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Physical Environmental Monitor Conceptual Design

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D R A F T

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1 INTRODUCTION

1.1. Purpose

The purpose of this document is to describe the conceptual design for the Physical Environmental Monitor (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).

1.3. Definitions and Acronyms

- BT - Beam Tube
- CDS - Control and Data Systems
- IFO - LIGO interferometer
- LVEA - Laser Vacuum Equipment Area
- VEA - Vacuum Equipment Area
- PEM - Physical Environmental monitor
- RGA - Residual Gas Analyzer
- SEI - Seismic Isolation
- SUS - Suspension Control
- TBA/D - To Be Analyzed/Determined

1.4. Applicable Documents

1.4.1. LIGO Documents

1.4.1.1 PEM DRD LIGO-T960127-00-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

2 GENERAL DESCRIPTION

We repeat here the requirements for the sensors and sources of excitation, and then give the conceptual design which responds to those requirements.

Many of the elements for the PEM can be purchased commercially, and in these cases the conceptual design consists of citing the relevant item; the electrical interface to the Data Acquisition system and the mechanical interface will be the subject of the Preliminary Design. We give here likely candidates for the sensors to be used in the PEM, but may wish to search alternatives for the actual implementation (principally to reduce costs or ease interfacing).

The conceptual design is given for those elements which require in-house development.

This document is largely based on the Cost Book backup research, coordinated by R. Weiss.

3 CONCEPTUAL DESIGNS

Note that the quantities of sensors given below are for a full implementation of the PEM. The tables at the end of the PEM DRD document give totals for various scenarios and are consistent with the present document at this time. The prices quoted do not include in all cases necessary accessories such as cables and/or power supplies; need will depend on the specific implementation chosen.

3.1. Sensors

3.1.1. Low frequency 3 axis seismometer

3.1.1.1 Requirements

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

3.1.1.2 GURALP CMG-40T Seismometer

- manufacturer/distributor: GURALP/Digital Technology
- model: CMG-40T
- 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
- 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
- optional digitizer and software unit price $13194 (no power supply)

3.1.2. Low Frequency 2 Axis tiltmeter

3.1.2.1 Requirements

- sensitivity: $\theta(f) \leq (2 \times 10^{-9} / f^2) rad / \sqrt{Hz}$
- maximum noise level: TBD
- 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

3.1.2.2 Applied Geomechanics 500 series Tiltmeters

- manufacturer/distributor: Applied Geomechanics
- models considered: 520 Geodetic Tiltmeter
- resolution: 10nRad or better
- Output Voltage Range: up to ±8 VDC 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

3.1.3. High frequency 1 axis PZT accelerometer

3.1.3.1 Requirements

- sensitivity: $x(f) \leq (10^{-8} / f^2) m / \sqrt{Hz}$
- maximum noise level: $a < 10^{-9} g$ TBD
- dynamic range 100 dB
- bandwidth: 10-200 Hz
- estimated data rate per accelerometer: 1x16 bit, 256 Hz sample rate
- three accelerometers mounted on a single block to measure 3 degrees of translation
- 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)

3.1.3.2 ISOTRON Accelerometer

- manufacturer/distributor: Endevco Meggitt Aerospace
- model: ISOTRON Accelerometer 7754-1000
- range $\pm 5g$
- voltage sensitivity 1000mV/g
- maximum Voltage: $\pm 5V$
- bandwidth 1Hz-10kHz
- residual equivalent g-rms noise for broadband 0.1-100Hz typical: $10^{-5} g_{rms}$
- power requirement: +18-24VDC max 20mA
- 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)

3.1.4. Acoustic Microphones

3.1.4.1 Requirements

- sensitivity $p(f) \leq 10^{-4}(N/m^2/\sqrt{Hz}) = 10^{-9} atm/\sqrt{Hz}$
- maximum noise level $p_{noise} < 10^{-10} atm$
- dynamic range 60 dB
- bandwidth: 10Hz - 1kHz, TBD
- 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: 2 in WA and 2 in LA (not in the initial PEM)

3.1.4.2 Electret Condenser Capsule Microphones

This is a product made by many manufacturers, and one with a more convenient interface may be found.

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

3.1.5. Infra Acoustic Detectors TBA (not in the initial PEM)

The usefulness of those detectors was indicated by the ASC analysis of stack tilt as a function of atmospheric pressure change (1.4.1.5). Further refinement of these requirements are is required.

3.1.5.1 Requirements TBD

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

3.1.5.2 Low Pressure Low Frequency detector TBD

A sensor is yet to be selected.

3.1.6. 3 Axis Magnetometer

3.1.6.1 Requirements

- sensitivity $B(f) \leq 2 \times 10^{-11}(T/\sqrt{Hz})$
- Internal Noise $n_{rms} \leq 10^{-11} T_{rms}/\sqrt{Hz}$ at 1Hz
- 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)

3.1.6.2 Magnetometer

- manufacturer/distributor: Bartington/GMW

- model: MAG-03MCES100-L7 Environmentally sealed with low noise option
- 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 $7 pT_{rms} / \sqrt{Hz}$
- unit price with cylindrical probe: $2900.
- 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.*

3.1.7. High Sensitivity Coil Magnetometer (not in the initial PEM)

3.1.7.1 Requirements

- sensitivity $B(f) \le 2 \times 10^{-12} T / \sqrt{Hz}$ at 1kHz
- Internal Noise $n_{rms} \le 10^{-12} T_{rms} / \sqrt{Hz}$ at 1Hz
- dynamic range 100 dB
- bandwidth: 1kHz
- 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

3.1.7.2 Custom Made Coil

The objective is to sense fields which can cause motion of the test masses at the LIGO sensitivity level. We propose to develop in-house a coil magnetometer and amplifier. This may be the most cost-effective way, and in fact the only way, to obtain the required sensitivity. The coil would be of the dimensions of a BSC chamber, and thus somewhat unwieldy if a conventional design. A means to avoid saturation of the amplifier by the 60 Hz and multiples may be needed, in the form of a bucking coil or other feedback at the amplifier input.

- sensitivity $B(f) \le 2 \times 10^{-12} T / \sqrt{Hz}$ at 1kHz
- number of turns: about 100000
- diameter: 3m TBD

3.1.8. Radio Frequency Multi-channel Antenna/Receiver

3.1.8.1 Requirements

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

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

3.1.8.2 HP 8902A Multichannel Receiver and Antenna

  - manufacturer/distributor: Hewlett Packard
  - model: Signal Analyzer HP 8902A (many options available)
- RF power (with 11722 sensor module)
  - range 30dBm(1W) to -20dBm(10microW)
  - 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: total around $40000
  - receiver only HP 8902A: $31500
  - HP 11722 module: $2570
  - Various frequency filters (including cellular) in sets of two: $2965
  - manuals: $533 (not necessarily for all units)
  - matched antenna HP 11966x: $2500-5000 TBD

3.1.8.3 Other Multichannel Receivers

Other options are considered, with less coverage or performance. TBD. As for example, we will list some of the considered units with their main characteristics:

- HP 8901B almost same parameters but:
  - RF power amplitude measurement range 30 to -20 dBm
  - overall less features and ranges in power RF, modulation, single measurement band, etc.
  - total cost: $25000 with required options
- HP 8901A almost same as 8901B but
  - RF power amplitude measurement range 30 to 0 dBm
  - No audio frequency and distortion measurement capability
  - total cost: $20000 with options

3.1.9. Charged Particle Detector

3.1.9.1 Requirements

  - sensitive to charged particles, in particular muons
  - sensitivity $F(E > 100MeV) \le 10^{-4} \mu / s / m^2$
  - 1msec timing resolution or better
  - dynamic range: 60dB
  - estimated data rate per detector: 1x16 bit 2048 Hz sample rate
  - one per building: 5 in WA and 3 in LA

3.1.9.2 Scintillator Detector and PMT

We propose to assemble the detector in-house from standard components.

- Scintillator sensitivity: min 50 Photoelectrons/cm for Minimum Ionizing Particles
- recommended 2.5cm thickness scintilator
- 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 generator.
- resolution: better than 0.01ms
- analog signal after a charge/shaping amplifier: 10V
- estimated costs per detector: $9000

3.1.10. Power Line Fluctuations (see 2.4.8)

3.1.10.1 Requirements

- sensitivity: fractional fluctuations in voltage:

  long period: $\Delta V / V|_{rms} \leq 0.02$, for minutes;

  $\Delta V / V|_{rms} \leq 0.01$ for 1sec to 1msec

  $\Delta V / V|_{rms} \leq 0.05$ for less than 0.2 msec
- harmonic content: less than 0.05 for line harmonics to 2kHz
- dynamic range: 60dB
- estimated maximum data rate per power line monitor: 4x16 bit, 2048 Hz sample rate, at threshold crossing
- one per building: 5 in WA and 3 in LA

3.1.10.2 BMI Power Line Monitor

The sensor described here may be well in excess of our needs in some aspects (sophisticated internal data thresholding and recording). It is the unit described in the Cost Book.

- manufacturer/distributor: BMI
- model: 8800 Power Scope
- 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
- spectrum analysis
- price: $13495 + probes($355-545 each, in function of total current and bandwidth)
- 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. TBD

3.1.11. Residual Gas Monitor (RGA)

3.1.11.1 Requirements

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

- the system to be able to determine the contribution of gas bursts and other coherent residual gas fluctuations, leaks, etc.; to measure the composition of the residual gas (1-100amu, $10^{-14} torr$)
- to stamp the time dependence of the pressure and bursts measurements.
- sensitivity: partial pressures $P_p \leq 10^{-14} torr$ 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.

3.1.11.2 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

3.1.12. Vacuum Contamination Monitor TBD

The requirements are listed in APPENDIX 1 of PEM DRD. Due to the lack of information on the nature of contamination, we cannot yet specify a system which is sure to be useful.

3.1.12.1 Requirements TBD

- Capability to measure deposition of 1 monolayer/month on ambient temperature surface.
- Capability to perform qualitative desorption analysis to separate water from other adsorbed molecules
- Digital control and read interface to LIGO instrumentation system.
- The 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. temperature of the crystal oscillator sample collector
  2. measurement of the evaporated layer by an RGA (see below)
- 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)

3.1.12.2 Contamination Monitor TBD

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

- 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

3.1.13. Weather monitor

Not in the initial PEM but parts were included in facility monitoring system. Some of the required weather sensors might be combined in a weather station.

3.1.13.1 Requirements

3.1.13.1.1 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

3.1.13.1.2 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

3.1.13.1.3 Precipitation

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

3.1.13.1.4 Wind monitors

- wind speed precision: 1mph
- wind direction precision: 5deg
- estimated data rate: 2x16 bit sample rate 2Hz
- one per building: 5 in WA and 3 in LA
- optional temperature/humidity probes (up to 8): $1180 each

3.1.13.2 RH and Temperature Detector

3.1.13.2.1 RH and Temperature transmitter

- manufacturer/distributor: Omega
- model: HX 93V
- RH range and accuracy: 3-95%; ±2 %
- Temperature range and accuracy: -20 to 75^0 C; $\pm 0.6^0$ C
- Output 0-1VDC for each channel
- RH temperature compensation
- power requirements: unregulated 16-23VDC
- price: $210
- calibration kit: $65 (not required for each transmitter)
- optional power supply: $40

3.1.13.2.2 Low cost Hand held RH and temperature monitor

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

3.1.13.3 Weather Stations

We give two options for the weather stations, with a selection to be made after further consideration.

3.1.13.3.1 Low Cost Weather Station

- manufacturer/distributor: Cole Parmer
- model: 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

3.1.13.3.2 Advanced Weather Station

- manufacturer/distributor: Cole Parmer
- model: 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)

3.2. Characteristics of the PEM Excitation System

(not in the initial PEM) TBD

NOTE: All the excitation systems except the seismic PZT (3.2.1.) are part of the PEM moveable cart and not permanently installed.

3.2.1. 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

3.2.2. Acoustic Noise Generator

3.2.2.1 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

3.2.2.2 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

3.2.3. Magnetic Field Generator (TBD)

3.2.3.1 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)

3.2.3.2 Magnetic Field Generator TBD

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

3.2.4. RF generator

3.2.4.1 Requirements

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

3.2.4.2 HP RF generator TBD

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

3.3. Reliability

TBD.

4 QUALITY ASSURANCE PROVISIONS

TBD.

APPENDIX 1 SUMMARY OF PEM

- Table 2 presents the summary of the PEM components, performance and estimated costs for the full PEM implementation. The data rates are estimated as follows:

$$DataRate[KBytes \times Hz] = \frac{ChanNr \times 16(bits/chan)}{8(bits/Byte) \times 1024} \times SampleRate[Hz]$$

Table 1: Full PEM System characteristics and estimated costs. (For carts see table 4)

	Detector	*Sensitivity*	*Range*	*Nr WA LA*	*Sample rate per chan*	*Chan WA+LA*	*DataRate 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

Table 1: Full PEM System characteristics and estimated costs. (For carts see table 4)

	Detector	*Sensitivity*	*Range*	*Nr* *WA LA*	*Sample rate per chan*	*Chan WA+LA*	*DataRate WA+LA KBytes/ sec*	*Cost Unit Total k$*
Cosmic Muons	Scintilator Detector	$\frac{10^{-6}\cdot\mu}{s\cdot m^2}$	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	$P \le 10^{-14}$ torr	1-100 amu	2/BT 1/bldg 13 +11	2048	13 +11	52+44	42 1008
Contamina-tion	Crystal Head	monolayer/ week		1/tank 14 + 7				4 84
Monitor	RGA Head	$P \le 10^{-14}$ 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**

- *As an option, we propose to, first, fully implement only the 4Km WA IFO and the buildings. Based on the acquired experience, we will continue to implement the rest of the LIGO IFO with the full or modified PEM system. (TBD). In this scenario, it is mandatory to implement from the beginning all the PEM parts for which a later implementation might interfere with the LIGO runs. This option is presented in Table 3.*
- Table 4 present the PEM cart components, characteristics and estimated cost. The cart estimated cost does not include the mechanical structure, optional batteries and the DAQ cart system (TBD: see 3.1.1.3).

Table 2: PEM First Stage (see text): Full 4Km WA IFO and partial PEM for the other IFOs.

	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)	13 312
Residual Gas	RGA	$P \leq 10^{-14}$ torr	1-100 amu	13 +11 TBD	13 +11	42 1008
Contamination Monitor	Crystal Head	monolayer/ week		14 + 7		4 84
	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)**	**2163**
TOTAL	**COST**	**for PEM**	**with 2**	**sets of**	**carts**	**2491**

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

	Equipment	*Sensitivity*	*Range*	*Sample 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		below 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**