LIGO LABORATORY
CALTECH, MS 18-34
PASADENA, CA 91125

TEL: 626/395-2129
FAX: 626/304-9834

Date: July 7, 2003
Refer to: LIGO-M030132-00-P
To/Mail Code: Distribution
From/Mail Code: P. Lindquist/18-34
Phone/FAX: 395-3193/304-9834

Subject: LIGO Change Control Board (CCB) Meeting Minutes - June 23, 2003

Keywords: Change Control Board, Livingston Civil Construction, Operations Budgets, External Pre-Isolation, Atomic Clock

References: CR-030008—Livingston Facilities Furniture for Auditorium, etc.
CR-030011—Seismic External Pre-Isolation (EPI) at LIGO Livingston Observatory
CR-030013—Atomic Clock Timing System

**Attendees:**

| | | | |
|---|---|---|---|
| B. Barish | D. Coyne (tel.) | R. DeSalvo | E. Jasnow |
| E. Katsavounidis (tel.) | F. Kaufman | A. Lazzarini | P. Lindquist |
| O. Matherny (tel.) | N. Mavalvala (tel.) | I. Petrac | F. Raab (tel.) |
| G. Sanders | P. Saulson (tel.) | D. Shoemaker (tel.) | A. Sibley (tel.) |
| L. Wallace | R. Weiss (tel.) | S. Whitcomb | M. Zucker (tel.) |

**Agenda:**

The LIGO Change Control Board met on Monday, June 23, 2003 during the normally scheduled Executive Committee meeting. The following change requests were discussed:

| CR Number | WBS | Description | Submitted By | Date |
|---|---|---|---|---|
| CR-030008 | OPS | Livingston Facilities-Furniture for Auditorium, etc. | M. Coles | April 29, 2003 |
| CR-030011 | OPS | Seismic External Pre-Isolation (EPI) at LIGO Livingston Observatory | Kern, Coyne | May 16, 2003 |
| CR-030013 | OPS | Atomic Clock Timing System | D. Coyne | June 9, 2003 |

**General**

The change log is attached.

## CR-030008– Livingston Facilities-Furniture for Auditorium, etc.

The funds requested provide for furnishing the auditorium lobby, the interaction area underneath the skylight atrium in the Operations Support Building (OSB), and on the second floor interaction area in the new laboratory/office building. Recent quotes are significantly less than the original estimates. The total now needed is less than the threshold requiring formal change board approval. This change request is for information only.

### CR-030011–Seismic External Pre-Isolation (EPI) at LIGO Livingston Observatory

This change request was previously discussed on June 2, 2003 (LIGO-M030122-00-P). The estimated cost has been reduced by $500K as a result of recent quotes for electronics and the decision to implement EPI on one less chamber at LASTI. Therefore, the total requested is $2.6 million.

**CR-030011 is approved for $2.6 million.**

### CR-030013-- Atomic Clock Timing System (Operations WBS 2.02.8.X and 2.03.8.X)

LIGO and the LSC have established the need for an independent timing system. This proposal is based upon atomic clocks ands fiber optic distribution. The request has been reviewed by a Technical Review Board and was also presented to and discussed by the LIGO Scientific Collaboration (LSC).

Less expensive alternatives have been evaluated but do not satisfy all criteria.

Part of the cost is for a master that will drive slaves to safeguard against glitches. The designated atomic clock scientist will probably be Daniel Sigg.

**CR-030013 is approved. Implementation is required for the third science run (S3).**

PEL:pel

Attachments: CR-030008—Livingston Facilities Furniture for Auditorium, etc.
CR-030011—Seismic External Pre-Isolation (EPI) at LIGO Livingston Observatory
CR-030013—Atomic Clock Timing System
Change Log (page 34)

### Distribution:

| | | | |
|---|---|---|---|
| R. Bork | D. Coyne | E. Jasnow | L. Jones |
| E. Katsavounidis | F. Kaufman | A. Lazzarini | K. Libbrecht |
| O. Matherny | I. Petrac | F. Raab | D. Shoemaker |
| A. Sibley | L. Wallace | A. Weinstein | R. Weiss |
| S. Whitcomb | J. Worden | M. Zucker | |

### cc:

B. Barish
G. Sanders
Chronological File
Document Control Center

# LIGO Change Request

**Change Request No.: CR-030008** **Date: April 29, 2003**

**WBS Element and Title: 3.2 LIGO Livingston Facilities**

**Originator: Mark Coles** **Telephone: 225-686-3113** **CCB Sponsor: M. Coles**

**Technical Change Description:**

**Furniture for the auditorium lobby, interaction area underneath the skylight atrium in the OSB, and on the second floor interaction area of the new laboratory/office building. Furniture is commercial grade for durability.**

**Quote, pictures, drawings, etc. retained in Change Request folder..**

**Budget Impact: $60,958**

**See next page (Additional Information).**

**Schedule Impact:**

**Concurrence Signatures:**

| | |
|---|---|
| Technical and Engineering Support: | Date: |
| Detector Support: | Date: |
| Advanced LIGO Development | Date: |
| Data and General Computing: | Date: |
| Hanford Observatory: | Date: |
| Livingston Observatory: | Date: |
| Project Controls Manager: | Date: |

**Approval/Disposition (CCB Chairman):** Date:

# LIGO Change Request

**<u>Additional Information</u>:**

LIGO

Interior design proposal—Final
Tim Moss
Hurwitz-Mintz
3/25/2003

Drawing #1—Conversational Area (included in CR Folder)

| Item | Qty | Price Each | Total |
|---|---|---|---|
| Kennet Sofa | 2 | $3660 | $7320 |
| Lisbon Chair | 2 | $1583 | $3166 |
| Visions Bookcase | 1 | $1467 | $1467 |
| Visions Console | 2 | $936 | $1872 |
| 48" Inspirations Table | 1 | $936 | $936 |
| Subtotal | | | $14,671 |

Drawing #2—Small Lounge (included in CR Folder)

| Item | Qty | Price Each | Total |
|---|---|---|---|
| Lisbon Chair | 3 | $1583 | $4749 |
| Visions End Table | 1 | $612 | $612 |
| 48" Inspirations Table | 1 | $747 | $747 |
| Visions Shelving | 1 | $1656 | $1656 |
| Subtotal | | | $7764 |

Drawing #4—Lobby/Auditorium (included in CR Folder)

| Item | Qty | Price Each | Total |
|---|---|---|---|
| 3-Seat Museum Bench | 5 | $1631 | $8155 |
| 2-Seat Museum Bench | 3 | $1235 | $3705 |
| Matinee Sofa | 2 | $3035 | $6070 |
| Matinee Chair | 2 | $2295 | $4590 |
| Matinee Pillows | 8 | $113 | $904 |
| Visions Dining Table | 1 | $1467 | $1467 |
| Visions End Table | 3 | $612 | $1836 |
| Visions Bookcase | 3 | $1467 | $4401 |
| Visions Pedestal. Small | 1 | $333 | $333 |
| Visions Pedestal Large | 1 | $369 | $369 |
| Visions Corner Table | 2 | $558 | $1116 |
| Cylinder Table | 2 | $369 | $738 |
| Lisbon Chair | 3 | $1583 | $4749 |
| Subtotal | | | $38,433 |
| Grand Total | | | $60,958 |

# LIGO Change Request

**Change Request No.: CR-030011** **Date: 16 May 2003**

**WBS Element and Title: Seismic External Pre-Isolation at LIGO Livingston Observatory**

**Originator: Kern, Coyne** **Telephone: 626-395-2034** **CCB Sponsor: D. Coyne**

**Technical Change Description:** The addition of an External Pre-Isolation (EPI) stage to the seismic isolation systems on the LIGO Livingston Observatories. This change is meant to improve the low frequency isolation of the currently installed seismic isolation systems as a retrofit with little or no disturbance to the alignment of the optics and without entry to the vacuum system.

LIGO.2.03.8 Seismic External Pre-Isolation at LIGO Livingston Observatory

LIGO.EPI/1 NSFLIGO.FY02CA Alias P352744 - EPI at Livingston

LIGO.EPI/2 NSFLIGO.FY02CA Alias P352751 - EPI at MIT

(See page 2 for additional information.)

**Budget Impact: $3,130K** from LIGO operations funds (most of the funds are needed in FY03; a small amount can be deferred to early FY04).

See page 2 for additional information.

**Schedule Impact: This is a schedule critical item.**

See page 2 for additional information.

**Concurrence Signatures:**

| | |
|---|---|
| Technical and Engineering Support: | Date: |
| Detector Support: | Date: |
| Advanced LIGO Development: | Date: |
| Data and General Computing: | Date: |
| Hanford Observatory: | Date: |
| Livingston Observatory: | Date: |
| Project Controls Manager: | Date: |

**Approval/Disposition (CCB Chairman):** Date:

# LIGO Change Request

**Additional Information:**

**Technical Change Description:** The addition of an External Pre-Isolation (EPI) stage to the seismic isolation systems on the LIGO Livingston Observatories. This change is meant to improve the low frequency isolation of the currently installed seismic isolation systems as a retrofit with little or no disturbance to the alignment of the optics and without entry to the vacuum system. The chosen approach at the outset was to accelerate the development of the pre-isolator intended for advanced LIGO. Since the baseline hydraulic actuator for the advanced LIGO system required considerable development, an alternate approach with a commercially available electro-magnetic actuator was also pursued. Recently a review of the two EPI approaches was held and the hydraulic external pre-isolator (HEPI) system was recommended for application at LLO. (see attached **LIGO-M030101-00**).

A comparison of the two approaches to each other and to the requirements is made in **LIGO-T030074-01** and **LIGO-G030226-00** (both attached).

Other review documentation are posted at
http://www.ligo.caltech.edu/~coyne/IL/EPI/review2/EPI_review2.htm

**Budget Impact:** $3130K from LIGO operations funds (most of the funds are needed in FY03; a small amount can be deferred to early FY04).

This is the total of an estimate for the following scope:

- HEPI systems for all 4 HAM systems and all 5 BSC systems at LLO,
- HEPI systems for all 3 HAM systems at LASTI,
- Structural modifications (stiffening and damping) for all HAM and BSC systems listed above, and
- Isolation systems for all ISC tables at LLO (based on Stacis commercial isolation systems)

This estimate is based on the prototype costs, with estimated production cost reduction, plus the estimated complement of required in-process and delivered spares but without contingency. All of the labor required for completion of design, fabrication oversight, assembly, test, installation and commissioning comes from operations staff (LLO, CIT and MIT), with the exception of a 4 month temporary engineering hire for LLO to support drawing modification/release and procurement and fabrication support.
**Cost estimate details are in attached LIGO-M030082-01.**

Options:

- Leave one LASTI HAM as a MEPI system
- Don't outfit all 3 HAMs at LASTI (only 2 are planned for use in adv. LIGO currently)
- Defer assembly, test and installation of more than a single HAM at LASTI (does not save much funds)
- Purchase commercial off the shelf components for LASTI later to defer payment till FY04 (may loose a quantity discount)

Note: We are reviewing the alloy for the bellows in the hydraulic actuator. If changed from 304SS to 17-7, this will add $110K to the total.

**Schedule Impact:** This is a schedule critical item. It is imperative that the seismic noise at Livingston be reduced so that interferometer up-time is increased for science runs and for commissioning efficiency (use of the instrument for noise studies during the day). The earliest start date for installation at LLO is estimated to be 10/1 if NSF review of the procurements which exceed $100K in value do not add delay. Although the time for NSF review is not known at this time, a realistic assessment is at least a few weeks of delay. The estimated completion date of the EPI commissioning effort is 13 Feb 2004.

A detailed schedule is given in attached M020142-08. This schedule does not attempt to include an NSF review cycle as yet until this is better defined. This issue is being worked by Phil Lindquist. A single package with all of the large EPI procurements is being prepared by Jonathan Kern and Ken Mason. We may argue a sole source on the welded assembly of the actuators since a number of problems during prototype assembly cost us dearly in parts and schedule. It is not possible to capture all of these 'lessons' into build-to-print drawings and specifications. We are nonetheless asking for quotes on the basis that the contractor replace all parts damaged from improper welding assembly.

LIGO LABORATORY
MS 18-34
PASADENA CA 91125

TEL: 626.395.2129
FAX: 626.304.9834

*MEMORANDUM*

DATE: May 16, 2003

TO: Dennis Coyne, Gary Sanders, Barry Barish
FROM: Stan Whitcomb for the EPI Review Committee
SUBJECT: EPI Review Committee Report
Refer to: LIGO- M030101-00-D

On April 18, a committee consisting of

Rana Adhikari
Mark Coles
Joe Kovalik
Nergis Mavavala
Fred Raab
Dave Trumper
Rai Weiss
Stan Whitcomb (chair)
Mike Zucker

met to review the status and progress of the EPI development for use at LLO. The EPI development team made presentations and provided back-up documentation for review. The material presented to the committee is available at:

http://www.ligo.caltech.edu/~coyne/IL/EPI/review2/EPI_review2.htm.

The charge to the committee was:

> “The issues/decisions for which we would like committee input:
>
> 0) Are we ready to commit (considerable) funds for the procurement of the hardware for an EPI system? If not, what milestones or tests/analyses should be completed before committing funds? Answering this question involves assessing the risk of failing to robustly meet requirements (stated or unstated) with the basic design(s) against the continued delay and impact to commissioning if pre-isolator deployment is further delayed. Of course, the development at LASTI can proceed in parallel with the procurement of hardware for the observatories, in particular for control law development, a VME compatible electronics and software implementation, structural plant improvements, supervisory control, etc. Since we cannot afford the procurement of hardware for duplicate sets of actuators, a decision to proceed with the procurement of hardware for the observatories means a selection between HEPI or MEPI. (Although some common parts can of course be ordered pending a later decision.)
>
> 1) With which approach do we proceed: HEPI or MEPI? or a combination of both. The development effort would benefit if focused on a single EPI design. Here we need evaluation factors and a careful, evaluation of the relative importance and ratings for each system. We will provide evaluation factors for the committee's consideration and will evaluate each system against these factors. The evaluation will not be binary, but will lay out the pluses and minuses with some narrative response to each evaluation factor. We then leave it to the review committee to review/critique the evaluation and make their recommendation. This is not designed to lead the committee, but rather to make their job easier. Ultimately it will be a management decision. At the very least by way of a CCB review to allocate the funds.
>
> 2) If the HEPI or MEPI approaches are shown to fall short of the established requirements, or perhaps do not have sufficient margin or robustness to eventual needs, in the committee's

> estimation, then do we proceed nonetheless hoping that the performance will be sufficient for some period of time or explore entirely different approaches?"

The committee commends the EPI team for its achievements and for its effort in making this review a success.

### *Findings*

The real requirements for EPI are not as well understood as we would like. The general correlation of poor locking and high ground vibration is clear, but the precise causes (which degrees of freedom, which frequencies, etc.) are still poorly identified. The performance requirements as written may be too stringent in some areas and too lax in others. A system that meets them should provide improved performance for the LLO interferometer, but may not be adequate for all conditions.

There is great urgency to move forward with EPI. The loss of duty cycle at LLO for both Science Runs and commissioning is a major impediment for achieving full operation.

Both actuator systems have demonstrated performance near the (admittedly uncertain) requirements, and the teams working on them deserve congratulations on this achievement. Detailed performance comparisons are difficult. Because the two actuators were applied to different chamber types with significantly different responses, it is difficult to determine whether the differences in performance are due to the actuator or to the plant to which it was applied. The committee heard arguments that the HEPI system offers a simpler control problem and a more robust solution, and the majority of the committee agreed with this assessment.

Neither system has shown a significant performance potential at the optic bounce frequency (~12 Hz). The lack of higher frequency isolation may eventually be a significant performance limit.

Earlier concerns about "other factors" in both systems (e.g., contamination and leakage for HEPI, magnetic field leakage for EPI) have been satisfactorily addressed and do not provide a clear preference for one system over the other.

### *Recommendations*

We recommend that the Lab move forward with procurement of an EPI system, without waiting for further testing or modeling.

To maximize the probability of success, we recommend that a single approach be selected and that all available resources be applied to that approach.

Although both systems have demonstrated their viability, the HEPI system appears to be the simpler to implement and may thus provide the most robust solution.

If the Laboratory adopts HEPI, we recommend that there be an aggressive campaign of continued development, in parallel with procurement. In particular the highest priority items are modeling the HEPI system applied on the HAM chamber, and understanding and improving the high frequency limits to isolation. The investigations into conditioning the mechanical plant in the MEPI work look very promising and can be applied fruitfully to either EPI and so should be further pursued.

**LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY**

*LIGO Laboratory / LIGO Scientific Collaboration*

LIGO-T030074-01-D *LIGO* 16 April 2003

# External Pre-Isolation (EPI) Evaluation

Dennis Coyne

Distribution of this document:
LIGO Science Collaboration

This is an internal working note
of the LIGO Project.

**California Institute of Technology**
**LIGO Project – MS 18-34**
**1200 E. California Blvd.**
**Pasadena, CA 91125**
Phone (626) 395-2129
Fax (626) 304-9834
E-mail: info@ligo.caltech.edu

**Massachusetts Institute of Technology**
**LIGO Project – NW17-161**
**175 Albany St**
**Cambridge, MA 02139**
Phone (617) 253-4824
Fax (617) 253-7014
E-mail: info@ligo.mit.edu

**LIGO Hanford Observatory**
**P.O. Box 1970**
**Mail Stop S9-02**
**Richland WA 99352**
Phone 509-372-8106
Fax 509-372-8137

**LIGO Livingston Observatory**
**P.O. Box 940**
**Livingston, LA 70754**
Phone 225-686-3100
Fax 225-686-7189

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

# 1 Introduction

The External Pre-Isolator (EPI) design effort was initiated in response to the need to provide better seismic isolation for the LIGO Livingston Observatory (LLO) environment. The concept was to accelerate the pre-isolation design effort already underway as part of the advanced LIGO seismic development. The advanced LIGO EPI system, as originally conceived, was to employ a quiet hydraulic actuator. Since the hydraulic actuator required considerable development risk, a commercial-off-the-shelf electro-magnetic actuator was chosen for a parallel effort to reduce the overall development risk. The EPI version using a hydraulic actuator is known as HEPI (Hydraulic EPI) and the EPI version using an electro-Magnetic actuator is known as MEPI (electro-Magnetic EPI).

In the interim period the Fine Actuation System (FAS) was used for active damping of the seismic support structure with feedback from sensitive (GS-13) geophones placed on the crossbeams near the piers. This Piezo-electric EPI (or PEPI) has control in the x-direction (optical axis direction) and yaw (rotation about the vertical axis) degrees of freedom.

Although MEPI was originally planned to be a fallback option only to be used if the HEPI development ran into problems, we have since found that the costs for the HEPI system are considerably higher than for the MEPI system. There are also positive and negative aspects for both systems. In addition, the PEPI system has been able to afford reasonable performance.

The purpose of this note is to (i) define appropriate evaluation factors, (ii) provide input to the design review committee on an evaluation of the relative importance and ratings for each system. The evaluation is not intended to be binary, but rather defines the pluses and minuses with some narrative response to each evaluation factor. We then leave it to the review committee to review/critique the evaluation and make their recommendation. This is not designed to lead the committee, but rather to make their job easier. Ultimately it will be a management decision. At the very least by way of a CCB review to allocate the funds.

This report is not considered complete as a few significant un-addressed (or insufficiently addressed) issues remain. Conclusions are therefore with caveats and may change as more information is gathered. Nonetheless it was felt important to define what we know (and don't know) now as input to a project level evaluation of the correct course(s) of action.

# 2 Evaluation Factors

## 2.1 Isolation Performance

The isolation performance is addressed by frequency band for steady-state performance, in accordance with the requirements[1]. There is also an added evaluation factor for the isolation performance for a transient event. In the appendix an alternative set of isolation performance criteria are also discussed. The absolute noise performance is basically dictated by the choice of low noise instrumentation, which are common to all of the EPI concepts. Consequently the focus of this evaluation is on the gain limited performance of the systems. The latest performance

[1] B. Lantz, et. al., "Initial LIGO Seismic Isolation Upgrade Design Requirements Document", LIGO-T020033-02, 26 Mar 2002

estimates/measurements and system identification measurements are reported in the design review presentations[2,3] and not here.

### 2.1.1 Drift

As far as we know both HEPI, MEPI and PEPI can meet the long term drift (1 month) requirement of less than 10 microns pk-pk, although this has not been verified experimentally. There is no reason to believe that either system is superior with regard to this requirement.

### 2.1.2 Tidal

Since the EPI system replaces the current piezo-electric Fine Actuation System (FAS), it must also perform tidal correction at the End Test Mass (ETM) chambers (2 BSC chambers). The feedback signal for tidal correction is derived from the interferometricly sensed cavity length and is common to all EPI instantiations. All EPI systems are inherently capable of performing this function and none is thought to be superior with regard to this requirement. HEPI has the most actuation range (± 1 mm), but the MEPI range (± 300 microns) is adequate. The PEPI range (± 90 microns) is adequate as compared to an original requirement of ± 60 microns[4] and inadequate (or marginal at best) against the revised requirement of ± 130 microns[5].

It should be noted that the isolation performance of the PEPI system while providing tidal correction has been tested at LLO. There is no noticeable degradation in performance when the PEPI actuators are operating at an offset from the null position.

The HEPI system has been operated off of the null position to investigate a bilinear noise coupling with source pressure noise. The supply pressure fluctuations were found to be low enough that this bilinear coupling mechanism is not a limiting noise source.

The isolation performance of the MEPI/HAM system when the actuation has a significant DC position offset has not been tested as yet. Since the maximum change in actuator response with a maximum offset (on axis or transverse to the actuation axis) is only 15%, it is not expected to be a problem.

### 2.1.3 Microseismic

Since the EPI system replaces the current piezo-electric Fine Actuation System (FAS), it must also perform microseismic feedforward correction. All derive the sensor correction, or feedforward, signal from a floor mounted STS-2 seismometer. All EPI systems are inherently capable of performing this function and none is superior with regard to this requirement. [Are the HEPI & MEPI systems better than PEPI because we can sensor correct the Kaman eddy current position sensor, rather than the internal strain gauge sensor in the piezoelectric actuator?]

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[2] B. Lantz, et. al., HEPI/BSC System Controls and Performance, LIGO-G03xxxx

[3] R. Mittleman, et. al., MEPI/HAM System Controls and Performance, LIGO-G03xxxx

[4] LIGO-T960065-03, section 3.2.1.7.1, pg. 20.

[5] LIGO-T020033-02, section 3.2.1.1.4.3, pg. 15.

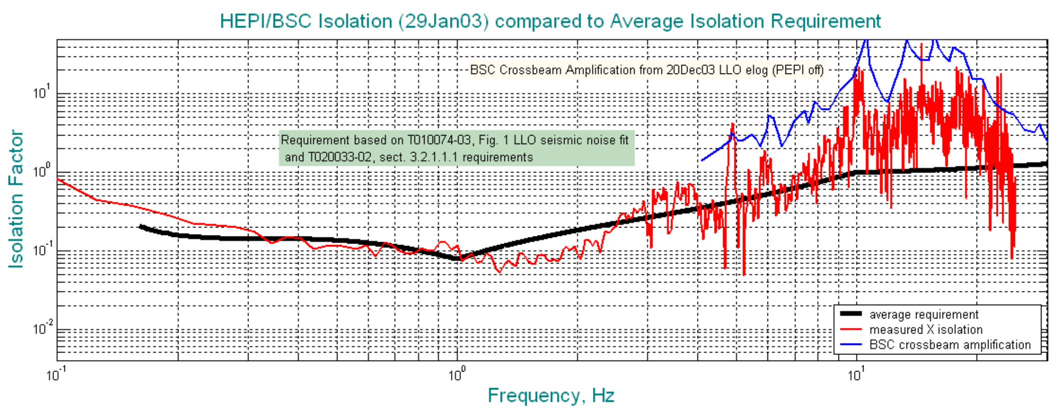
### 2.1.4 Stack Modes (1 to 3+ Hz)

At the LIGO Advanced Systems Test Interferometer (LASTI) facility, the HEPI isolation on a BSC platform and the MEPI isolation on a HAM platform have both basically met the gain limited performance implied by the requirements, in the 1 to 3 Hz band. Both systems can achieve a factor of ~15 reduction[6] across the 1 to 3 Hz band and more isolation at stack modes when resonant gain stages are added at the two lower stack mode frequencies. The PEPI system has demonstrated a factor of ~7 reduction in the rms at the support structure crossbeam (Figure 2.3). With use of resonant gain stages at the two lower BSC stack modes (1.2 Hz and 2.1 Hz), the rms reduction of the ITM-ETM relative velocity, in the 1 to 3 Hz band, is about a factor of 4 (Figure 4.3).

The measured MEPI/HAM isolation and the HEPI/BSC isolation are compared to the requirements in the following figures (see also the HEPI/BSC and MEPI/HAM Control and Performance presentations which are part of the 18 April 2003 EPI review). Some notes on isolation requirements are given in the appendix.

[Note: Should overlay requirement curve and crossbeam amplification on figures 2.2 through 2.4]

Figure 2.1: HEPI/BSC X-direction Isolation Performance vs Requirements
Note that more recent HEPI/BSC performance includes the addition of resonant gain at the lower stack modes.




[6] The factor of 15 reduction in the 1 to 3 Hz band limited rms is motivated in section 6 of T020033-02

Figure 2.2 HEPI/BSC X-direction Isolation ASD (control on and off) at LASTI

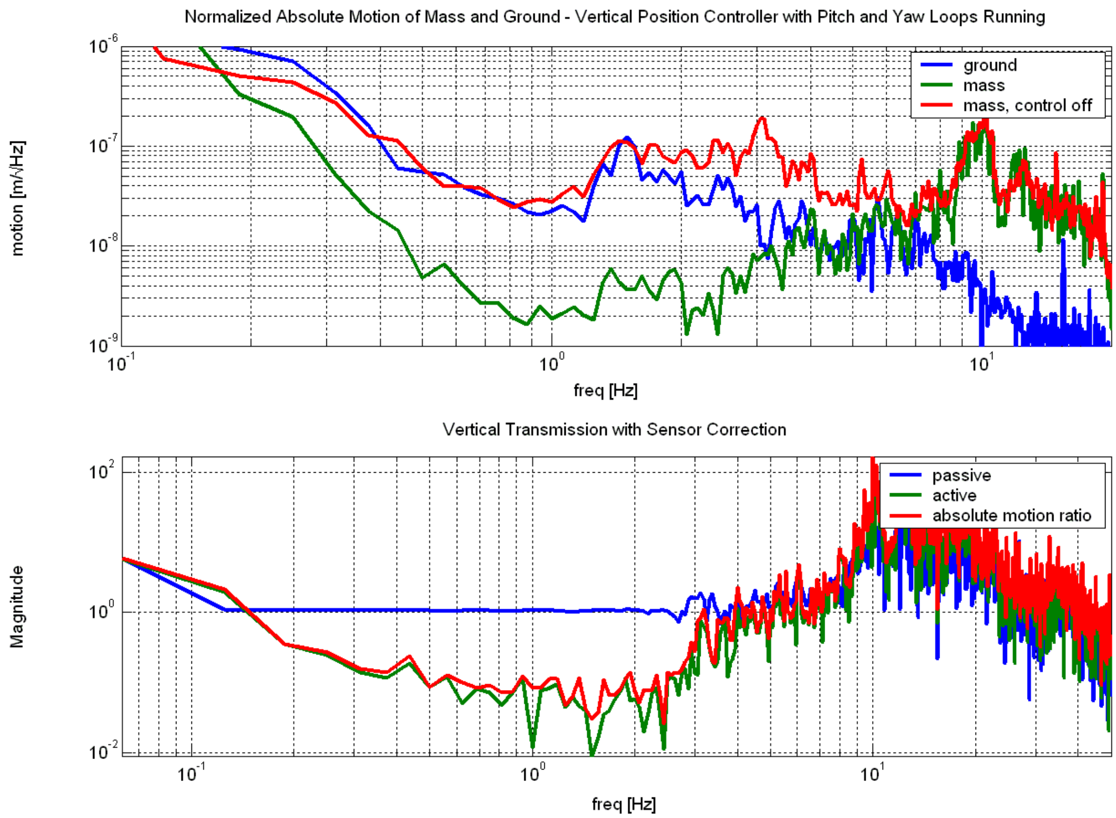



Figure 2.3 HEPI/BSC Y-direction Isolation ASD (control on and off) at LASTI

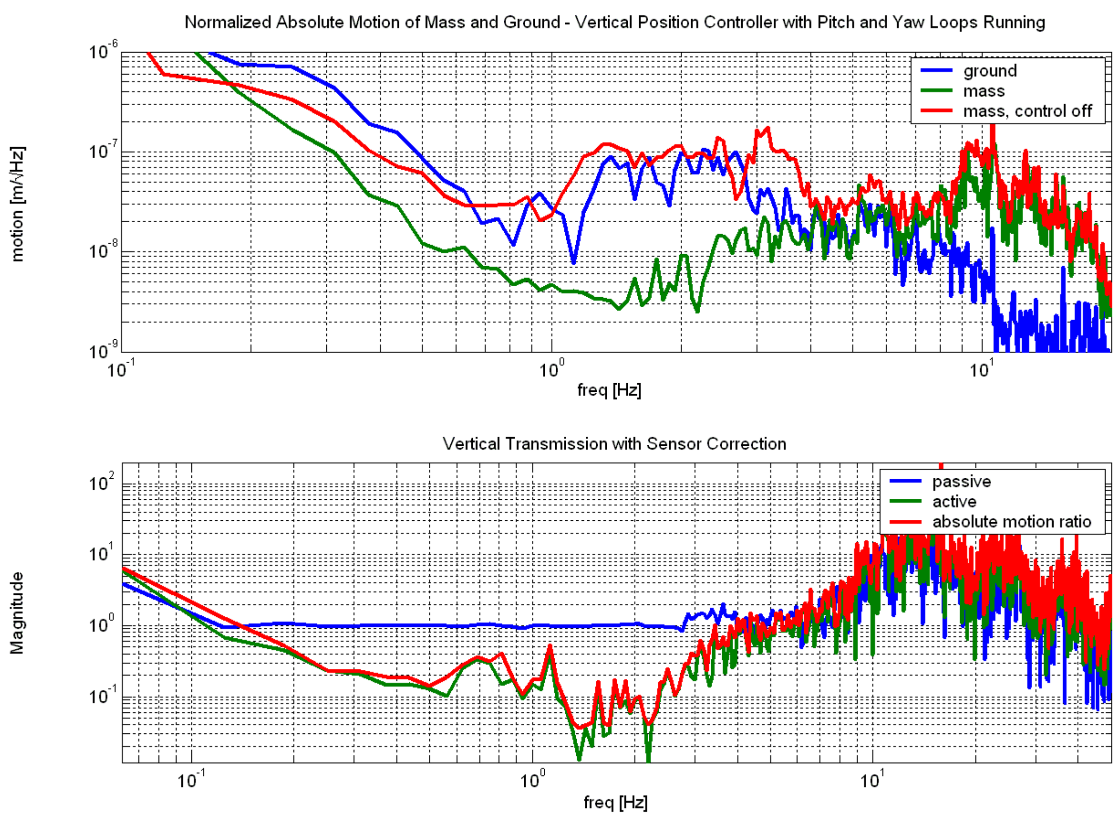


Figure 2.4 HEPI/BSC Z-direction Isolation ASD (control on and off) at LASTI

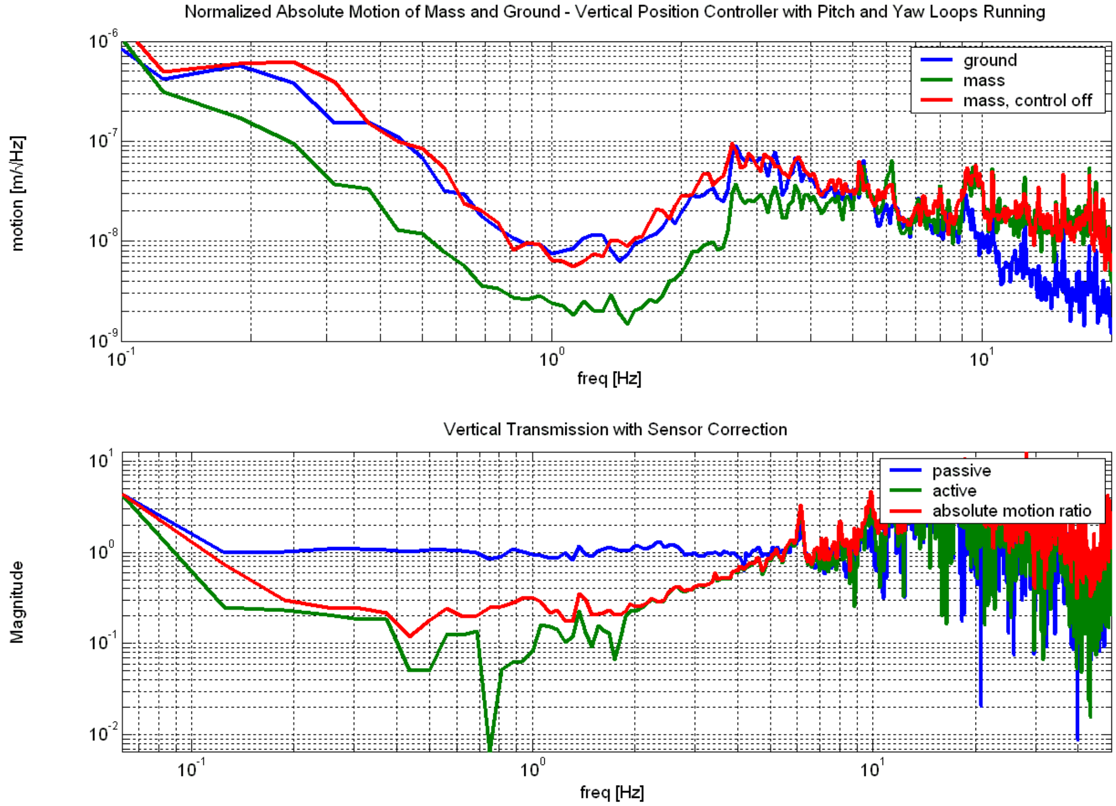
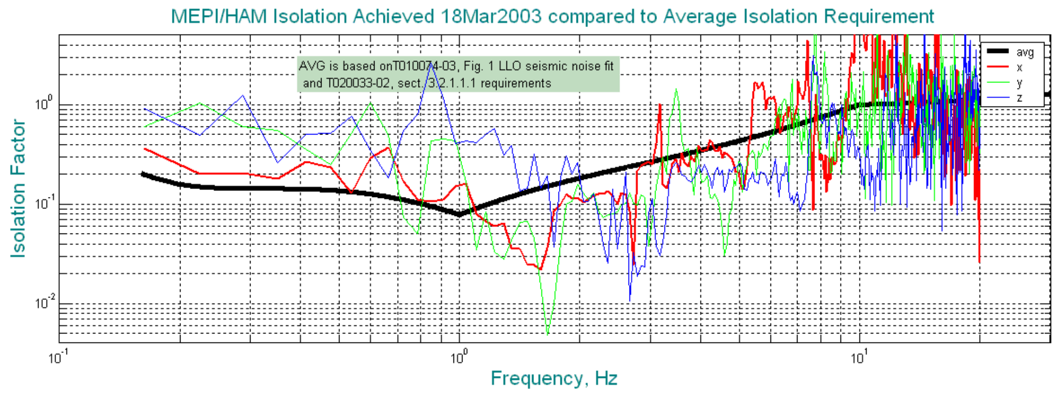


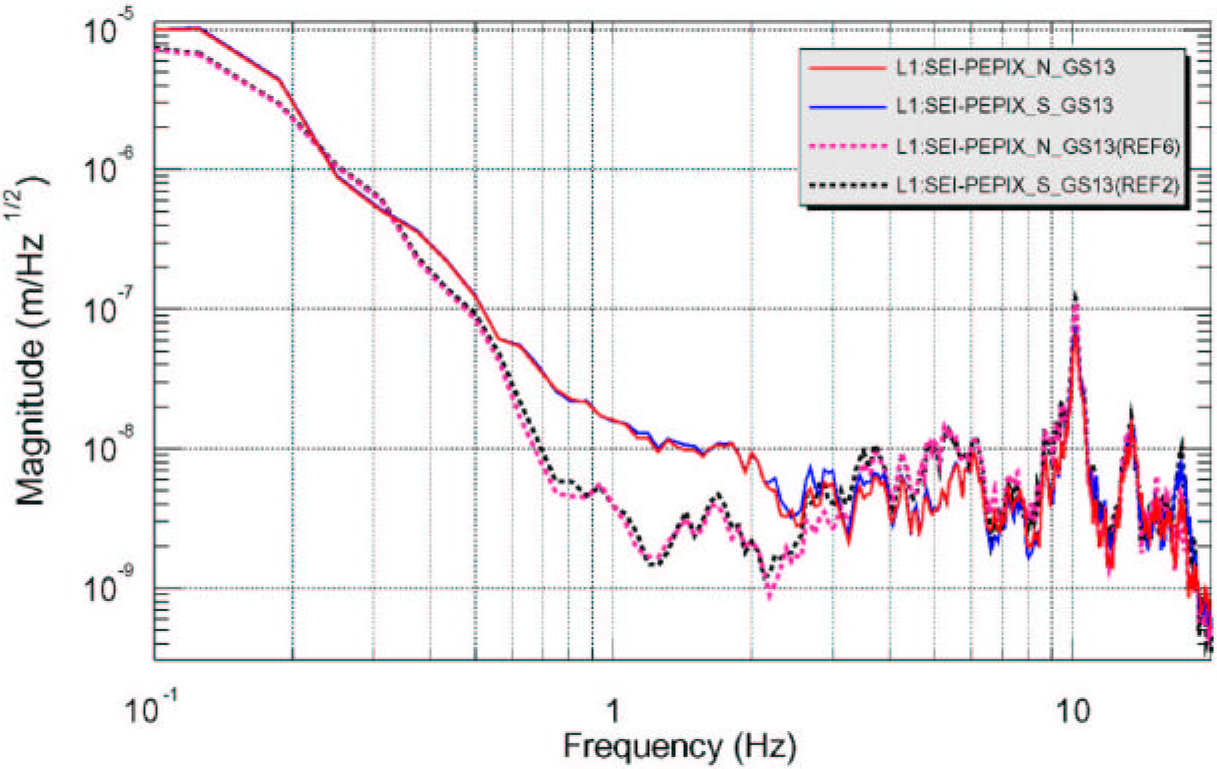

Figure 2.5: MEPI/HAM X-Direction Isolation Performance vs Requirements

Note that it is expected that the performance of the MEPI/HAM system below 1 Hz is can be improved through more optimal filtering and setting of the sensor correction gain.




[Note: Should include MEPI/HAM ASD, not just attenuation. See better and more recent MEPI/HAM isolation performance plots in D. Ottaway, R. Mittleman, presentation for the 4/18 review]

Figure 2.6: PEPI/BSC X-Direction Isolation Performance
Microseismic correction was off during this data capture.




### 2.1.5 "High" Frequency Noise (>4 Hz)

Considerable amplification of ground motion from ~4 Hz to ~25 Hz (up to a factor ~40) is apparent in both the HAM and BSC isolation responses. In fact this amplification is observed in the BSC crossbeams with the currently installed PEPI structures (with the PEPI system open loop), as shown in the appendix. Apparently this amplification is due to the dynamics of the piers and crossbeams. If one considers the transfer function of the passive isolation stack and the LOS pendulum, the amplification of ground noise above 4 Hz does not appear to be significant. This is addressed further in the form of revised, or alternative, requirements in the appendix of this document. As a minimum some allowance seems appropriate for amplification of ground noise above the control bandwidth. As noted in the appendix, this amplification of the ground noise does not add to the rms motion of the optics significantly. None of the EPI systems seem superior with regard to this evaluation factor.

### 2.1.6 Suspension Vertical Bounce Modes (~15 Hz)

It would be helpful if the EPI system could reduce the ground motion at the vertical bounce frequency of the suspensions (since this vertical bounce motion then couples into cavity length due to wedge angles (transmission) and non-vertical reflective surfaces). The Large Optics Suspensions (LOS) have bounce modes at ~12 Hz, while the Small Optics Suspensions (SOS) have bounce modes at ~15 Hz (steel wires) and ~19 Hz (Mo wire). The PEPI system has no actuation in the vertical direction. One can imagine that a resonant gain stage in the feedback controller, for either HEPI or MEPI, might be able to afford some noise reduction at these bounce mode frequencies. This seems possible for MEPI on the HAM where the upper unity gain points in the vertical mode is ~60 Hz. HEPI should likewise be able to get a high upper unity gain in the vertical mode. [To date this has not been tried on either HEPI or MEPI, either by simulation or by test.]

### 2.1.7 Transients

Transient noise events can cause the interferometer to break lock. All testing and modeling to date has been on quasi-stationary ground noise. This is clearly the usual condition even during periods of elevated noise (such as when the train passes at LLO). However, sudden sharp transitions in ground velocity may not be as well attenuated as the steady-state performance. [Can we make relative/qualitative statements about the systems on the basis of maximum slew rate?]

## 2.2 Form, Fit, Function

Mechanical interferences, thermal control, electronics packaging, etc. all seem to be within acceptable limits for all of the EPI systems on all of the platforms. This does not appear to be a discriminator.

## 2.3 Contamination

Neither the PEPI not the MEPI systems present contamination risks to the LIGO Ultra-High Vacuum (UHV) systems. The hydraulic fluid used in the HEPI system presents a small risk of contamination:

- Exposure tests[7] in the LIGO high irradiance optical exposure cavities, of the hydraulic fluid used in the LASTI prototype, indicates no observable effect on optical absorption (0.2 +/- 0.4 ppm/year compared to a requirement of < 2 ppm/year) or optical scattering (-8 +/- 2 ppm/year compared to a requirement of <10 ppm/year).
- There have been no leaks in the system after about 3 months of operation.
- We have replaced one servo-control valve in situ with no problems or fluid contamination.
- The fluid used is a clear, water soluble, non-toxic, non-flamable fluid with bio and corrosion inhibitors. No biological growth has been observed after 18 weeks of exposure to air and after seeding. Lubricity is adequate according to the manufacturer and there isn't evidence of any problems after running for 3 months.
- The HEPI application is low pressure (< 100 psi) and all fittings are face sealed o-rings or hermetic (with the possible exception of some isolation valves which can be double sealed).
- The design of the pump station controller has incorporated monitoring of a fluid level sensors which can be used to trigger a shut down in the event of loss of a small amount of fluid
- The pump station can be enclosed in an outer box with air exchange to the outside environment if concern about integrated exposure of possible small leaks over long periods remains; We do not think that this is needed.

[7] LIGO-T030023-00

## 2.4 Environmental Disturbances

### 2.4.1 Magnetic Field and RFI

The RFI and EM field emissions by the control electronics and power supplies common to all the EPI systems are not any more significant than other LIGO control electronics now in the high bay (Vacuum Equipment Area (VEA) spaces). However the MEPI system presents a potential hazard for (i) elevated magnetic fields leaking from the electro-magnetic actuator and (ii) possibly increased RFI emissions (radiated and conducted) due to the (likely) need for a switching supply for the 10A coil drivers. Analysis[8] on the basis of measurements on the radiated magnetic field coupling to the test mass magnets indicate that shielding would be required to ensure that the effect of magnetic field coupling to the test masses is well below the Science Requirements Document (SRD) performance requirements. The shielding would require a 2.5 mm thick inner steel box surrounding by a thin mu-metal foil. This magnetic shielding has not been designed or built to date, but does not present any significant problems.

The 10A coil drivers are sized for peak advanced LIGO needs. For initial LIGO, the ETMs in the X-direction only, would require about 3A continuously (at the peak range of the tide). The vertical direction should need only about 1A peak under normal operating conditions. If one considers the power supply used in the tidal servo (HP6267B; 40 volt, 10A) or similar HP units, they require about 5U of rack space and cost a few $1K. These supplies almost universally use a circuit called a pre-regulator. The pre-regulator uses a thyristor or scr to chop the input AC waveform to limit the power dissipation on the series pass transistor bank, thus improving the efficiency and size of internal elements in the supply. The "chopping" may rival a switching supply so far as dV/dT, and dI/dT, which might be a problem for RF emission. Perhaps it is best to consider putting the supplies (or at least the supply for the ETM horizontal actuators) far away from the loads (e.g. in the mechanical rooms) and running cables to the chambers. At any rate this is not an insurmountable problem.

### 2.4.2 Acoustic and Seismic Noise

The acoustic and seismic noise generated by the control electronics and power supplies common to all the EPI systems are not any more significant than other LIGO control electronics now in the high bay (Vacuum Equipment Area (VEA) spaces). The HEPI system requires a hydraulic fluid pump stations (one for every two chambers in the current design) which would reside in the mechanical room slab. The motor and pump rotate at 20 rps. Both the motor and pump are balanced and have some mechanical isolation from the slab. These are small, but additional, noise sources added to the mechanical room. No measurements on the floor induced motion from the prototype pump station have been made to date.

## 2.5 Reliability

This reliability assessment is based upon engineering judgment and no data on mean between failure (MTBF) or for repair (MTBR). The MTBF for the electronics should be about the same for all EPI systems and not significantly different than for other LIGO control electronics.

[8] LIGO-T030072-00

- The MEPI actuator is over-rated for its application and should run cool[9] and does not present a significant repair/replacement risk.
- The position sensors of both the MEPI and HEPI systems (Kaman eddy current transducer) are fragile and represent a risk for initial installation. However, once installed should not represent an increased risk for failure or repair.
- The PEPI system does not have any low MTBF/MTBR components either. Although piezo-electric actuators are sensitive to lateral loads and so there is a risk of failure during installation or coarse re-alignment, we have had no failures to date in LIGO.
- The HEPI actuator though a complex system has no parts which should fail or wear, with the exception of the servo-control valve. One unit had an intermittent failure after relatively few test hours on the LASTI BSC system (the flapper apparently went into a flutter oscillation; the cause is still unknown). Replacement with a new unit (approx. $700 hardware cost) was done in about 1 hour.
- The HEPI pump station should have long mean time between servicing/inspection and possible replacement of filters (order of 4 to 12 months). Pump and motor life should be years. Although the pump station represents an added complexity, as compared to the MEPI power supply, the reduction in system reliability should be small.

## 2.6 Robustness

### 2.6.1 Control

#### 2.6.1.1 Position Sensor Correction

All of the isolation provided by the HEPI system, except for the additional isolation afforded by resonant gain stages at the two lower BSC stack modes, is obtained from sensor correction (feed forward, inertial correction to the position sensor used in position feedback control). All of the low frequency isolation (lower than the blending frequency of the position and geophone sensors, or ~0.5 Hz) on the MEPI system is due to sensor correction. The same is true for the PEPI system. The sensor correction control concept common to all EPIs is to use a sensitive, low noise, low frequency response seismometer (the Streckeisen STS-2) mounted on the slab "near" the chambers. Mechanical interaction from the actuators to the seismometer has not been observed in the thick slab at LLO with PEPI and can be controlled at LASTI (with a much thinner slab) by appropriate placement of the seismometer. Mechanical interaction of one chamber with the next chamber (through reaction forces/torques in the slab) has not been tested or analyzed to date, but is not likely to be a problem.

Although there is some evidence in the HEPI/BSC testing that the optimal sensor correction gain may not be stationary, this has not been confirmed and is hard to understand, if real. One would expect that baring aging of the sensors, the transfer functions from the ground motion to seismometer, and from the ground motion to the position sensor response, should be quite stable on any of the EPI platforms. The variation might be due to changes in the directionality (or mode of coupling) of ground noise sources in the LASTI environment. If real, based on rather limited

[9] LIGO-T030072-00

experience to date, this effect might limit broad band isolation performance (0.1 to 3 Hz) to a factor of about 5 instead of 10, or better, if sensor correction gain was not adaptively re-tuned.

The sensor correction concept relies upon good correlation between the seismometer and the displacement sensor; The correlated frequency range is typically from < 0.1 Hz to ~3 Hz (and occasionally higher at LASTI) for the HEPI/BSC system.

Since we plan to use the PEM STS-2 seismometers as feedforward sensors to the EPI systems, we will not have independent PEM seismometer sensors, unless additional units are purchased (at $14K each).

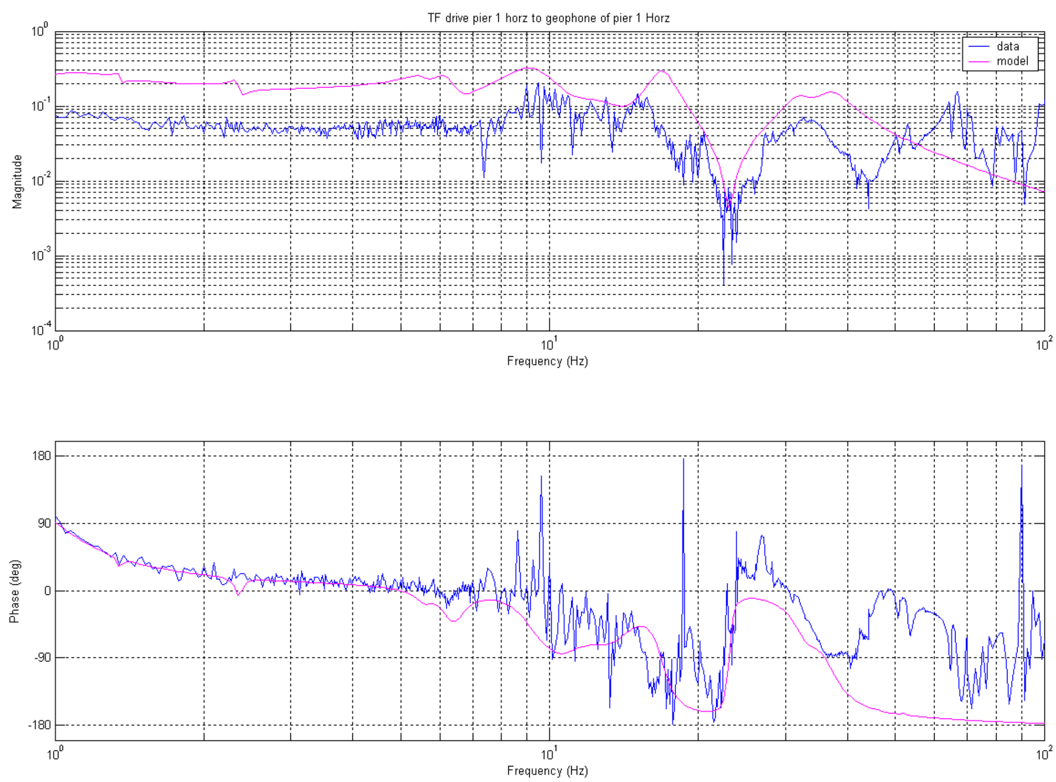
### 2.6.1.2 Velocity Feedback Control

In order to extend the control bandwidth, geophones were designed into the EPI systems collocated, and co-axial with, the actuators. These geophones are intended for use in inertial velocity feedback to the actuators.

#### 2.6.1.2.1 HEPI on the BSC Platform

With the high Q pier resonance at 23 Hz and the bellows breathing mode resonance (in the hydraulic actuator) at 47 Hz (Figure 2.7), it is not practical to get any significant broadband control authority by feeding back the geophone signal to the hydraulic actuator. Resonant gain stages have been added at the two lower BSC stack modes to increase isolation gain at the these stack modes.

Figure 2.7: HEPI/BSC Horizontal Actuator to Horizontal Geophone Transfer Function



#### 2.6.1.2.2 HEPI on the HAM Platform

Simulation results are pending. We expect a much better behaved plant since the quasi-rigid body modes will be much higher (out of the control band) and they will be well damped (passively) by the HEPI actuator. The bellows breathing mode resonance at 47 Hz will still be a limitation.

#### 2.6.1.2.3 MEPI on the BSC Platform

Simulation results are pending. We expect that the pier resonance will be less of a problem for the MEPI system than for the HEPI system. The pier resonance will couple to the geophones through the offload springs, but no longer through the actuator. The actuator reaction mass will be much less at the pier resonance, but it should still be possible to invert the response and push the bandwidth above the pier resonance.

#### 2.6.1.2.4 MEPI on the HAM Platform

Modal control of the MEPI/HAM system at LASTI has been successful after stiffening the HAM crossbeams with the addition of the stiffening beam. The control objective (in response to the requirements as posited in T020033-02) has been broadband control with > 10 Hz upper unity gain and significant gain in the 1 to 3 Hz band. To this is added resonant gain stages at the two lower HAM stack modes (1.7 Hz and 2.5 Hz). In order to achieve this control with the quasi-rigid body modes (from 3.0 to 9.3 Hz by modal survey[10] prior to the stiffening beam attachment), it has been necessary to implement partial plant inversion to recover phase; By partial plant inversion we mean not a precise inversion of the phase loss for in-line resonance, but rather a broad gain and phase bump (with a zero-pole pair) which very approximately recovers the phase loss and should be fairly robust to shifts in the precise frequency or narrowness of the transfer function features. Either 2nd order notch filters and/or elliptic low pass filters are used to suppress the 'forest' of high Q modes just beyond the upper unity gain point. The resulting control laws, for each of the eight global modes, typically employ ~8 pole-zero pairs for loop shaping, ~3 pole-zero pairs for partial plant inversion, ~3 second order resonant gain stages for stack mode suppression or high Q, high frequency support structure suppression and a second order elliptic filter. Although plant inversion is generally to be avoided because it is not robust to plant variation, in the LIGO application the plant should not change - at all; The entire system is in a temperature controlled environment, the payload is not varying, the alignment is not varying - it is as stable a plant as one might imagine. The bottom line is that the control is not overly complex and should be robust.

### 2.6.2 Alignment (angular and translational)

There is no requirement for active (dynamic or DC) alignment (angular or positional) other than tidal correction (which is covered above). However there is a "goal" of ± 1 mm range to (i) permit month long continuous locking and (ii) (presumably) to allow for translation of an optic (optics table) to effect an intentional de-centering of the beam (either vertically or horizontally) with the intent of finding the optimal position with respect to minimizing sensing noise, and (iii) (presumably) to correct aperture clipping in the optical port relay optic chains within the vacuum system. Only the HEPI system can achieve the goal of ± 1 mm of positional range.

Since de-centering on the test mass optics can be accomplished by 'walking the beam' in the input optics section with suspension system controllers, the need for de-centering capability in the seismic isolation system is not significant.

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[10] LIGO-G030187-00

### 2.6.3 Passive performance

In the event of a failure of the active controls, the EPI systems behave differently. The HEPI system provides significant passive damping (?% or Q?) to the rigid body modes of the support structure, which are created by the addition of the offload springs. The PEPI system provides a similarly stiff connection between the support structure and the pier. In contrast, when uncontrolled, the MEPI system has quasi-rigid body modes (six modes between 3.0 to 9.3 Hz) and elastic bending/torsion modes (9 modes from 9.9 to 20 Hz), which amplify the ground motion. It is not clear that this graceful degradation to a state of approximately "no worse than not present" when uncontrolled merits much value, but it is a comforting feature in the HEPI and PEPI systems.

### 2.6.4 Earthquake Response

No analysis has been performed to determine the effect of any of the systems in an earthquake. This is not a significant factor for the LLO location, but would be if the EPI systems are fielded in the LHO facility.

## 2.7 Compatibility with Advanced LIGO

The PEPI system is not in accord with the advanced LIGO design, which calls for a 6 degree of freedom pre-isolator system. HEPI systems are compatible with the advanced LIGO system as presently designed. MEPI systems are probably compatible with the advanced LIGO system as presently designed, but this has not been explored.

## 2.8 Applicability to LHO Wind Noise

The applicability of the EPI systems to the wind induced seismic noise at LHO has not been studied; This is a significant open issue. The current (technically unsupported) planning baseline is to move the four PEPI systems at LLO to LHO, when either HEPI or MEPI are installed at LLO. To these four PEPI systems we would add the sensor and electronics systems required to complement the four Fine Actuation Systems (FAS) currently on the ETMs at LHO, resulting in PEPI systems on all test mass chambers for the two LHO interferometers. It is unclear at this time if pre-isolation systems are required on the HAM chambers at LHO.

Recently it has been observed[11] that the control signals in MICH and PRC are completely dominated by the 12 Hz LOS vertical bounce modes, at the level of 1000 counts p-p during 20 mph winds. If the vertical bounce modes require isolation then PEPI systems will not be sufficient. Furthermore, as indicated in section 2.1.6, the capability of the HEPI and MEPI system to effect significant isolation at the vertical bounce modes is as yet unproven.

## 2.9 Cost

The costs for the systems are roughly:

- $125K/chamber for a PEPI system (with GS-13 geophones). The cost of the PEPI system could be reduced from it's current implementation (with GS-13 geophones borrowed from the advanced LIGO effort) by use of L4-C geophones, which would bring the total down to $98K/chamber.

[11] N. Mavalvala, LHO elog, 15 Apr 2003.

- $160K/chamber for a MEPI system, and
- $251K/chamber for a HEPI system.

These costs do not include:

- any structural modifications (stiffening or damping) which might be required (or desired) on the seismic support structures (and are presumed to be common to any EPI system).
- Seismic isolation of the ISC tables with optical readouts, which are likely to be required to prevent fringe wrapping. This might be accomplished with commercial-off-the-shelf units such as TMC's Statis system (at ~$35K per table for a set of three - should check this estimate)
- There is no contingency in the above estimates and a healthy (often 30%) reduction in unit costs over the prototype unit costs have been assumed for production

## 2.10 Extensibility

The requirements were motivated by the coincidence of what seems achievable and a vibration level which does not currently limit interferometer noise performance. However, we have not yet achieved the design noise floor of the LIGO interferometers. As the interferometer improves, we may yet reveal a nonlinear coupling which up-converts the at low frequency residual motion into in-band noise. Consequently it would be good to know if there are ways to extend the performance of the EPI systems in the future.

HEPI could be augmented with a reaction mass actuator mounted on the crossbeam with higher frequency control authority to complement the low frequency (sensor correction) compensation by the hydraulic actuator. One could also add optical levers to sense the bending modes of the crossbeams and use this to correct the tilt coupling to the geophones. Low frequency performance is not likely to be significantly improved over the current performance.

MEPI low frequency performance is also not likely to be significantly improved over the current performance. Stiffening and increased damping of the support structure, particularly for modes near the upper unity gain frequency, could increase the bandwidth and performance of the system.

# 3 Summary

The state of the evaluation of the HEPI and MEPI systems against each of the factors described above is summarized in the table below. PEPI does not quite meet performance requirements, nor does it allow for future extensibility and improvement. Both HEPI/BSC and MEPI/HAM will meet requirements.[12] However further simulation and testing is needed to be absolutely sure that either system will perform on either the BSC or HAM chamber. Given the large cost differential between the HEPI and MEPI systems, I recommend that the following steps be taken:

1) Complete the simulation of the performance of a MEPI system on a BSC plant to verify assumptions that the MEPI/BSC system will meet requirements,

[12] Will meet requirements with allowance for amplification of ground noise, at the support structure, in the 4 to 40 Hz region, when accompanied by attenuation at the vertical bounce mode of the suspension systems. As indicated in the appendix this does not significantly effect the total rms motion.

2) Move the MEPI system from the HAM to the BSC at the LASTI facility and verify the performance by test,

3) Order all long lead items common to HEPI and MEPI designs,

4) Migrate the control from dSpace to VME compatible hardware (in parallel with continued prototyping in the dSpace environment)

Table: Summary Evaluation of HEPI and MEPI

| | HEPI | | MEPI | | PEPI | |
|---|---|---|---|---|---|---|
| | BSC | HAM | BSC | HAM | BSC | HAM |
| **Isolation Performance** | | | | | | |
| **drift** | OK | OK | OK | OK | OK | OK |
| **tidal** | OK | OK | OK | OK | OK | OK |
| **microseismic** | OK | OK | OK | OK | OK | OK |
| **stack modes (1 - 3+ Hz)** | >15 iso | TBD | TBD | >15 iso | ~7 iso | ? |
| **vertical bounce mode (~15Hz)** | TBD | TBD | TBD | TBD | No | No |
| **low noise at high freq (>10 Hz)** | housing & crossbeam modes damped? | housing & crossbeam modes damped? | housing, RB & crossbeam modes amplify | housing, RB & crossbeam modes amplify | crossbeam modes amplify | crossbeam modes amplify |
| **Transient** | ? | ? | ? | ? | ? | ? |
| **Form, Fit, Function** | OK | OK | OK | OK | OK | ? |
| **Contamination** | low risk | low risk | none | none | none | none |
| **Environmental Disturbance** | | | | | | |
| **Magnetic Field** | NA | NA | need mu-shield | need mu-shield | none | none |
| **RFI** | OK | OK | remote PS? | remote PS? | OK | OK |
| **Acoustic, seismic** | minimal, pump in mech rm | minimal, pump in mech rm | none | none | none | none |
| **Reliability** | lower | lower | higher | higher | highest | highest |
| **Control Robustness** | | | | | | |
| **Control** | OK < 3Hz complex > 3Hz | best | don't know yet | OK | OK | ? |
| **alignment** | OK | OK | OK | OK | OK | ? |
| **passive performance** | OK | OK | poor | poor | OK | OK |
| **Earthquake response Note: not a factor for LLO** | ? | ? | ? | ? | ? | ? |
| **Comaptibility with Adv. LIGO** | OK | OK | probably | probably | No | No |
| **Applicability LHO Wind Noise** | ? | ? | ? | ? | ? | ? |
| **Cost** | 2.0x | 2.0x | 1.3x | 1.3x | 1x | 1x |

# 4 Appendix: Revised Isolation Requirements

The isolation requirements in LIGO-T020033-02 (section 3.2.1.1.1) are stated in terms of absolute displacement noise performance at the support structure. These requirements do not take into account the amplification of the noise by the passive isolation stack. A better, or at least alternate set of requirements, which allows for meeting performance objectives by reducing support structure vibration at the stack resonances is needed. Furthermore, since our testing is performed in the noisy Cambridge environment (LASTI) we need requirements stated in terms of gain limited isolation performance.

Recently it was pointed out that the presence of the pier and support structure dynamics causes an amplification of the ground noise in the ~10 to ~50 Hz range, as shown in Figure 4.1. This additional noise is common to any EPI system and cannot be significantly reduced (the upper unit gain points for the MEPI loops are about 30 Hz).

If a fit to the crossbeam ground noise is then multiplied by the BSC stack transfer function and the horizontal transfer function of the LOS, the velocity amplitude spectral density shown in Figure 4.2 results, for the horizontal (optical axis) motion of an LOS mounted on the BSC optics table without the benefit of any pre-isolation. It is apparent from figure 4.2 that the largest contributions to the rms motion of the optic along the optical axis is from the microseismic peak at ~0.15 Hz, the LOS positional mode resonance (with the suspension controller tuned to a Q of 10) and the first two stack resonances (at 1.2 Hz and 2.1 Hz), even when one includes the amplified ground noise due to the presence of the support structure. Using the locked interferometer control signals to infer the relative motion of the ITM and ETM (Figure 4.3) one reaches a similar conclusion. However, from this measurement one observes that there is a much larger relative contribution to the total rms from the stack modes at 2.1 Hz and ~7.5 Hz.

[More work is needed here to complete a crisp restatement of the requirement for the X & Y-directions and to state a requirement for the Z-direction.]

## Figure 4.1: Ground Noise Amplification at the BSC Crossbeam

In this graph, ground noise measured by the STS-2 located in the PEM area (near ITMY) is compared with vibration seen by a crossbeam-mounted GS-13 on the ITMX BSC SEI frame. The two signals track well, with good coherence, below about 2 Hz (apart from a slight calibration difference that I have not yet resolved). Above 2 Hz, though, the crossbeam moves a lot more, showing the resonant peaks in the external SEI structure, and without much coherence with the slab motion in the same direction. PEPI is off for this measurement. (LLO 20Dec2002 elog)

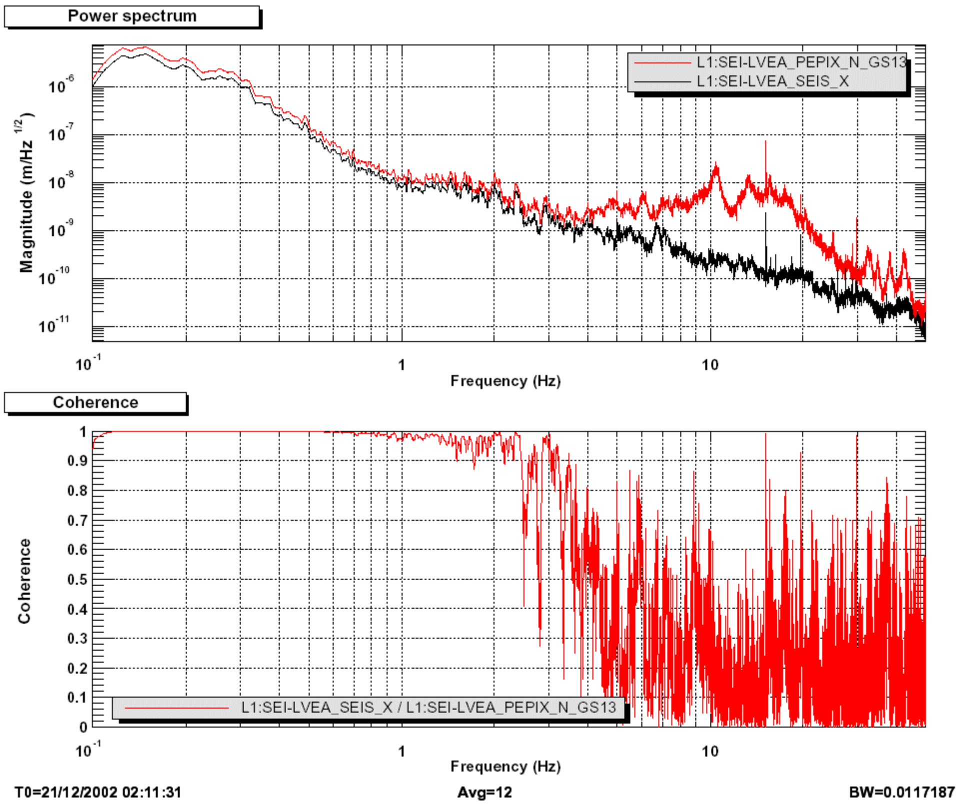


Figure 4.2: Predicted Velocity ASD for an LOS Optic on a BSC optics table
(Using a fit to the crossbeam vibration spectrum, the BSC stack transfer function and the LOS transfer function)

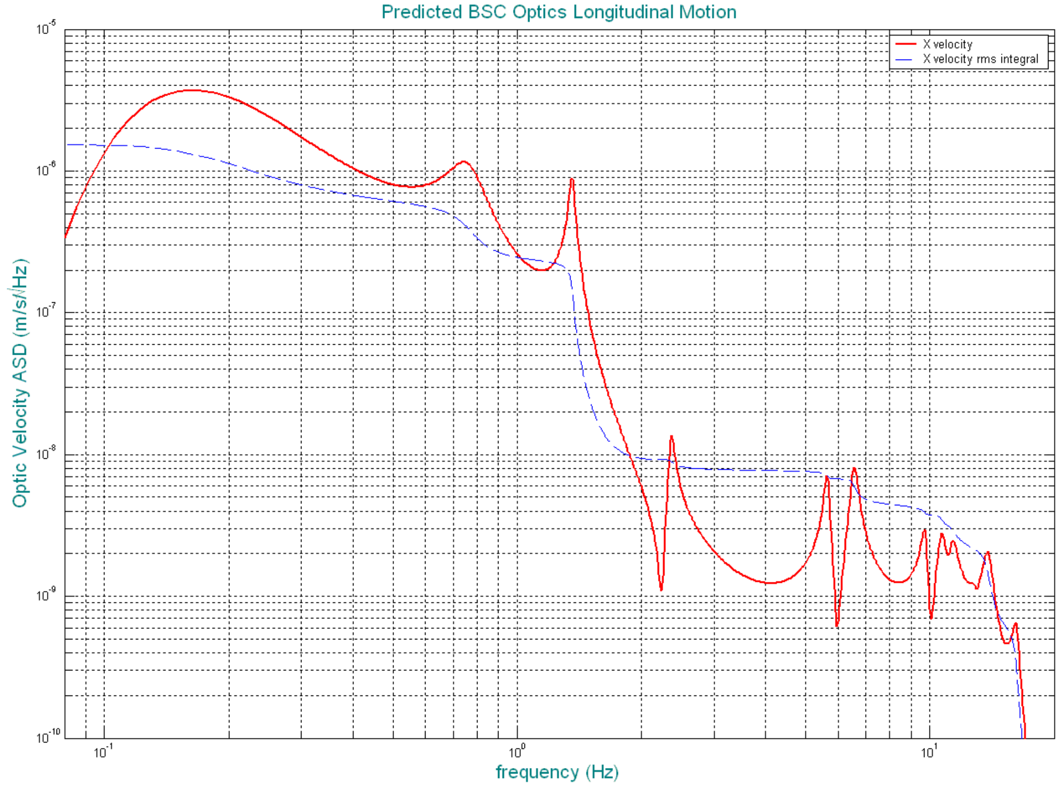
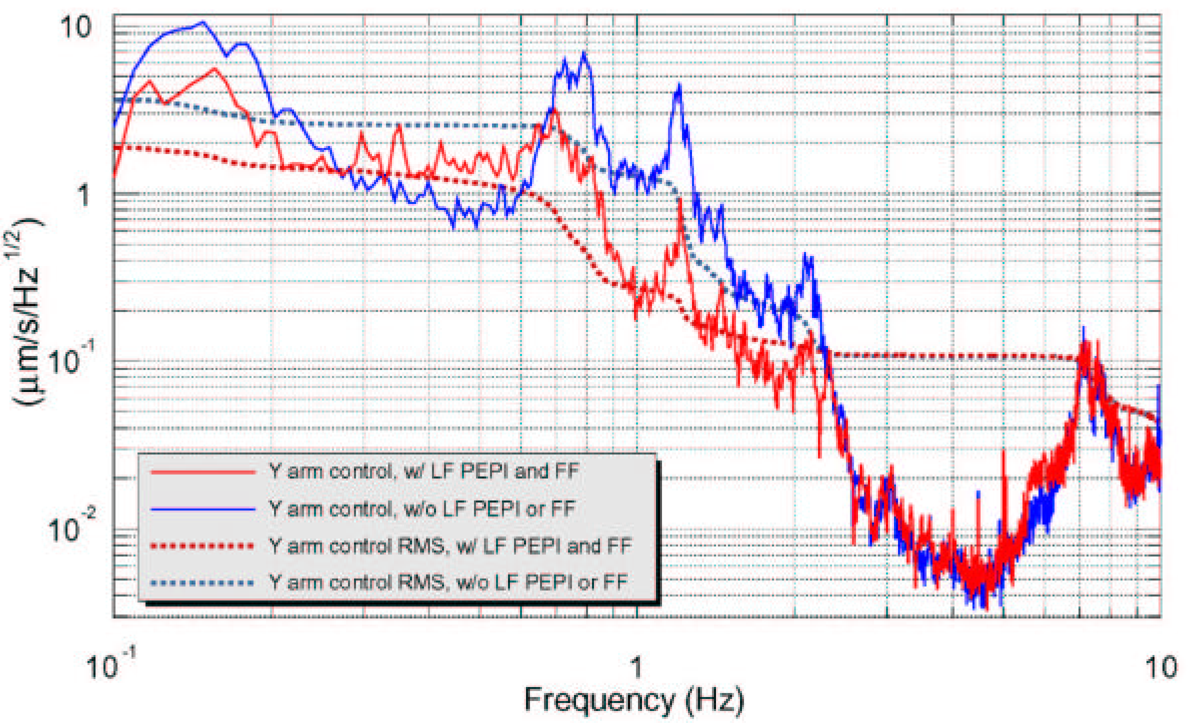



Figure 4.3: Velocity between ITM and ETM inferred from locked control signals



# *Evaluation of EPI Approaches*

Dennis Coyne

18 April 2003

EPI Design Review #2

# Evaluation of EPI Approaches

- HEPI is the default or primary approach
  - » MEPI was conceived as backup to reduce risk
- Both systems appear to meet requirements
  - » both systems have pros and cons
  - » Both have remaining uncertainties
  - » It is reasonable & responsible to revisit the choice of a hydraulic actuator (chosen for adv. LIGO) in this application for initial LIGO
- Evaluation
  - » Comparison to PEPI is needed to insure that the increment in performance justifies the cost
  - » Factors have been proposed with the intent of choosing between HEPI or MEPI
  - » There are differences of opinion on the relative importance of these factors and the on the evaluation of some of the factors
  - » Answers are not currently known to all evaluation questions

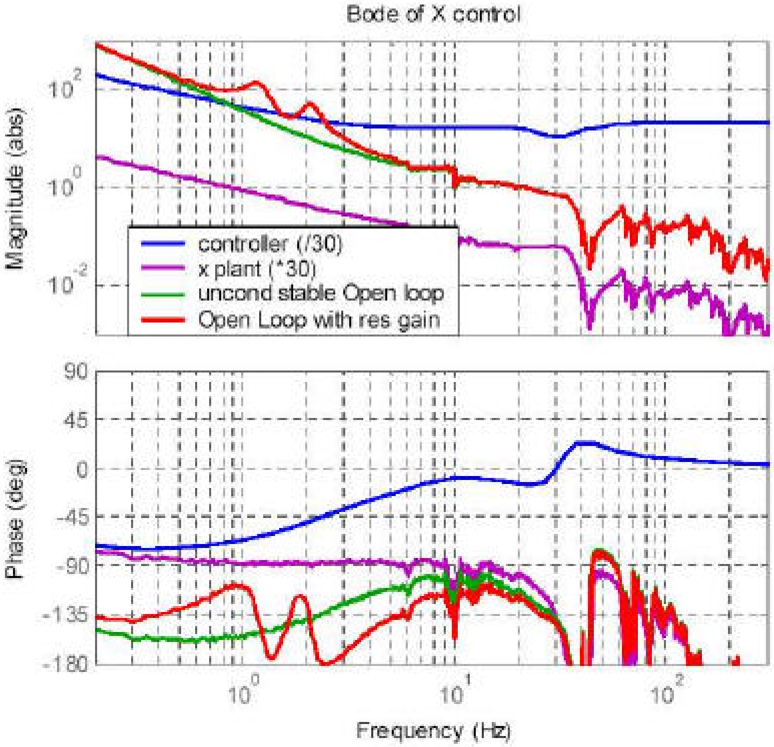
# *Evaluation of EPI Approaches*

- Sensing
  - » All rely upon interferometric sensing for tidal correction
  - » All rely upon the STS-2 for microseismic sensing
  - » PEPI uses a GS-13 geophone mounted near the actuator, but atop the crossbeam
  - » HEPI and MEPI both use co-located and co-axial eddy current position sensors and L4C geophones; i.e there is no difference in the sensing

# Evaluation of EPI Approaches

- HEPI/PEPI/BSC Dynamics & Control
  - » Both PEPI and HEPI are "stiff", displacement actuators
  - » HEPI/BSC system has passive, critically damped modes to 40 Hz (except for the pier resonance)
  - » The HEPI actuator has a bellows breathing mode resonance at 47 Hz and can't actuate beyond this frequency
  - »The BSC has a high Q first bending mode at 23 Hz
    - –The associated phase loss represents a limit to the upper unity gain, unless this feature is inverted in the control or the pier is significantly stiffened (which may not be practical)
    - –Since the greatest contribution to the rms velocity of the optic is from the microseismic peak and the first 2 stack resonances, the 23 Hz pier resonance is not a serious problem
  - »Perhaps possible to add a resonant gain stage to HEPI in the vertical direction to provide some isolation at the suspension vertical bounce modes? (12 Hz for LOS, 15 Hz and 16 Hz for SOS)

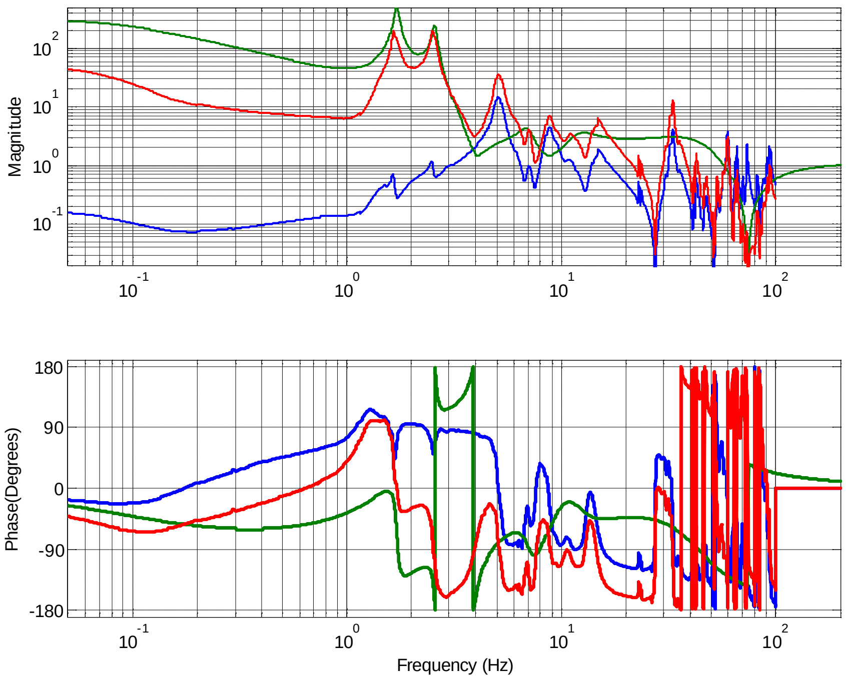
Sweet!



# Evaluation of EPI Approaches

- MEPI/HAM Dynamics & Control
  - » MEPI is a “soft”, force actuator
  - » The MEPI system has high Q modes associated with the offload springs (rigid body modes)
    - – On the HAM, these modes are from 3 to 10 Hz
    - – Left as is, these modes amplify the ground motion and increase the rms velocity of the optics

Sour!




»The HAM platform has elastic modes from 13 Hz as well as elastic compliance in the “rigid body” modes (i.e. quasi-rigid body modes)

–Either system must address these modes either through structural modifications (stiffening &/or damping) or through active control

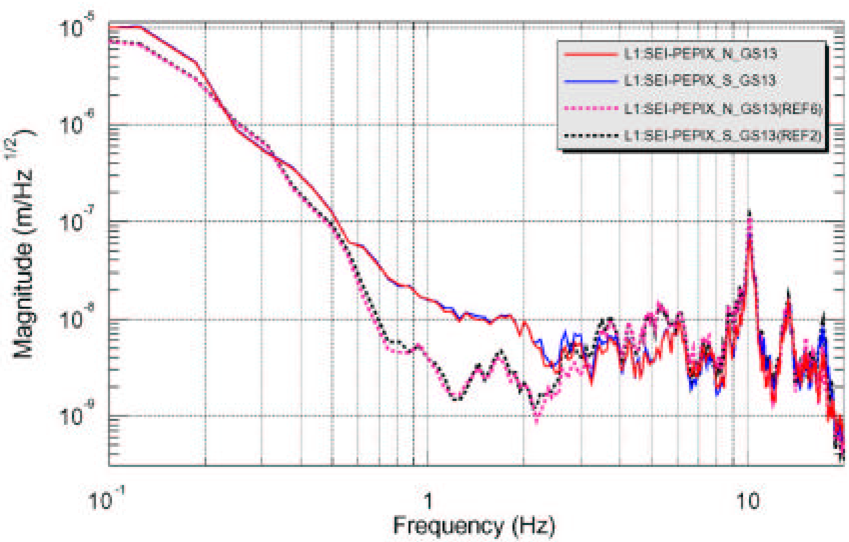
»MEPI deals with these elastic modes by damping them or filtering to avoid exciting the higher order modes, i.e. with control complexity

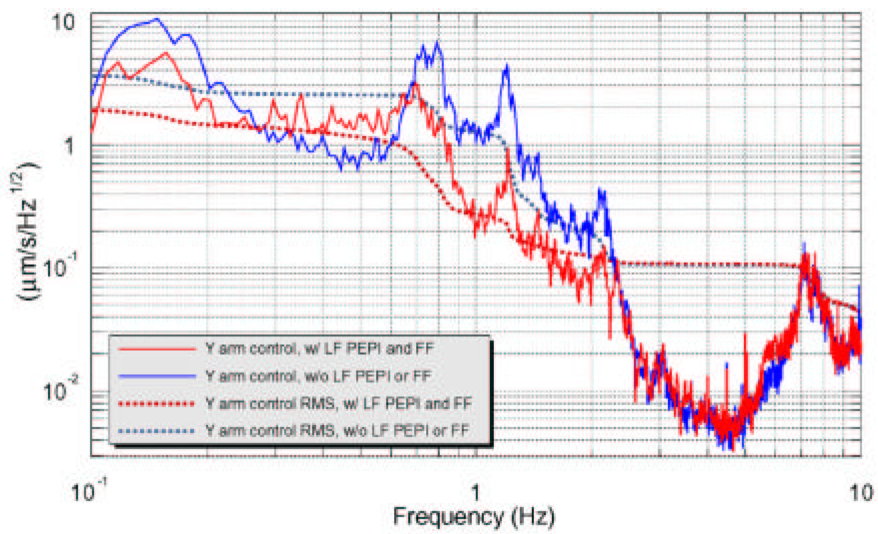
# Evaluation of EPI Approaches

- Tidal & Mircoseismic Performance
  - » One expects PEPI, HEPI and MEPI to all perform about equally well for tidal and microseismic correction:
    - – All rely upon the IFO for tidal sensing
    - – All rely upon the STS-2 for microseismic sensing
    - – All are adequate DC actuators
    - – This actuation is below the dynamics of the system
  - » PEPI and to a lesser extent HEPI and MEPI have performed microseismic compensation
    - – Loop shaping for the lower unity gain point has not been a priority in LASTI testing
- Drift
  - » PEPI and HEPI are OK
  - » MEPI is susceptible to thermal expansion & E(T) induced drifts
    - – Spring deflection under load is about 6mm x <1% $\Delta$E = <0.06mm, OK
    - – Spring length is 1m x 11 microns/m/C x +/-2C = +/-0.02 mm OK

# Evaluation of EPI Approaches

- Stack Modes (1 to 3+ Hz)
  - » PEPI has achieved an attenuation factor of ~7 in rms motion at the crossbeam
  - » … and a factor of ~4 in relative velocity between the ITM and ETM

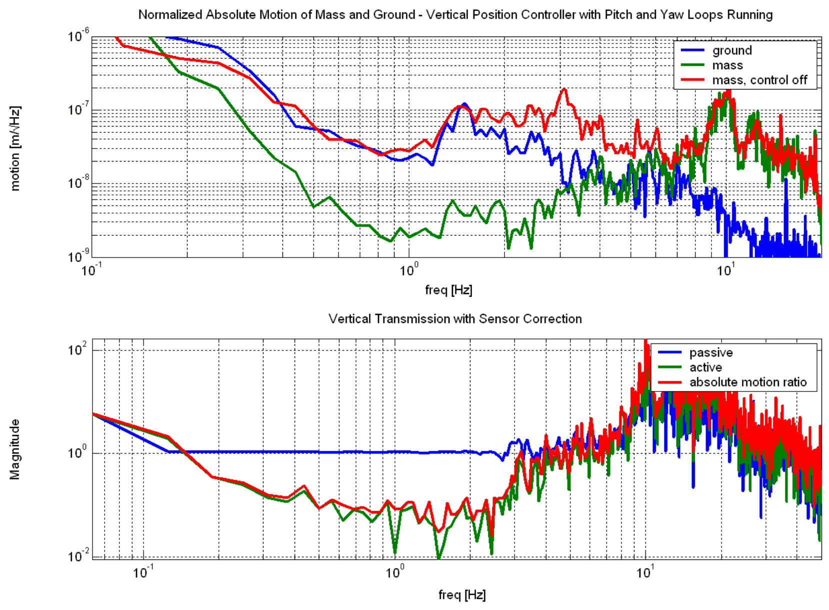


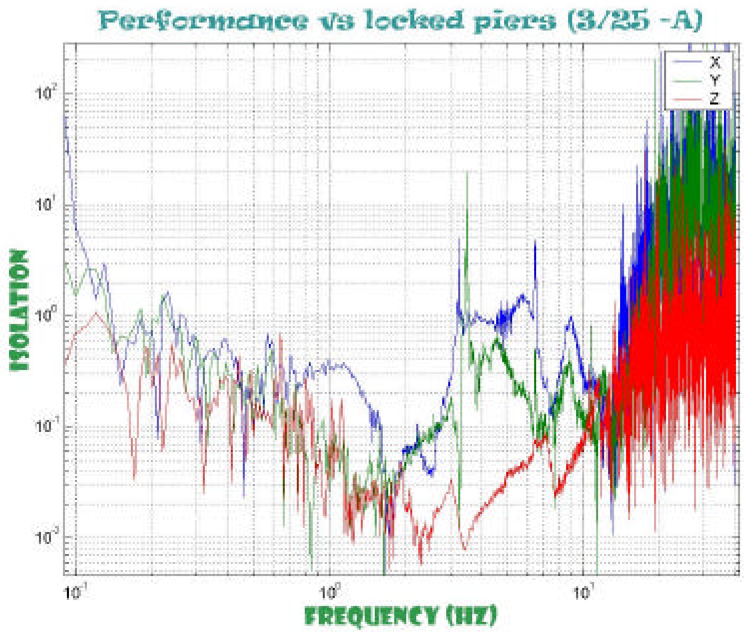

Note: microseismic compensation was off during this data capture

# Evaluation of EPI Approaches

- Stack Modes (1 to 3+ Hz) [continued]
  - » Both the HEPI and MEPI systems can achieve a broadband attenuation factor of ~15 in rms motion at the crossbeam
  - » more isolation at stack modes when resonant gain stages are added at the two lower stack mode frequencies



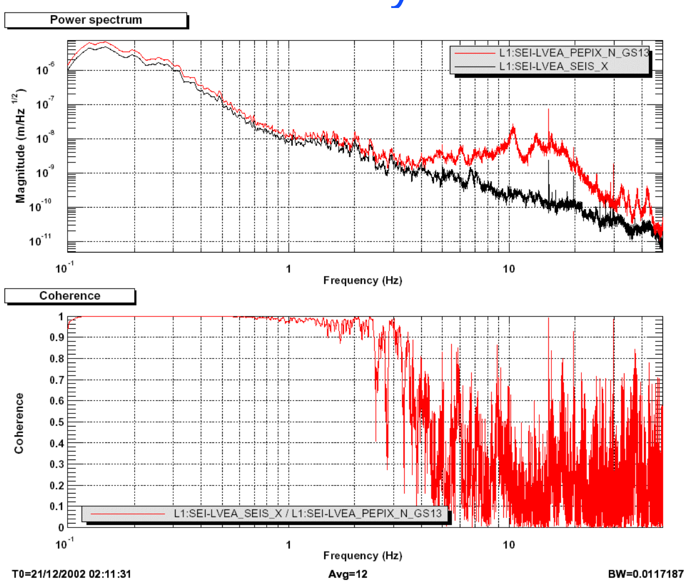

HEPI/BSC to the support table

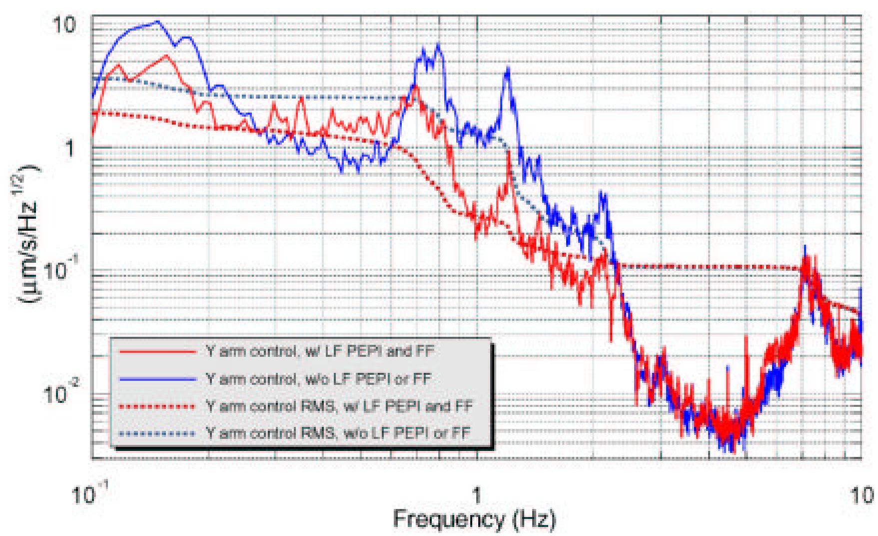



MEPI/HAM to the optics table

# Evaluation of EPI Approaches

- “High” Frequency Noise (>4 Hz)
  - » Considerable amplification of ground motion from ~4 Hz to ~25 Hz (up to a factor ~40) is apparent in both the HAM and BSC isolation responses, including PEPI
  - » Apparently due to dynamics of the piers, crossbeams, etc.
  - » However, this does not contribute significantly to the test mass rms velocity



# Evaluation of EPI Approaches

- Isolation Robustness
  - » Low frequency (<0.5 Hz) isolation with position sensor correction is common to all the EPI concepts
    - – Some evidence that the performance is not stationary? (for all EPIs)
  - » Velocity Feedback Control
    - – HEPI control (to date) only uses the vertical geophones
      - Simple control laws
      - Good phase and gain margins
      - Robust to plant changes (were any to occur)
    - – MEPI control uses horizontal and vertical geophones
      - Complex control laws (partial plant inversion, elliptic LP filters)
      - Multiple unity gain crossings, generally low to moderate phase & gain margins (for the performance reported); the margins can be increased with some degradation in performance
      - Not Robust to plant changes – but do plant changes occur? [see next page]

# Evaluation of EPI Approaches

- Plant Changes?
  - » Sensitivity to environment (dE/dT, $\alpha$dT), creep → negligible
  - » Reconfiguration (adding or shifting positions of payload) is very infrequent
    - – After initial installation, this has been done only a few times to fix positional errors at the ~1cm level (may not have altered the plant significantly)
    - – About to be done again to correct the Schnupp asymmetry
  - » Macroscopic re-alignment (~ mrad) is infrequent
    - – Tried twice(?) with current coarse actuation systems during initial installation
    - – Used to align the APS port telescope without a vent
  - » load redistribution of the platform (adjusting offload spring tension,re-leveling of the support platform)
    - – Only done on initial installation
  - » Is the infrequent macroscopic table re-alignment due to a poor existing capability, or the lack of a need to do so? (I think the later)
- Consequences?
  - » For HEPI – nada
  - » For MEPI:
    - – Re-measure transfer functions, experts redesign/tweak the control laws, and re-test

# Evaluation of EPI Approaches

- Alignment Robustness (angular and translation)
  - » Support control re-allocation from the suspensions
    - – ~100 rad, or ~0.2 mm actuator range
  - » Desirable to have large actuation range:
    - – Long duration locks (~ months) where more range may be required than predicted for tides and estimated thermal effects
    - – Allow for intentional de-centering of optics (to find optimal position for minimizing thermal noise)
  - » HEPI actuators provide ±1 mm range with low (10W) power dissipation
  - » MEPI actuators provide ±0.19 mm range with low (16W) power dissipation ($\Delta T$ = 4.9C at actuator)

# Evaluation of EPI Approaches

- HEPI Hydrocarbon Contamination:
  - » Using clear, water soluble, non-toxic, non-flammable fluid with bio and corrosion inhibitors
  - » Exposure to a high irradiance, optical cavity indicates no measurable absorption or scattering change to the level required in LIGO
  - » No leaks at LASTI (3 months testing)
  - » Have sensitive level monitoring for leak detection; can seal pump station and exchange air directly with exterior rather than the building air
  - » Low pressure (100 psi) system with high reliability seals
  - » Bottom line: low risk

# Evaluation of EPI Approaches

- MEPI Magnetic Field Contamination:
  - » Requires shielding (to be designed)
  - » Requires linear power supplies, or supplies placed in mechanical room with long cables
  - » Bottom Line: not a problem

# Evaluation of EPI Approaches

- Costs
  - » The costs indicated for stiffening and damping modifications are for “modest” changes, i.e. not intended to damp all the modes ‘created’ by the addition of MEPI
    - – For the HAM: the stiffening beams plus passive tuned dampers
    - – For the BSC: don’t know

| | | Costs ($K) | |
|---|---|---|---|
| | | per Chamber | 5 BSC Chambers 3 HAM Chambers |
| 1A | MEPI Mechanics | $104 | $833 |
| | MEPI Electronics | $55 | $438 |
| | MEPI Subtotal | $159 | $1,271 |
| | | | |
| 1B | HEPI Mechanics | $193 | $1,547 |
| | HEPI Electronics | $56 | $450 |
| | HEPI Subtotal | $250 | $1,997 |
| | | | |
| 2 | HAM Stiffening | $4 | $32 |
| | HAM Damping | $2 | $16 |
| | HAM Mods Subtotal | $6 | $48 |
| | | | |
| 3 | BSC Stiffening | $8 | $64 |
| | BSC Damping | $2 | $16 |
| | BSC Mods Subtotal | $10 | $80 |
| | | per Table | 3 ISC Tables |
| 4 | ISCT Isolation | $35 | $105 |
| | | TOTALS for LLO: | |
| | | MEPI | **$1,504** |
| | | HEPI | **$2,230** |

# Evaluation of EPI Approaches

- Don't know:
  - » Earthquake response (though not significant for LLO)
  - » Compatibility with advanced LIGO?
    - – HEPI is compatible
    - – Support structure/system dynamics would have to be considered in the internal active isolation system design
  - » Reliability
    - – 3 months experience isn't much, but neither system has had significant problems
    - – Not likely a discriminator
  - » Transient (non steady-state) response
  - » Applicability to LHO wind noise:
    - – Resonant gain stages at SUS vertical bounce mode frequencies?

# *Evaluation of EPI Approaches*
# *Conclusions?*

- If performance, robustness and range alone are the key criteria, then HEPI is the likely choice
  - » Particularly if some reduction of the vertical bounce modes were possible
- If cost and reduction of hydrocarbon contamination risk are key criteria, then MEPI is the likely choice
- No/little simulation of HEPI/HAM and MEPI/BSC have been done to date
  - » If an immediate decision is required for selecting a system with maximum confidence of success, then the likely choice is HEPI
  - » Best is to choose a system and test it on the other platform

# M030082-01
# EPI Hardware Cost Estimates at LLO & LASTI

| | | Costs ($K) | | |
|---|---|---|---|---|
| | | per Chamber | LLO: 5 BSC Chambers 4 HAM Chambers 3 ISCTs | LASTI: 3 HAM Chambers 1 BSC Mods 2 HAM Mods |
| 1A | **MEPI Mechanics** | $98 | $882 | $294 |
| | **MEPI Electronics** | $55 | $493 | $164 |
| | **MEPI Spares** | $6 | $69 | $0 |
| | **MEPI Subtotal** | $153 | $1,444 | $458 |
| | | | | |
| 1B | **HEPI Mechanics** | $179 | $1,615 | $538 |
| | **HEPI Electronics** | $56 | $506 | $169 |
| | **HEPI Spares** | $8 | $101 | |
| | **HEPI Subtotal** | $236 | $2,222 | $707 |
| | | | | |
| 2 | **HAM Stiffening** | $4 | $16 | $8 |
| | **HAM Damping** | $2 | $8 | $4 |
| | **HAM Mods Subtotal** | $6 | $24 | $12 |
| | | | | |
| 3 | **BSC Stiffening** | $8 | $40 | $8 |
| | **BSC Damping** | $2 | $10 | $2 |
| | **BSC Mods Subtotal** | $10 | $50 | $10 |
| | | **per Table** | **3 ISC Tables** | |
| 4 | **ISCT Isolation** | $35 | $105 | $0 |

| TOTALS: | LLO | LASTI | LLO & LASTI |
|---|---|---|---|
| MEPI | $1,623 | $480 | $2,104 |
| **HEPI** | **$2,401** | **$729** | **$3,130** |

**Notes:**

1) MIT funds of $450K were used to fund much of the HEPI and MEPI installations currently at LASTI. The existing HEPI/BSC system will stay as is. The current MEPI/HAM system is proposed to be replaced with a HEPI/HAM and the other 2 LASTI HAMs are proposed to get HEPI systems as well.

2) BSC Stiffening and damping costs are only guesses

3) HAM stiffening and damping costs are rough estimates

4) ISCT isolation cost is based on 40m Lab costs for 3 Stacis systems per table

5) There is no contingency in the above estimates

6) Details for MEPI and HEPI costing are on the following sheets

7) The electronics costs are defined for MEPI, based on an old block diagram and need to be revised. HEPI costs are assumed to be similar, plus $2K for pump controller.

8) Sparing is as listed on the following sheet.

9) The triaxial, low frequency, low noise seismometers (STS-2) are assumed to be availabel from PEM and not part of the costs above.

| Vessel | EPI | HAM Piers | Springs | Actuators | Kaman Sensors | L4Cs | Valve Tree | Pump Station |
|---|---|---|---|---|---|---|---|---|
| LLO | | | | | | | | |
| ETM-x | 4 | | 8 | 8 | 4 | 8 | 4 | 0.5 |
| ETM-y | 4 | | 8 | 8 | 4 | 8 | 4 | 0.5 |
| ITM-x | 4 | | 8 | 8 | 4 | 8 | 4 | 0.5 |
| ITM-y | 4 | | 8 | 8 | 4 | 8 | 4 | 0.5 |
| BSC | 4 | | 8 | 8 | 4 | 8 | 4 | 0.5 |
| HAM-1 | 4 | 4 | 8 | 8 | 4 | 8 | 4 | 0.5 |
| HAM-2 | 4 | 4 | 8 | 8 | 4 | 8 | 4 | 0.5 |
| HAM-3 | 4 | 4 | 8 | 8 | 4 | 8 | 4 | 0.5 |
| HAM-4 | 4 | 4 | 8 | 8 | 4 | 8 | 4 | 0.5 |
| Spares | 1 | | 2 | 2 | 8 | 8 | 1 | 1 |
| LASTI | | | | | | | | |
| BSC | | | | | | | | 0.5 |
| HAM-1 | 4 | 4 | | 8 | 4 | | 4 | 0.5 |
| HAM-2 | 4 | 4 | 8 | 8 | 4 | 8 | 4 | 0.5 |
| HAM-3 | 4 | 4 | 8 | 8 | 4 | 8 | 4 | 0.5 |
| Spares | 0 | | 0 | 0 | 4 | 0 | 0 | 0 |
| **Totals** | **49** | **28** | **90** | **98** | **60** | **96** | **49** | **7.5** |

**MEPI Block Diagram (draft), D020393**

| | | | | | chamber | Corner | X-end | Y-end | Total for LLO | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **item #** | **Assy or Part Name** | **part no** | **vendor** | **unit cost** | **qty** | **qty** | **qty** | **qty** | **qty** | **total cost** | **comments** |
| | Sensor interfaces and cabling: | | | | | | | | | | |
| 1 | Interface for L4C & Inductive Position Sensors | D020242 | CIT | 500 | 4 | 24 | 4 | 4 | 32 | 16000 | |
| 2 | STS-2 Seiemometer Receiver Module | D020194 | CIT | 1500 | | 1 | 1 | 1 | 3 | 4500 | one STS-2 per building |
| 3 | Rack-mounted receiver for field modules | pending | CIT | 3500 | 1 | 6 | 1 | 1 | 8 | 28000 | |
| 4 | Cables and interfacing connectors | pending | CIT | 750 | 1 | 6 | 1 | 1 | 8 | 6000 | |
| | VME Components | | | | | | | | | | |
| 5 | ADC, 32 channel, 16 bit | ICS110B | | 9600 | | 4 | 1 | 1 | 6 | 57600 | 19 channels used per chamber (8 L4C, 8 DIT, 3 STS-2) |
| 6 | Digital Output, 32 channel, isolated | XY-220 | Xycom | 1000 | | 2 | 1 | 1 | 4 | 4000 | |
| 7 | Baja Processor | | Baja | 18200 | | 0 | 0 | 0 | 0 | 0 | assume not needed for now |
| 8 | Processor | M-162 | Motorola | 3500 | | 2 | 1 | 1 | 4 | 14000 | |
| 9 | VME Pentium (1.26 GHz) | 7751 | | 3900 | | 2 | 1 | 1 | 4 | 15600 | |
| 10 | Rack Mounted Pentium | | | 1500 | | 2 | 1 | 1 | 4 | 6000 | |
| 11 | DAC, 8 channel, 16 bit | 6102 | Pentek | 9000 | 1 | 6 | 1 | 1 | 8 | 72000 | |
| 12 | Scanning ADC, 64 input, 12 bit | VMIVME-3113 | VMIC | 2800 | | 2 | 1 | 1 | 4 | 11200 | |
| 13 | VME Crate | | | 4182 | | 2 | 1 | 1 | 4 | 16728 | based on EMI rated VME crate plus filters (see M. Zucker's RFI cost estimates) |
| 14 | Red Hat Linux | | | 200 | | 2 | 1 | 1 | 4 | 800 | guess |
| 15 | PMC Reflective Memory | 5565 | | 2400 | | 2 | 1 | 1 | 4 | 9600 | |
| 16 | PCI Reflective Memory | 5565 | | 2400 | | 2 | 1 | 1 | 4 | 9600 | |
| | Analog Electronics | | | | | | | | | | |
| 17 | anti-image board (8 channel) | | CIT | 1000 | 1 | 6 | 1 | 1 | 8 | 8000 | |
| 18 | power supplies | | | 7953 | | 2 | 1 | 1 | 4 | 31812 | based on Kepco quotes in M. Zucker's RFI mitigation cost estimates = $7953 |
| 19 | Driver, electromagnetic actuator (8 channel) | | CIT | 4000 | 1 | 6 | 1 | 1 | 8 | 32000 | |
| 20 | Driver cabling & field connectors | | CIT | 500 | 1 | 6 | 1 | 1 | 8 | 4000 | |
| 21 | DAQ interface card | | CIT | 1000 | 1 | 6 | 1 | 1 | 8 | 8000 | |
| 22 | Euro crate | | | 4353 | | 2 | 0 | 0 | 2 | 8706 | based on EMI rated Euro crate plus filters (see M. Zucker's RFI cost estimates) |
| 23 | Rack | | | 6000 | | 3 | 1 | 1 | 5 | 30000 | based on several EMI rated rack quotes that Jay received; 2 racks for control, 1 for power supplies |
| 24 | Cross-connect & internal rack hardware | | | 800 | | 3 | 1 | 1 | 5 | 4000 | |

| | | |
|---|---|---|
| **total =** | **398146** | w/o spares |
| | **39815** | 10% spares cost? |
| **total with spares estimate =** | **437961** | |

**MEPI Top-Level Assy** **D020182**

| | | | | prototype | | | production | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **item #** | **Assy or Part Name** | **part no** | **vendor** | **unit cost** | **qty** | **total cost** | **unit cost** | **qty** | **total cost** | **% prototype** | **comments** |
| 1 | Spring adjust plate | D020001-01 | Lavallee Machine | $129 | 2 | $258 | $129 | 2 | $181 | -30% | |
| 2 | Spring mount plate | D020002-01 | Lavallee Machine | $62 | 2 | $124 | $62 | 2 | $87 | -30% | |
| 3 | Housing | D020004-05 | Southbridge Sheet Metal | $2,375 | 1 | $2,375 | $2,375 | 1 | $2,138 | -10% | |
| 4 | Crossbeam attachment plate | D020008-01 | Arland Tool | $254 | 1 | $254 | $254 | 1 | $178 | -30% | |
| 5 | Spring attachment nut | D020009-1 | Lavallee Machine | $12 | 4 | $47 | $12 | 4 | $33 | -30% | |
| 6 | Spring jam nut | D020009-2 | Lavallee Machine | $10 | 4 | $41 | $10 | 4 | $29 | -30% | |
| 7 | Ham support pier, short | D020126-02 | Southbridge Sheet Metal | $1,600 | 1 | $1,600 | $1,600 | 1 | $640 | -60% | |
| 8 | Blank-off plate | D020128-03 | Lavallee Machine | $384 | 1 | $384 | $384 | 1 | $346 | -10% | |
| 9 | Crossbeam foot | D020195-01 | Arland Tool | $2,661 | 1 | $2,661 | $2,661 | 1 | $2,129 | -20% | |
| 10 | Brace, right | D020249-02 | Lavallee Machine | $115 | 2 | $230 | $115 | 2 | $161 | -30% | |
| 11 | Front brace plate | D020250-01 | Lavallee Machine | $133 | 1 | $133 | $133 | 1 | $93 | -30% | |
| 12 | Lower weldment | D020251-01 | Lavallee Machine | $378 | 1 | $378 | $378 | 1 | $265 | -30% | |
| 13 | Left actuator bracket | D020252-00 | Lavallee Machine | $264 | 1 | $264 | $264 | 1 | $185 | -30% | |
| 14 | Actuator base plate | D020253-01 | Lavallee Machine | $75 | 2 | $150 | $75 | 2 | $105 | -30% | |
| 15 | Base insulator | D020254-00 | Lavallee Machine | $27 | 2 | $54 | $27 | 2 | $43 | -20% | |
| 16 | Position flag | D020255-02 | Lavallee Machine | $41 | 2 | $82 | $41 | 2 | $57 | -30% | |
| 17 | Push bar | D020256-01 | Lavallee Machine | $288 | 2 | $576 | $288 | 2 | $461 | -20% | |
| 18 | Position switch housing | D020257-01 | Lavallee Machine | $68 | 2 | $136 | $68 | 2 | $122 | -10% | |
| 19 | L4C kinematic plate | D020258-00 | Lavallee Machine | $208 | 2 | $416 | $208 | 2 | $291 | -30% | |
| 20 | L4C tube mount | D020259-00 | Lavallee Machine | $189 | 2 | $378 | $189 | 2 | $265 | -30% | |
| 21 | Horizontal adjust plate | D020260-01 | Lavallee Machine | $48 | 1 | $48 | $48 | 1 | $34 | -30% | |
| 22 | Vertical arms | D020261-01 | Lavallee Machine | $68 | 2 | $136 | $68 | 2 | $95 | -30% | |
| 23 | Coil insulator | D020264-00 | Lavallee Machine | $19 | 4 | $76 | $19 | 4 | $61 | -20% | |
| 24 | Pnuematic support plate | D020265-00 | Lavallee Machine | $45 | 4 | $180 | $45 | 0 | $0 | -10% | 1 set used for setup |
| 25 | Die roller plate | D020266-01 | Lavallee Machine | $38 | 4 | $152 | $38 | 0 | $0 | -10% | 1 set used for setup |
| 26 | Shim plate | D020267-00 | Lavallee Machine | $22 | 4 | $88 | $22 | 0 | $0 | -10% | 1 set used for setup |
| 27 | Push rod | D020268-01 | Lavallee Machine | $15 | 8 | $120 | $15 | 0 | $0 | -10% | 1 set used for setup |
| 28 | Double clamp | D020269-01 | Lavallee Machine | $118 | 2 | $236 | $118 | 2 | $189 | -20% | |
| 29 | Offset clamp, right | D020270-01 | Lavallee Machine | $86 | 1 | $86 | $86 | 0 | $0 | -30% | needed for right-handed version |
| 30 | Straight clamp | D020271-01 | Lavallee Machine | $62 | 1 | $62 | $62 | 1 | $50 | -20% | |
| 31 | Brace, left | D020276-02 | Lavallee Machine | $115 | 2 | $230 | $115 | 1 | $81 | -30% | |
| 32 | Right actuator bracket | D020277-00 | Lavallee Machine | $264 | 1 | $264 | $264 | 0 | $0 | -30% | needed for right-handed version |
| 33 | Rear brace plate | D020279-01 | Lavallee Machine | $148 | 1 | $148 | $148 | 1 | $104 | -30% | |
| 34 | Sensor post | D020305-01 | Lavallee Machine | $9 | 2 | $18 | $9 | 2 | $13 | -30% | |
| 35 | Housing stiffener, right | D020329-01 | Southbridge Sheet Metal | $300 | 1 | $300 | $300 | 0 | $0 | -10% | needed for right-handed version |
| 36 | Housing stiffener, short right | D020330-01 | Southbridge Sheet Metal | $300 | 1 | $300 | $300 | 0 | $0 | -10% | needed for right-handed version |
| 37 | Housing stiffener, left | D020331-01 | Southbridge Sheet Metal | $300 | 0 | $0 | $300 | 1 | $270 | -10% | |
| 38 | Housing stiffener, short left | D020332-01 | Southbridge Sheet Metal | $300 | 0 | $0 | $300 | 1 | $270 | -10% | |
| 39 | Offset clamp, left | D020453-00 | Lavallee Machine | $86 | 1 | $86 | $86 | 1 | $60 | -30% | |
| 40 | Miscellaneous hardware | XXXXXXXXXX | McMaster-Carr | $390 | 1 | $390 | $390 | 1 | $390 | same | |
| 41 | Pneumatic cylinder | CRS2U63X3/4 | Action Automation | $73 | 4 | $291 | $73 | 0 | $0 | same | 1 set used for setup |
| | **subtotal (mechanical housing assembly sans machined springs, actuators, sensors)** | | | | | $13,752 | | | $9,422 | 31% | |
| | | | | | | | | | | | |
| | Maraging Steel, 300 (for helical springs) | | Dynamic Metals | $714 | 2 | | $0 | 2 | $0 | same | |
| | Spring, helical machined (maraging 300) | | Digital Machining Systems | $1,396 | 2 | | $1,992 | 2 | $3,984 | same | |
| | Load Cells (through hole) | | | | | | $513 | 2 | $1,026 | same | share a single set of readout displays |
| | Load Cell digital display units | | | | | | $375 | 1 | $188 | | 16 units shared among 8 chambers |
| | Electro-magnetic linear actuator | LA50-62-004Z | BEI | $2,486 | | | $1,990 | 2 | $3,980 | same | BEI Quotation Number 9771, revised 11/7/2002 |
| | Vertical Seismometer, 1 Hz | | Sercel Inc. | $1,195 | | | $1,195 | 1 | $1,195 | same | PO #4500400825, 3/15/2002 |

**MEPI Top-Level Assy** **D020182**

| | | | | prototype | | | production | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **item #** | **Assy or Part Name** | **part no** | **vendor** | **unit cost** | **qty** | **total cost** | **unit cost** | **qty** | **total cost** | **% prototype** | **comments** |
| | Horizontal Seismometer, 1 Hz | | Sercel Inc. | $1,200 | | | $1,200 | 1 | $1,200 | same | PO #4500400825, 3/15/2002 |
| | Inductive Position Sensor (2 channels/unit) | DIT-5200-20N | Kaman Instrumentation Inc. | $3,515 | | | $3,515 | 1 | $3,515 | same | PO #4500392101, 3/5/2002 |
| | **subtotal (all items atop a single pier)** | | | | | | | | $24,509 | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | Triaxial Seismometer | | Quanterra Inc. | $13,826 | 1 | | $13,826 | 0 | $0 | | PO #4500367940, 11/20/2001; All units already purchased for the sites on PEM |
| | | | | | | | | | | | |
| | Spares | | | | | | | | TBD | | |

| | |
|---|---|
| **$98,037** | **total per chamber (average), no spares** |
| | **Spares:** |
| $9,422 | 1 EPI Housing |
| $3,984 | 2 Springs |
| $3,980 | 2 Actuators |
| $42,180 | 12 Position Sensors |
| $9,600 | 8 L4Cs |
| **$69,166** | **Spares Total** |

**HEPI Top-Level Assy**

| Assy or Part Name | | part no | vendor | prototype unit cost | prototype qty | prototype total cost | production unit cost | production qty | production total cost | Prototype comments | Production comments |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Hydraulic actuator** | | | | | | | | | | | |
| | Actuator Plate | D020285-00-E | P & N | $ 442.86 | 12 | $5,314 | 413.70 | 72 | $29,786.40 | Quotation # 1, 7/3/2002 MIT PO | Quotation by e-mail 1/16/2003 |
| | Diaphragm | D020286-00-E | P & N | $ 12.50 | 12 | $150 | 28.09 | 72 | $2,022.48 | Quotation # 1, 7/3/2002 MIT PO | Quotation by e-mail 1/16/2003 |
| | Diaphragm Restraint | D020287-00-E | P & N | $ 129.32 | 12 | $1,552 | 147.00 | 72 | $10,584.00 | Quotation # 1, 7/3/2002 MIT PO | Quotation by e-mail 1/16/2003 |
| | Pair of Resistor Plates | D020288-00-E | P & N | $ 419.68 | 12 | $5,036 | 171.15 | 144 | $24,645.60 | Quotation # 1, 7/3/2002 MIT PO | Quotation by e-mail 1/16/2003 |
| | Resistor Cap | D020289-00-E | P & N | $ 76.86 | 12 | $922 | 59.85 | 72 | $4,309.20 | Quotation # 1, 7/3/2002 MIT PO | Quotation by e-mail 1/16/2003 |
| | Top Foundation Plate | D020290-00-E | P & N | $ 533.14 | 12 | $6,398 | 408.45 | 72 | $29,408.40 | Quotation # 1, 7/3/2002 MIT PO | Quotation by e-mail 1/16/2003 |
| | Top Bellows Slug | D020291-00-E | P & N | $ 84.79 | 12 | $1,017 | 67.20 | 72 | $4,838.40 | Quotation # 1, 7/3/2002 MIT PO | Quotation by e-mail 1/16/2003 |
| | Top Bellows Cap | D020291-00-E | P & N | $ 39.65 | 12 | $476 | 30.45 | 72 | $2,192.40 | Quotation # 1, 7/3/2002 MIT PO | Quotation by e-mail 1/16/2003 |
| | Bottom Foundation Plate | D020292-00-E | P & N | $ 533.75 | 12 | $6,405 | 410.55 | 72 | $29,559.60 | Quotation # 1, 7/3/2002 MIT PO | Quotation by e-mail 1/16/2003 |
| | Bottom Slug | D020293-00-E | P & N | $ 76.86 | 12 | $922 | 65.63 | 72 | $4,725.36 | Quotation # 1, 7/3/2002 MIT PO | Quotation by e-mail 1/16/2003 |
| | Bottom Cap | D020293-00-E | P & N | $ 39.65 | 12 | $476 | 30.45 | 72 | $2,192.40 | Quotation # 1, 7/3/2002 MIT PO | Quotation by e-mail 1/16/2003 |
| | Right Side Foundation Plate | D020296-00-E | P & N | $ 211.06 | 12 | $2,533 | 211.05 | 72 | $15,195.60 | Quotation # 1, 7/3/2002 MIT PO | Quotation by e-mail 1/16/2003 |
| | Left Side Foundation Plate | D020297-00-E | P & N | $ 229.36 | 12 | $2,752 | 227.85 | 72 | $16,405.20 | Quotation # 1, 7/3/2002 MIT PO | Quotation by e-mail 1/16/2003 |
| | Back Foundation Plate | D020298-00-E | P & N | $ 240.34 | 12 | $2,884 | 243.60 | 72 | $17,539.20 | Quotation # 1, 7/3/2002 MIT PO | Quotation by e-mail 1/16/2003 |
| | Parallel Motion Mount | D020299-00-E | P & N | $ 59.78 | 12 | $717 | 51.45 | 144 | $7,408.80 | Quotation # 1, 7/3/2002 MIT PO | Quotation by e-mail 1/16/2003 |
| | Parallel Motion Flexure | D020299-00-E | P & N | $ 9.15 | 12 | $110 | 6.83 | 144 | $983.52 | Quotation # 1, 7/3/2002 MIT PO | Quotation by e-mail 1/16/2003 |
| | Manifold Plate | D020300-00 | P & N | $ 630.74 | 12 | $7,569 | 585.90 | 72 | $42,184.80 | Quotation # 1, 7/3/2002 MIT PO | Quotation by e-mail 1/16/2003 |
| | Manifold Cap | D0020301-00-E-1 | P & N | $ 163.48 | 24 | $3,924 | 96.86 | 72 | $6,973.92 | Quotation # 1, 7/3/2002 MIT PO | Quotation by e-mail 1/16/2003 |
| | Manifold Cap | D0020301-00-E-2 | P & N | | | | 85.05 | 72 | $6,123.60 | | Quotation by e-mail 1/16/2003 |
| | Manifold Cap | D0020301-00-E-3 | P & N | | | | 96.86 | 72 | $6,973.92 | | Quotation by e-mail 1/16/2003 |
| | Manifold Cap | D0020301-00-E-34 | P & N | | | | 85.05 | 72 | $6,123.60 | | Quotation by e-mail 1/16/2003 |
| | Bellows Shield Unit Pair | D0020302-01-E | P & N | $ 384.30 | 12 | $4,612 | 221.55 | 144 | $31,903.20 | Quotation # 1, 7/3/2002 MIT PO | Quotation by e-mail 1/16/2003 |
| | Oil Catch Aluminum | D020303-00-E | P & N | $ 136.64 | 12 | $1,640 | 76.65 | 72 | $5,518.80 | Quotation # 1, 7/3/2002 MIT PO | Quotation by e-mail 1/16/2003 |
| | Pin Valve | D020359-1 | P & N | $ 38.10 | 60 | $2,286 | 19.69 | 360 | $7,088.40 | Quotation dated 8/28/2002 MIT PO | Quotation by e-mail 1/16/2003 |
| | Actuator Plate Plug Pin | D020359-2 | P & N | $ 57.95 | 60 | $3,477 | 17.59 | 360 | $6,332.40 | Quotation dated 8/28/2002 MIT PO | Quotation by e-mail 1/16/2003 |
| | Large Pin Valve | D020367-1 | P & N | $ 100.05 | 12 | $1,201 | 43.05 | 72 | $3,099.60 | Quotation dated 8/28/2002 MIT PO | Quotation by e-mail 1/16/2003 |
| | Manifold Large Plug | D020367-2 | P & N | $ 108.58 | 12 | $1,303 | 49.35 | 72 | $3,553.20 | Quotation dated 8/28/2002 MIT PO | Quotation by e-mail 1/16/2003 |
| | Attach Plate | D020369-1 | P & N | $ 200.10 | 12 | $2,401 | 121.80 | 72 | $8,769.60 | Quotation dated 8/28/2002 MIT PO | Quotation by e-mail 1/16/2003 |
| | Sensor Holster | D020369-2 | P & N | $ 182.50 | 12 | $2,190 | 81.90 | 72 | $5,896.80 | Quotation dated 8/28/2002 MIT PO | Quotation by e-mail 1/16/2003 |
| | Tripod Bar | D020369-3 | P & N | $ 32.95 | 36 | $1,186 | 24.41 | 216 | $5,272.56 | Quotation dated 8/28/2002 MIT PO | Quotation by e-mail 1/16/2003 |
| | Sensor Flag | D020370-1 | P & N | $ 212.28 | 12 | $2,547 | 113.40 | 72 | $8,164.80 | Quotation dated 8/28/2002 MIT PO | Quotation by e-mail 1/16/2003 |
| | Nut | D020370-2 | P & N | $ 156.15 | 12 | $1,874 | 54.60 | 72 | $3,931.20 | Quotation dated 8/28/2002 MIT PO | Quotation by e-mail 1/16/2003 |
| | Tripod Base | D020371-1 | P & N | $ 483.12 | 13 | $6,281 | 310.80 | 72 | $22,377.60 | Quotation dated 8/28/2002 MIT PO | Quotation by e-mail 1/16/2003 |
| | Vertical Post | D020371-2 | P & N | $ 48.20 | 36 | $1,735 | 29.93 | 216 | $6,464.88 | Quotation dated 8/28/2002 MIT PO | Quotation by e-mail 1/16/2003 |
| | Tripod Sensor Housing | D020372-1 | P & N | $ 229.35 | 12 | $2,752 | 119.70 | 72 | $8,618.40 | Quotation dated 8/28/2002 MIT PO | Quotation by e-mail 1/16/2003 |
| | Sensor Post | D020372-2 | P & N | $ 62.20 | 12 | $746 | 31.24 | 72 | $2,249.28 | Quotation dated 8/28/2002 MIT PO | Quotation by e-mail 1/16/2003 |
| | Circuit Board | D020372-3 | P & N | $ 136.65 | 12 | $1,640 | 56.70 | 72 | $4,082.40 | Quotation dated 8/28/2002 MIT PO | Quotation by e-mail 1/16/2003 |
| **Bellows** | | | | | | | | | | | |
| | Bellows (unusable Hyspan) | D020295-00-E | Hyspan | $ 598.00 | 24 | $14,352 | | 72 | | Quotation # H-372 Rev 5, 7/18/2002 MIT PO | |
| | Bellows | D020295-00-E | Ameritech | $ 386.00 | 24 | $9,264 | 318.00 | 150 | $47,700.00 | Quotation by e-mail 10/29/2002 CIT P-Card | (SPECIAL BELLOWS 4.713"X.006"X4.88"OAL |
| **Assembly** | | | | | | | | | | | |
| | Assembly of #1 & #2 w/Hyspan bellows | | KineOptics | $ 4,785.00 | 2 | $9,570 | | | | Quotation dated 8/28/2002 MIT PO | |
| | Assembly of 3,4,5 & 6 w/Ameritech bellows | | KineOptics | $ 2,925.00 | 4 | $11,700 | 2,175.00 | 72 | $156,600.00 | Invoice # 474, 11/22/02 CIT PO | Quotation by e-mail 1/9/03 |
| | Assembly of # 7 > 12 w/Ameritech bellows | | KineOptics | $ 2,925.00 | 6 | $17,550 | | | $0.00 | Invoice # 478, 12/16/02 CIT PO | |
| | Various Hydrotests and fixtures | | KineOptics | $ 1,575.00 | 1 | $1,575 | | | $0.00 | Invoice # 478, 12/16/02 CIT PO | |
| | Misc Vacuum Brazing | | Solar Atmospheres | $ 3,610.00 | 1 | $3,610 | 250.00 | 72 | $18,000.00 | Invoice # 473, 11/5/02 CIT PO | |
| | Swagelok hardware | | Capitol Valve | $ 100.00 | 100 | $10,000 | 80.00 | 72 | $5,760.00 | Catalog items | Catalog items, est. |
| | Misc hardware and tubing | | McMaster-carr | $ 500.00 | 12 | $6,000 | 500.00 | 72 | $36,000.00 | Catalog items | Catalog items, est. |
| **DPY-2S proportional valves** | | | Parker | $ 902.75 | 12 | $10,833 | 730.00 | 72 | $52,560.00 | Quotation by e-mail 5/28/2002 CIT P-Card | Quotation by e-mail 1/8/2003; revised 5/16 per Jonathan -- distributor quoted $730 ea. In qty (from $976.50) |

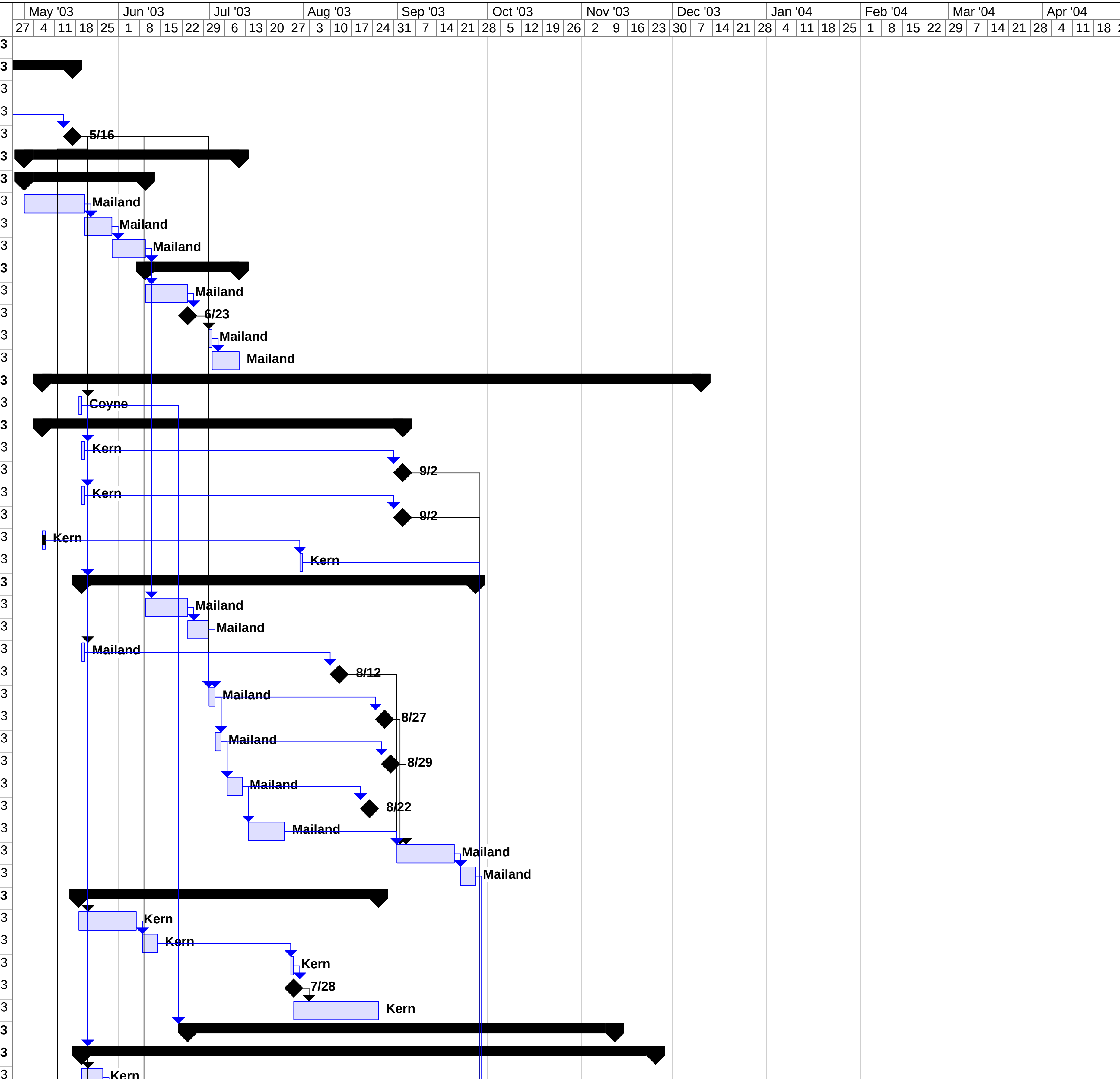
**HEPI Top-Level Assy**

| Assy or Part Name | | part no | vendor | prototype unit cost | prototype qty | prototype total cost | production unit cost | production qty | production total cost | Prototype comments | Production comments |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Custom Nozzles for DPY-2S** | | D020278-00-D | P & N | $ 39.50 | 105 | | 39.50 | 300 | $11,850.00 | Invoice 444, 7/3/02 | Invoice 444, 7/3/02 |
| | | | | | | | | | | | |
| **Double start spring** | | | | | | | | | | | |
| | Machine, assemble and plate | D020498-A-E | Digital Machine | $ 1,395.97 | 16 | $22,336 | 1,992.13 | 72 | $143,433.36 | Quotation #LIGO-008, 9/11/2002 MIT PO | Quotation #LIGO-011, e-mail 1/14/2003 |
| | A300 maraging steel | billet x 16 | Dynamic Metals | $ 13.73 | 832 | $11,423 | | | | | |
| | | | | | | | | | | | |
| **L4C Geophone mounts** | | | | | | | | | | | |
| | L4C mount, complete | D020498-00-E | Digital Machine | $ 645.00 | 4 | $2,580 | 355.48 | 36 | $12,797.28 | Quotation #LIGO-009, 11/6/2002 CIT P-Card | Quotation by e-mail 1/11/2003 |
| | Anodizing | | | $ 35.00 | 4 | $140 | | | | | |
| | Vertical Seismometer, 1 Hz | | Sercel Inc. | $1,195 | 4 | $4,780 | | | | MIT PO #4500400825, 3/15/2002 | |
| | Horizontal Seismomete, 1 Hz | | Sercel Inc. | $1,200 | 4 | $4,800 | | | | MIT PO #4500400825, 3/15/2002 | |
| | | | | | | | | | | | |
| **Thru-Hole load cells** | | | | | | | | | | | |
| | 2K thru-hole load cells | THD-2K-Y | Transducer Techniques | $ 545.00 | 16 | $8,720 | 513.00 | 72 | $36,936.00 | Quotation by e-mail 10/17/2002 CIT P-Card | Quotation by e-mail 1/10/03 TARE-TD-2K-C |
| | Digital display units | DPM-3 | Transducer Techniques | $ 385.00 | 8 | $3,080 | 375.00 | 16 | $6,000.00 | | Quotation by e-mail 1/10/03 TARE-TD-2K-C |
| | | | | | | | | | | | |
| **Distribution System 1** | | | | | | | | | | | |
| | five valve manifold assy | | RenTec Corporation | $ 3,992.00 | 8 | $31,936 | | | | Quotation #S21781A, 11/7/2002 | |
| | | | | | | | | | | | |
| **Distribution System 2** | | | | | | | | | | | |
| | Swagelok 4-way crossover valve | SS-45YF8 | Capitol valve | | | | 186.00 | 72 | $13,392.00 | | Quotation by e-mail 11/22/2002 |
| | Swagelok fittings to socket weld | assorted | Capitol valve | | | | 200.00 | 72 | $14,400.00 | | Quotation by e-mail 11/22/2002 |
| | fabricatton of manifold assembly | | KineOptics | | | | 500.00 | 72 | $36,000.00 | | Quotation by e-mail 11/22/2002 |
| **Sensors** | | | | | | | | | | | |
| | Vertical Seismometer, 1 Hz | | Sercel Inc. | | | | $1,195 | 36 | $43,020.00 | | |
| | Horizontal Seismometer, 1 Hz | | Sercel Inc. | | | | $1,200 | 36 | $43,200.00 | | |
| | Inductive Position Sensor (2 channe | DIT-5200-20N | Kaman Instrumentation Inc. | | | | $3,515 | 36 | $126,540.00 | | |
| | | | | | | | | | | | |
| | | | | | | $731,970 | | 1973.3 | $134,187.57 | actuator, sensor & spring unit costs per chamber (no spares) | |
| | | | | | | $10,166 | | | $37,686.69 | mechanical housing (w/o actuator, springs, sensors) per chamber | |
| | | | | | | $803,317 | | | $7,556 | pump station cost estimate per chamber (each pump station handles 2 chambers); see T030034-00 for pump station cost est. + $2K for electronics | |
| | | | | | | $11,157 | | | **$179,429.76** | **total HEPI mechanics per chamber** | |
| | | | | | | | | | | Spares: | |
| | | | | | | | | | $9,422 | 1 EPI Housing | |
| | | | | | | | | | $3,984 | 2 Springs | |
| | | | | | | | | | $20,332 | 2 Actuators | |
| | | | | | | | | | $42,180 | 12 Position Sensors | |
| | | | | | | | | | $9,600 | 8 L4Cs | |
| | | | | | | | | | $15,111 | 1 pump station | |
| | | | | | | | | | **$100,629.42** | **Spares Total** | |

16 May 2003

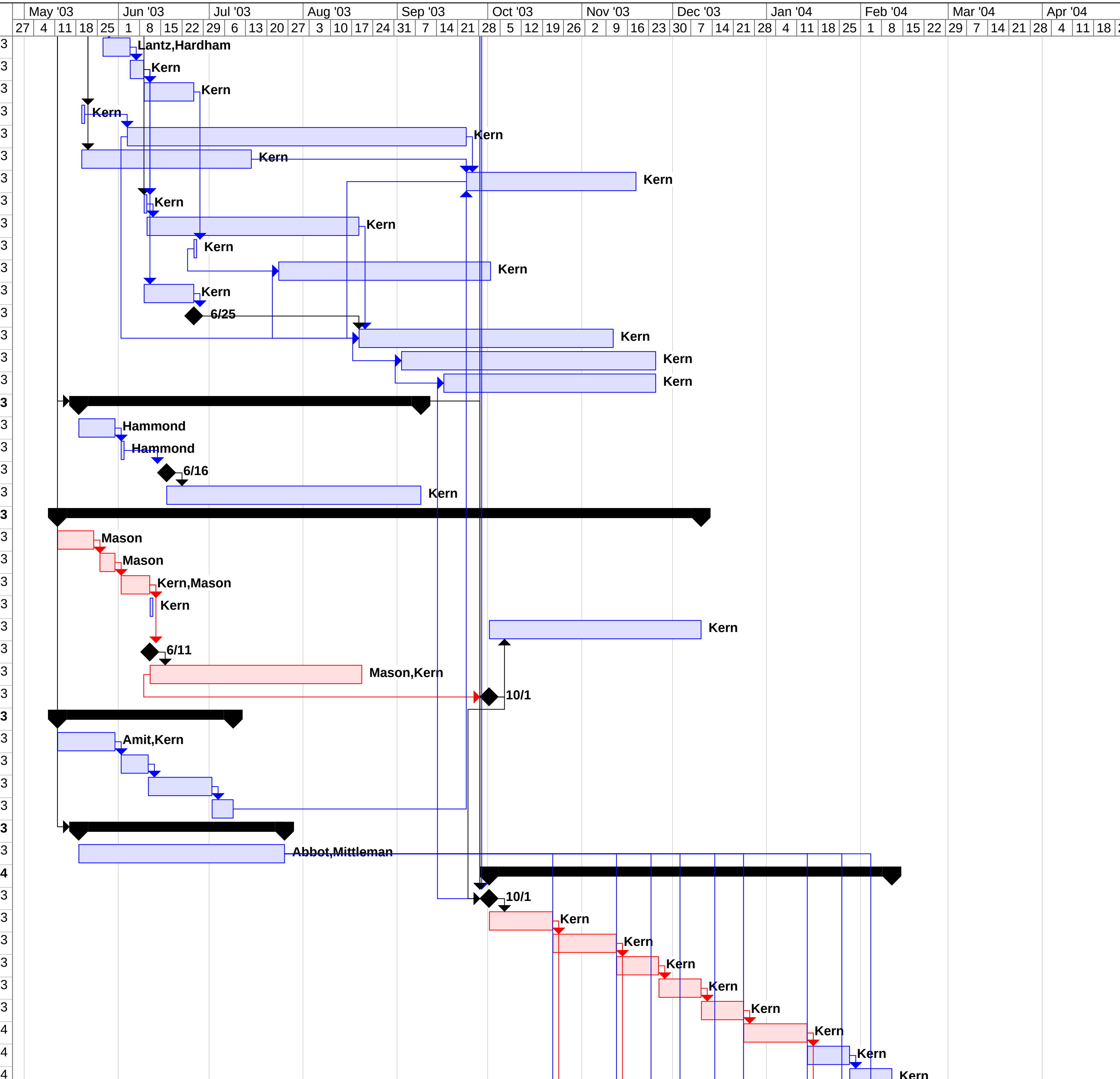
# M020142-08

| ID | Task Name | Duration | Start | Finish |
|---|---|---|---|---|
| 1 | **HEPI** | **127 days?** | **10/7/02** | **4/3/03** |
| 67 | **PDR** | **96 days** | **1/2/03** | **5/16/03** |
| 68 | release documents | 0 days | 1/2/03 | 1/2/03 |
| 69 | review | 1 day | 4/18/03 | 4/18/03 |
| 70 | final decision | 0 days | 5/16/03 | 5/16/03 |
| 71 | **Incremental FDRs** | **51 days** | **5/1/03** | **7/10/03** |
| 72 | **Pump Station FDR** | **28 days** | **5/1/03** | **6/9/03** |
| 73 | release documents | 14 days | 5/1/03 | 5/20/03 |
| 74 | review | 7 days | 5/21/03 | 5/29/03 |
| 75 | final decision | 7 days | 5/30/03 | 6/9/03 |
| 76 | **Distribution System FDR** | **23 days** | **6/10/03** | **7/10/03** |
| 77 | finalize design pkg/dws | 2 wks | 6/10/03 | 6/23/03 |
| 78 | docs released | 0 days | 6/23/03 | 6/23/03 |
| 79 | review | 1 day | 7/1/03 | 7/1/03 |
| 80 | incorporate recommendations of review | 7 days | 7/2/03 | 7/10/03 |
| 81 | **Production** | **155.5 days?** | **5/7/03** | **12/10/03** |
| 82 | CCB decision on production | 1 day | 5/19/03 | 5/19/03 |
| 83 | **EPI: order long lead items** | **85 days?** | **5/7/03** | **9/2/03** |
| 84 | L4C geophones | 1 day | 5/20/03 | 5/20/03 |
| 85 | receive L4C | 0 days | 9/2/03 | 9/2/03 |
| 86 | displacement sensors | 1 day | 5/20/03 | 5/20/03 |
| 87 | receive displacement sensors | 0 days | 9/2/03 | 9/2/03 |
| 88 | Maraging Steel order | 1 day? | 5/7/03 | 5/7/03 |
| 89 | receive maraging steel | 1 day? | 7/31/03 | 7/31/03 |
| 90 | **HEPI: Pump Station production** | **94 days** | **5/20/03** | **9/26/03** |
| 91 | finalize design pkg/dws | 2 wks | 6/10/03 | 6/23/03 |
| 92 | final design review | 1 wk | 6/24/03 | 6/30/03 |
| 93 | order pumps (7) | 1 day | 5/20/03 | 5/20/03 |
| 94 | receive pumps | 0 days | 8/12/03 | 8/12/03 |
| 95 | order reservoirs (7) | 2 days | 7/1/03 | 7/2/03 |
| 96 | receive reservoirs | 0 days | 8/27/03 | 8/27/03 |
| 97 | order machined parts | 2 days | 7/3/03 | 7/4/03 |
| 98 | receive machined parts | 0 days | 8/29/03 | 8/29/03 |
| 99 | order misc COTS parts | 1 wk | 7/7/03 | 7/11/03 |
| 100 | receive COTS parts | 0 days | 8/22/03 | 8/22/03 |
| 101 | obtain assembly quotes | 2 wks | 7/14/03 | 7/25/03 |
| 102 | assembly & air leak testing | 3 wks | 9/1/03 | 9/19/03 |
| 103 | ship to LLO | 1 wk | 9/22/03 | 9/26/03 |
| 104 | **HEPI: Actuator Isolation Valve Tree** | **71 days** | **5/19/03** | **8/25/03** |
| 105 | finalize design pkg/dws | 3 wks | 5/19/03 | 6/6/03 |
| 106 | final design review | 1 wk | 6/9/03 | 6/13/03 |
| 107 | order valves and fittings (48) | 1 day | 7/28/03 | 7/28/03 |
| 108 | receive valves and fittings | 0 days | 7/28/03 | 7/28/03 |
| 109 | assembly & He leak testing | 4 wks | 7/29/03 | 8/25/03 |
| 110 | **HEPI: Fluid distribution system production** | **101 days** | **6/24/03** | **11/11/03** |
| 122 | **HEPI: hydraulic actuator production** | **135.5 days** | **5/20/03** | **11/25/03** |
| 123 | finalize dwg pkg | 1 wk | 5/20/03 | 5/26/03 |



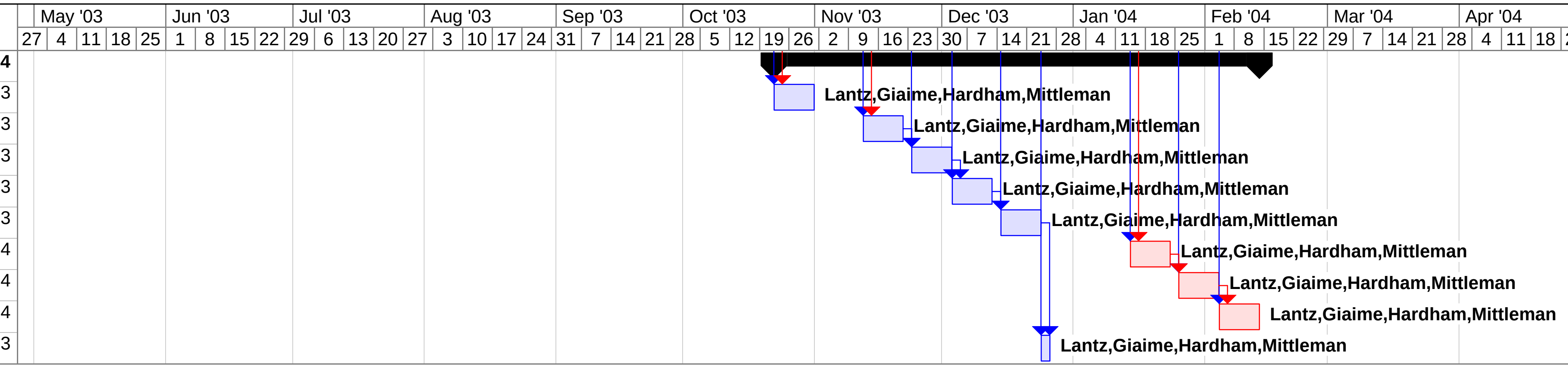
# M020142-08

| ID | Task Name | Duration | Start | Finish |
|---|---|---|---|---|
| 124 | higher BW redesign of bypass? | 7 days | 5/27/03 | 6/4/03 |
| 125 | review & DCN | 0.5 wks | 6/5/03 | 6/9/03 |
| 126 | get quotes | 2.5 wks | 6/9/03 | 6/25/03 |
| 127 | order ~100 servo-valves | 1 day | 5/20/03 | 5/20/03 |
| 128 | receive servo-valves | 4 mons | 6/4/03 | 9/23/03 |
| 129 | order ~500 nozzles | 8 wks | 5/20/03 | 7/14/03 |
| 130 | insert nozzles & test | 8 wks | 9/24/03 | 11/18/03 |
| 131 | order bellows | 1 day | 6/9/03 | 6/10/03 |
| 132 | receive bellows | 10 wks | 6/10/03 | 8/19/03 |
| 133 | order machined parts | 1 day | 6/26/03 | 6/26/03 |
| 134 | receive machined parts | 10 wks | 7/24/03 | 10/1/03 |
| 135 | get quotes for welded assy | 2.5 wks | 6/9/03 | 6/25/03 |
| 136 | award assy contract | 0 days | 6/25/03 | 6/25/03 |
| 137 | welded assembly | 12 wks | 8/19/03 | 11/11/03 |
| 138 | leak testing | 12 wks | 9/2/03 | 11/25/03 |
| 139 | units become available | 10 wks | 9/16/03 | 11/25/03 |
| 140 | **EPI Spring Production** | **81 days?** | **5/19/03** | **9/8/03** |
| 141 | finalize dwg pkg | 2 wks | 5/19/03 | 5/30/03 |
| 142 | final design review | 1 day? | 6/2/03 | 6/2/03 |
| 143 | get quotes | 0 wks | 6/16/03 | 6/16/03 |
| 144 | machine parts | 12 wks | 6/17/03 | 9/8/03 |
| 145 | **EPI Actuator Housing Production** | **152.5 days** | **5/12/03** | **12/10/03** |
| 146 | finalize dwg pkg | 2 wks | 5/12/03 | 5/23/03 |
| 147 | review & DCN | 1 wk | 5/26/03 | 5/30/03 |
| 148 | get quotes for welded assy | 1.5 wks | 6/2/03 | 6/11/03 |
| 149 | order 48 EPI housings | 1 day | 6/11/03 | 6/12/03 |
| 150 | receive machined parts | 10 wks | 10/1/03 | 12/10/03 |
| 151 | award assy contract | 0 days | 6/11/03 | 6/11/03 |
| 152 | welding and painting EPI assembly | 10 wks | 6/11/03 | 8/20/03 |
| 153 | 1st set available | 0 days | 10/1/03 | 10/1/03 |
| 154 | **HEPI: Flow bench for calibrating Parket valves** | **42 days** | **5/12/03** | **7/8/03** |
| 155 | finalize design of complete test fixture | 3 wks | 5/12/03 | 5/30/03 |
| 156 | order parts | 7 days | 6/2/03 | 6/10/03 |
| 157 | Assemble | 3 wks | 6/11/03 | 7/1/03 |
| 158 | ship to LLO | 1 wk | 7/2/03 | 7/8/03 |
| 159 | **VME System** | **50 days** | **5/19/03** | **7/25/03** |
| 160 | to be detailed | 2.5 mons | 5/19/03 | 7/25/03 |
| 161 | **Installation** | **95 days** | **10/1/03** | **2/11/04** |
| 162 | ready to start | 0 days | 10/1/03 | 10/1/03 |
| 163 | install X-end | 3 wks | 10/1/03 | 10/22/03 |
| 164 | Install Y-end | 3 wks | 10/22/03 | 11/12/03 |
| 165 | Install ITMx | 2 wks | 11/12/03 | 11/26/03 |
| 166 | Install ITMy | 2 wks | 11/26/03 | 12/10/03 |
| 167 | Install BSC | 2 wks | 12/10/03 | 12/24/03 |
| 168 | Install H1 | 3 wks | 12/24/03 | 1/14/04 |
| 169 | Install H2 | 2 wks | 1/14/04 | 1/28/04 |
| 170 | Install H3 | 2 wks | 1/28/04 | 2/11/04 |



# M020142-08

| ID | Task Name | Duration | Start | Finish |
|---|---|---|---|---|
| 171 | **Commissioning** | **82.5 days** | **10/22/03** | **2/13/04** |
| 172 | X-end | 1.5 wks | 10/22/03 | 10/31/03 |
| 173 | Y-end | 1.5 wks | 11/12/03 | 11/21/03 |
| 174 | ITMx | 1.5 wks | 11/24/03 | 12/3/03 |
| 175 | ITMy | 1.5 wks | 12/3/03 | 12/12/03 |
| 176 | BSC | 1.5 wks | 12/15/03 | 12/24/03 |
| 177 | H1 | 1.5 wks | 1/14/04 | 1/23/04 |
| 178 | H2 | 1.5 wks | 1/26/04 | 2/4/04 |
| 179 | H3 | 1.5 wks | 2/4/04 | 2/13/04 |
| 180 | ISC-EPI testing | 2.25 days | 12/24/03 | 12/26/03 |



# LIGO Change Request

**Change Request No.: CR-030013** **Date: 9 June 2003**

**WBS Element and Title: LIGO.2.02.8.x and LIGO.2.03.8.x, Atomic Clock Timing System**

**Originator: S. Marka, D. Sigg** **Telephone: 626-395-2034** **CCB Sponsor: D. Coyne**

**Technical Change Description:** The need for an independent timing system for the initial LIGO system has been established by LIGO and the greater LSC. A proposal for a system based upon atomic clocks and fiber optic distribution to the end/mid stations has been technically reviewed and approved by the Revision Technical Review Board (RTRB). This request is for the implementation of the proposed timing system.

(see attached LIGO-T030098-00 for a summary of the proposed system).

**Budget Impact:** $199K from LIGO operations funds. Commitment of funds is needed in FY03 since the intent is to get the system in place before the science 3 run. The cost estimate breakdown is indicated in the attached.

Capital equipment account requests are attached.

**Schedule Impact:** This is a schedule critical item for the science 3 run.

**Concurrence Signatures:**

| | |
|---|---|
| Technical and Engineering Support: | Date: |
| Detector Support: | Date: |
| Advanced LIGO Development: | Date: |
| Data and General Computing: | Date: |
| Hanford Observatory: | Date: |
| Livingston Observatory: | Date: |
| Project Controls Manager: | Date: |

**Approval/Disposition (CCB Chairman):** Date:

# LIGO Change Request

**Additional Information:**

| | |
|---|---|
| **WBS:** | LIGO.2.02.8.x and LIGO.2.03.8.x **(both capital accounts)** |
| **Title:** | Atomic Clock Timing System |
| **Project/Task-Award:** | LIGO.Clock/1 NSFLIGO.FY02CA – at Hanford<br>LIGO.Clock/2 NSFLIGO.FY02CA – at Livingston |

**Technical Change Description:** The need for an independent timing system for the initial LIGO system has been established by LIGO and the greater LSC. A proposal for a system based upon atomic clocks and fiber optic distribution to the end/mid stations has been technically reviewed and approved by the Revision Technical Review Board (RTRB). This request is for the implementation of the proposed timing system. (See attached LIGO-T030098-00 for a summary of the proposed system).

Other relevant documentation: Presentation to the commissioning team and RTRB: LIGO-G030233-00

Presentations to the All-LSC seminar on Friday May 23 on time stamps, time accuracy of data and its relevance to pulsar searches. (Bruce Allen, Szabi Marka, Daniel Siggs and M. Hewitson (GEO)): http://www.phys.utb.edu/lsc-colloquia/

**CALIFORNIA INSTITUTE OF TECHNOLOGY**
**MASSACHUSETTS INSTITUTE OF TECHNOLOGY**
Laser Interferometer Gravitational Wave Observatory (LIGO) Project

To/Mail Code:
From/Mail Code: Daniel Sigg
Szabi Márka
Phone/FAX:
Refer to: LIGO-T030098-00
Date: May 22, 2003

Subject: **Atomic Clock Proposal**

**Summary:**

We propose to install and integrate an independent timing system based on a caesium clock. The purpose of this system is twofold:
- Provide a diagnostics system to check and verify the current timing system which is based on GPS. And provide a NIST traceable calibration of absolute timing.
- Proof that we understand the arrival time of gravitational waves from an astrophysical point of view.

The equipment costs for this system are estimated to be 200k$.

**Requirements:**

The requirement of relating the arrival time of a gravitational wave at the vertex with the international timing standard is ±10µs. In the past the requirement of the clock was set to ±1 µs to allow for uncertainties in translating this time to the response of the interferometer. It is clear that one may relax the requirement on the clock as long as the overall uncertainty stays below ±10µs. We believe it is important to have both a primary system and an independent verification system that both deliver this accuracy. We feel strongly that it is not an option to miss a discovery just because of a relatively small timing error that has gone unnoticed.

**An Illustration:**

If one assumes a 1kHz signal and tolerates no more than a 20° phase mismatch between different detectors, the required timing precision has to be better than 50µs. Some people may argue that a 1kHz bandwidth isn't high enough, or that they would like to know the phase to better than 20°. This illustrates the ultimate need for a timing accuracy at the ±10µs level.

**Current System:**

The current timing is based on GPS master clocks that are located at every building. A quartz oscillator running at $2^{24}$Hz is phase locked to the GPS 1pps signal and serves as the main clock signal for the ADC and DAC boards. Data are collected in segments of 1/16s length before they are assembled into 16 second long frames. Whereas the exact time mark is provided by the front-end hardware, the GPS master clock is also read out to provide the time stamps of the 1/16s long data segments. To monitor the accuracy of the sampling process a ramp signal several samples long that is precisely aligned with the GPS 1pps is read in on an auxiliary channel. To check the time stamp of the data we also read in an IRIG-B signal that is derived from the same GPS master clock. Furthermore, the LSC software incorporates several internal consistency check to make sure that there is enough time to process the data before the next sample arrives, to make sure that each and every sample is actually seen by the ADC, and to make sure the DSCs in mid and end stations are working in synchronization with the LSC. To transfer the timing information to the physical arrival time of gravitational waves one has to calibrate the time delay—either in the input chain or, because of the current amplitude/phase calibration procedure, in the suspension chain. It is envisioned that the most accurate timing calibration will be derived from the photon calibrator. Because it uses radiation pressure to apply a force to the ETMs, it is the most direct way to induce a displacement.

**Proposal:**

Whereas the current system is good enough to meet the requirements (eventually), it is rather difficult to proof. Since absolute and long term timing accuracy is of outmost importance for the pulsar analysis, we propose to implement a second independent timing system that is capable of verifying the current system at the design requirement level. This independent timing system would serve as both a diagnostics system to check the performance of the current system as well as a monitor system to continuously evaluate the timing accuracy during science runs. This new system should fulfill the following criteria:

- Establish an independent time base at the same accuracy as the primary system, i.e., somewhat better than $\pm 10\,\mu$s.
- Be available in all buildings so that both the input and output chains can be tested. One should also be able to synchronize the photon calibrator, so that a direct measurement of the optical and electronic delays can be performed.
- Be conceived as both **independent** and **sufficient** by the LSC collaboration and the astrophysics community at large.

**Options:**

There is basally one option that will deliver the required accuracy as well the desired independence: a caesium based atomic clock. The option of using WWVB has been discarded because it won't deliver the required accuracy. The option of using an ensemble of GPS clocks from independent vendors has been discarded because another GPS system will not be considered independent by most. Installing an atomic clock should remove any doubts about the timing accuracy once and for all.

**Proposed System:**

We propose to install a caesium master clock at each site that serve as the long-term timing standard. We also propose to acquire a portable rubidium clock at each site to synchronize the caesium clock to NIST and other GW observatories, to perform diagnostics at the outbuildings and to serve as a short-term backup if the Caesium clock needs service. The time signal is sent to the outbuildings over an optical distribution system. We intent to sent the timing signal to all outbuildings and to use it there to synchronize the photon calibrator and to compare it against the local GPS master clock.

| Equipment | | unit | ext. |
|---|---|---|---|
| Caesium clock, Datum CS plus | 2 | 38k$ | 76k$ |
| Portable rubidium clock, AR-51A | 2 | 15k$ | 30k$ |
| Optical distribution system (LHO/LLO) | | 39/25k$ | 64k$ |
| Fiber cabling (single mode between LVEA/MSR) | | 3/2k$ | 5k$ |
| Time-Interval Measurement (e.g., Agilent 53131A) | 9 | 2k$ | 18k$ |
| UPS (36h for caesium clock) | 2 | 3k$ | 6k$ |
| Total | | | 199k$ |

cc:

commissioning group    revision technical review board

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# FABRICATED EQUIPMENT REQUEST FORM

FERF TRACKING NUMBER

## PART I — CAPITAL PROJECT INFORMATION

Please provide information requested in Parts I - IV for all fabricated equipment. This information is required to place fabricated assets into service.

1. CAPITAL PROJECT NO.:

| PROJECT | TASK | AWARD |
|---|---|---|
| LIGO.HANCA | 2.8.2.x | NSFLIGO.FY02CA |

2. FUNDING SOURCE AWARD NO.: PHY-9210038 Ownership (Title to Fabricated Equipment): GOVERNMENT

3. END-USER INFORMATION:
   AWARD MANAGER / P.I.: BARRY BARISH PHONE: 395-3853
   EMAIL ADDRESS: barish_b@ligo.caltech.edu MAIL CODE: 101EB

4. EQUIPMENT LOCATION INFORMATION: OFF CAMPUS: NO ☐ YES ☒
   IF NO, BUILDING NO.: ____ ROOM NO.: ____
   IF YES, PLEASE PROVIDE LOCATION: (include building, room, site, county and state): The Laser and Vacuum Equipment Area (LVEA) and the Mass Storage Room (MSR) in the corner station as well as the Vacuum Equipment Area (VEA) in the mid- and end-stations at the LIGO Hanford Observatory. Equipment is integrated into existing electronics racks.

5. DATE FABRICATED EQUIPMENT PLACED IN SERVICE: on or about October, 2003

REMARKS:

## PART II — FABRICATED EQUIPMENT IDENTIFICATION

| DESCRIPTION OF FABRICATED EQUIPMENT | QUANTITY | TOTAL COST | MAJOR EQUIPMENT CATEGORY (SEE LIST ON PAGE 2) | USEFUL LIFE |
|---|---|---|---|---|
| An independent timing system for the LIGO Hanford Observatory consisting of a caesium clock, a portable rubidium clock, an optical distribution system, a time interval measurement instrument and a UPS for the system. | 1 | $110,000 | OPTICAL AND ASTRONOMICAL | 10 years |

## PART III — CUSTODIAL DEPARTMENT INFORMATION

DIVISION NAME: PMA DEPARTMENT NAME: LIGO

DEPARTMENT MAIL CODE: 18-34

PREPARED BY NAME: FLORENCE KAUFMAN PREPARED BY EXT: 2057

PI / DIVISION ADMINISTRATOR: BARRY BARISH EXTENSION: 3853

## PART IV — APPROVALS

PI / DIVISION ADMINISTRATOR SIGNATURE

DATE:

BARRY BARISH

PLEASE TYPE OR PRINT NAME

FOR PROPERTY ACCOUNTING DEPARTMENT

Manager: DATE:

(Form Number CIT FERF-1) 1/2000

# INSTRUCTIONS FOR PREPARATION OF THE FABRICATED EQUIPMENT REQUEST FORM

Type all information to ensure all information is legible. One form should be completed for each fabrication. Do not enter information in shaded areas. Retain a copy for your records. Submit remaining copies to the Property Accounting Office, Keith Spalding Administration Bldg., Mail Code 215-6. A transaction confirmation document will be returned using the information entered in PART III - DEPARTMENT INFORMATION acknowledging receipt of your request.

## PREPARATION OF THE FORM

**1. CAPITAL PROJECT NUMBER (PART I - CAPITAL PROJECT INFORMATION)**
   A. To request a new capital project, provide the Award Number that will fund the capital project in PART I - CAPITAL PROJECT INFORMATION.
   B. To fabricate additional equipment under an existing capital project, provide the Project, Task and Award in PART I - CAPITAL PROJECT INFORMATION.

**2. FUNDING SOURCE AWARD NUMBER AND OWNERSHIP**
   A. Provide the funding agency contract or grant number in PART I - CAPITAL PROJECT INFORMATION.
   B. For Federally-funded fabrications, identify whether title will vest with the **"Government"** or **"Caltech"**. If fabrication is sponsored by a non-Federal agency, identify whether title will vest with **"Other"** or **"Caltech"**. Refer to the California Institute of Technology Resume to determine ownership of the fabricated equipment and provide that information in PART I - CAPITAL PROJECT INFORMATION.

**3. END-USER INFORMATION**
   A. Provide required end-user information in PART I - CAPITAL PROJECT INFORMATION.

**4. EQUIPMENT LOCATION INFORMATION**
   A. Provide required equipment location information in PART I - CAPITAL PROJECT INFORMATION.

**5. DATE FABRICATED EQUIPMENT PLACED IN SERVICE**
   A. Provide estimated or actual date fabricated equipment will be placed into service in PART I - CAPITAL PROJECT INFORMATION.

**6. REMARKS (Explain)**
   A. Explain special adjustment requested in Remarks PART I - CAPITAL PROJECT INFORMATION.

**7. FABRICATED EQUIPMENT IDENTIFICATION (PART II - FABRICATED EQUIPMENT IDENTIFICATION)**
   A. Complete all information requested in PART II - FABRICATED EQUIPMENT IDENTIFICATION.
   B. Assign a major equipment category to the equipment being fabricated from the list shown below:

| | | |
|---|---|---|
| Athletic | Lab Heating/Cooling | Photo/Video |
| Building | Lab Measuring | Radiation/Partical Sources |
| Computer | Machine Tool/Heavy Equipment | Radio/Communications |
| Electronic Lab | Music | Raw Materials |
| Electronic Parts | Office | Security/Emergency |
| Fine Arts | Optical and Astronomical | Vehicle |

**11. DEPARTMENT INFORMATION (PART III - CUSTODIAL DEPARTMENT INFORMATION)**
   A. Department information should be completed for all requested adjustments.

**12. APPROVALS (PART IV - APPROVALS)**
   A. Signature of Principal Investigator (PI) or Division Administrator from the Institute department/division requesting the capital project is required.

Caltech Property Accounting

Keith Spalding Administration Bldg., MC 215-6

FERF TRACKING NUMBER

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______ DATE: ______

BARRY BARISH

PLEASE TYPE OR PRINT NAME

FOR PROPERTY ACCOUNTING DEPARTMENT

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# LIGO Project Change Request Log

| Change Request No. | Description | Submitted By | Submit-tal Date | Current Status | Disposition Date | Baseline Date | Net Contin-gency |
|---|---|---|---|---|---|---|---|
| CR-030008 | Livingston Laboratory/ Office Building, Furniture | M. Coles | April 29, 2003 | Information Only (Below Threshold) | June 23, 2003 (LIGO-M030132) | OPS | ($406,516 |
| CR-030009 | Livingston Staging Building Cabinets, Casework, Lab Furnishing | A. Sibley | April 29, 2003 | Approved $170,000 | May 5, 2003 (LIGO-M030091) | May 2003 | ($576.516) |
| CR-030010 | Livingston Facilities, Upgrade Technical and Lightning Grounding Systems | A. Sibley | May 2, 2003 | Approved $80,000 | May 5, 2003 (LIGO-M030091) | OPS | ($576.516) |
| CR-030011 | Seismic External Pre-Isolation (EPI) at LIGO Livingston Observatory | J. Kern, D. Coyne | May 16, 2003 | Approved $2.6 million | June 23, 2003 (LIGO-M030132) | OPS | |
| CR-030012 | RFI Mitigation (Operations WBS 2.8.2 and 3.8.2) | D. Coyne | May 28, 2003 | Approved (first year) $580,140 | June 2, 2003 (LIGO-M030122) | OPS | ($576.516) |
| CR-030013 | Atomic Click Timing System (LIGO.2.02.8.x and LIGO.2.03.8.x) | S. Marka, D. Sigg | June 9, 2003 | Approved 199,000 | June 23, 2003 (LIGO-M030132) | OPS | |