD
Magnetic Field	TBD		DC-1kHz		1		1 TBD
RF noise	RF Generator		up to 1 3GHz		1		25 TBD
Total Data	Rates:	12 (256Hz) =	6KB/s ;	11(2kHz)	=44KB/ s		
TOTAL	COST	per	CART		(TBD)		164

PEM Cart Equipment

	Detector	Sensitivity	Range	Nr WA LA	Sample rate per chan	Chan WA+LA	Deteriorate WA+LA KBytes/ sec	Cost Unit Total k$
Seismic Noise	3 axis seismometer	10^{-10} m @1Hz	1 - 10Hz	1/bldg 5 + 3	256	15 + 9	8 + 5	14 112
	2 axis tiltmeter	10^{-9} rad @1Hz	1 - 10Hz	1/bldg 5 + 3	256	10 + 6	5 + 3	10 80
	1 axis accelerometer	10^{-11} m @100Hz	10Hz-200 Hz (new)	6/tank 12/BT 132+90	256	132+90	61+45	1.1 245
Acoustic Noise	Electret Microphones	2×10^{-9} atm @100Hz	~1kHz	1/tank 14 + 7	2048	14 + 7	56+28	0.2 5
Magnetic Field	3 axis magnetometer	10^{-11} T @100Hz	DC - 1kHz	1/tank 14 + 7	2048	42+ 21	168+84	3.5 74
RF Interference	Multichannel Receiver	0.01mV/m 6 channels	up to 1.3GHz	1/bldg 5 + 3	2048	30 +18	120+72	36 288
Cosmic Muons	Scintulator Detector	$10^{-6} \frac{\mu}{s\ m^2}$	100Mev 1ms res.	1/bldg 5 + 3	2048	5 + 3	20+12	9 72
Power Line	Line Monitor	see 2.4.8.1	up to 2kHz	1/bldg 5 + 3	2048	20+12	80+48	13 104
Residual Gas	RGA	$P \leq 10^{-14}$ torr	1-100 amu	2/BT 1/bldg 13 +11	2048	13 +11	52+44	42 1008
Contamination Monitor	Crystal Head	monolayer/ week		1/tank 14 + 7				4 84
	RGA Head	$P \leq 10^{-14}$ torr	1-100 amu	1/tank 14 + 7				13 273
	Contr.head control RGA			1/bldg 5 + 3	2048	5 + 3	20+12	51 408
TOTAL	: for 256	sample	rate			157+105	74 + 53	
TOTAL	: for 2048	sample	rate			129+ 75	516+300	
TOTAL	COST	for full	PEM	(NO	carts)			2753
TOTAL	COST	for full	PEM	with	2 sets	of carts	(TBD)	3081

PEM Full Implementation

	Detector	Sensitivity	Range	Nr WA LA (full)	Chan (full) WA+LA	Cost Unit Total k$
Seismic Noise	3 axis seismometer	$10^{-10} m$ @1Hz	1 - 10Hz	3 (5+3)	9 (15+9)	14 42
	2 axis tiltmeter	$10^{-9} rad$ @1Hz	1 - 10Hz	3 (5+3)	6 (10 + 6)	10 30
	1 axis accelerometer	$10^{-11} m$ @100Hz	10Hz-200 Hz	90(132 +90)	90 (132+90)	1.1 100
Acoustic Noise	Electret Microphones	$2 \cdot 10^{-9} atm$ @100Hz	~1kHz	7 (14 + 7)	7 (14 + 7)	0.2 1.5
Magnetic Field	3 axis magnetometer	$10^{-11} T$ @100Hz	DC - 1kHz	7 (14+7)	21 (42+ 21)	3.5 24.5
RF Interference	Multichannel Receiver	0.01mV/m 6 channels	up to 1 3GHz	3 (5 + 3)	18 (30 +18)	36 108
Cosmic Muons	Scintilator Detector	$\frac{10^{-6} \cdot \mu}{s \cdot m^2}$	100Mev 1ms res.	3 (5 + 3)	3 (5 + 3)	9 27
Power Line	Line Monitor	see 2.4.8.1	up to 2kHz	3 + 3 (5 + 3)	12+12 (20+12)	13 78
Residual Gas	RGA	$P \leq 10^{-14}$ torr	1-100 amu	13 +11 TBD	13 +11	42 1008
Contamination	Crystal Head	monolayer/ week		14 + 7		4 84
Monitor	RGA Head	$P \leq 10^{-14}$ torr	1-100 amu	14 + 7		13 273
	Contr.head control RGA			3 (5 + 3)	3 (5 + 3)	51 153
TOTAL	COST	for PEM		(NO	carts)	1929
TOTAL	COST	for PEM	with 2	sets of	carts	2093

PEM First Stage Implementation.

Pressing questions/actions

Choice of implementation philosophy
- how much to install up-front?

Resolution of specific implementation questions
- beam tube instrumentation
- cart: capabilities
- excitation system

Preliminary design
- choice of commercially available items
- design, prototyping, production of custom sensors
- interface to data acquisition system

Design of software to implement tests
- installation and commissioning
- coupling measurements

...and, what should the name be?