LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

LIGO Laboratory / LIGO Scientific Collaboration

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Pre-Isolator with Electromagnetic Actuator: Conceptual Design, Test Plan

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1 Introduction

1.1 Purpose

This document gives the conceptual design, derived requirements, and test plan for the variant of the initial LIGO seismic retrofit External Pre-Isolator using an electromagnetic actuator. Please see the documents on the Overall Conceptual Design and the Hydraulic External Pre-Isolator Actuator to put the content of this document in context.

1.2 Scope

The MEPI, or electroMagnetic External Pre-Isolator, is designed to reduce the control band (40 Hz and lower) motion of the initial LIGO Optics Platform through a reduction in the excitation of the horizontal crossbeams. It is targeted as an alternate to the baseline design using a hydraulic actuator for the same purpose.

The overall objective of the seismic retrofit is to reduce the RMS velocity and displacement of the optics platform, in all 6 degrees of freedom, thus reducing the actuator authority required in the suspension system. This will allow the goal sensitivity of the initial LIGO instruments to be reached.

1.3 Definitions

Please see the Design Requirements Document which addresses the External Pre-Isolator, LIGO-T020033-02-D, for Definitions.

1.4 Acronyms

See http://www.ligo.caltech.edu/LIGO_web/docs/acronyms.html

EPI: External Pre-Isolator

MEPI: electro**M**agnetic actuator **E**xternal **P**re-**I**solator

HEPI: Hydraulic actuator External Pre-Isolator

EM: electromagnetic

1.5 Applicable Documents

1.5.1 LIGO Documents

T020033-02-D Initial LIGO Seismic Isolation Upgrade: Design Requirements Document

T020050-00-D Initial LIGO Seismic Isolation Upgrade: Conceptual Design Document

T020040-00-D External seismic pre-isolation retrofit design

T020047-00-D Quiet Hydraulic Actuators for Initial LIGO

D020166-00-D Drawing and specifications of the target electromagnetic actuator, from BEI Kimco

1.5.2 Non-LIGO Documents

None at present.

2 General description

2.1 Relationship to other subsystems

The MEPI is intended to replace the initial LIGO airbearing, and fine and coarse actuators. It is an alternate to the Hydraulic External Pre-Isolator (HEPI), and the conceptual design is heavily based on the conceptual design of the HEPI.

2.2 Product Perspective

A rendering of the electromagnetic actuator in the pre-isolator structure is shown in Figure 1.

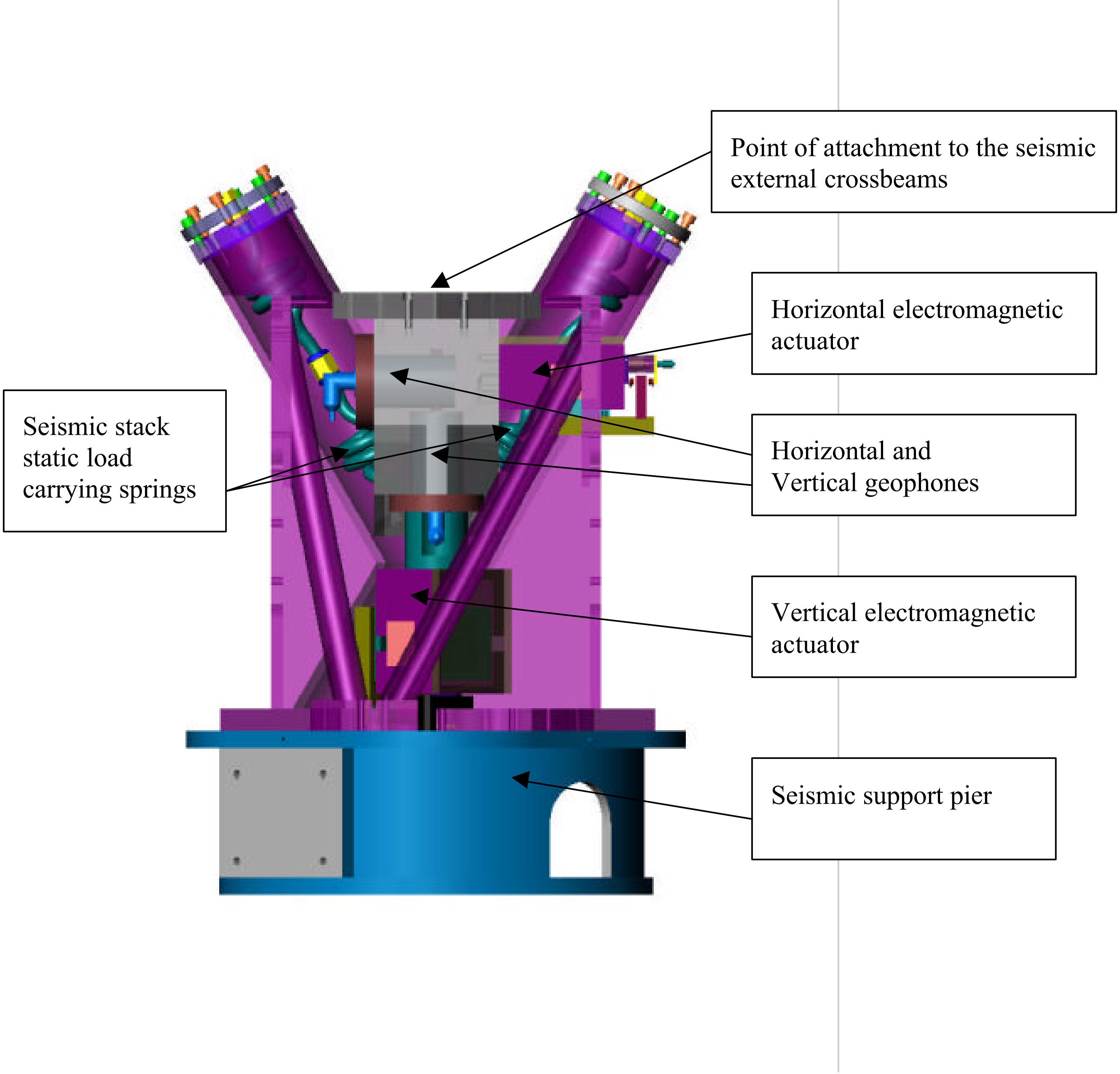


Figure 1: Rendering of the electromagnetic actuator placed in the standard pre-isolator structure.

2.3 Product Functions

The function of the External Pre-Isolator (EPI) is described in the requirements document and in the conceptual design for the Hydraulic EPI. The electromagnetic actuator would replace the hydraulic actuator, exerting a force between the seismic support pier and the crossbeam to hold the crossbeam stationary in inertial space while the pier moves with the seismic excitation.

2.4 General Constraints

The electromagnetic actuation alternate must fit in the basic structure created to house the Hydraulic actuator to minimize the engineering required for pursuing the two approaches. If the solution is chosen, some tuning of the design (e.g., spring stiffness) may be performed.

2.5 Assumptions and Dependencies

The loads seen by the system are assumed to be those of the initial LIGO Seismic Isolation system (HAM and BSC). The BSC piers are those of the initial LIGO isolation system, but modifications to the HAM piers are considered possible. The resonances of the BSC piers are assumed as described in the MIT Ilog measurements (MIT Ilog, 15 Feb 2001).

3 Conceptual Design

The conceptual design is based upon that for the Hydraulic External Pre-Isolalator (HEPI) and and understanding of that design is assumed in the description below.

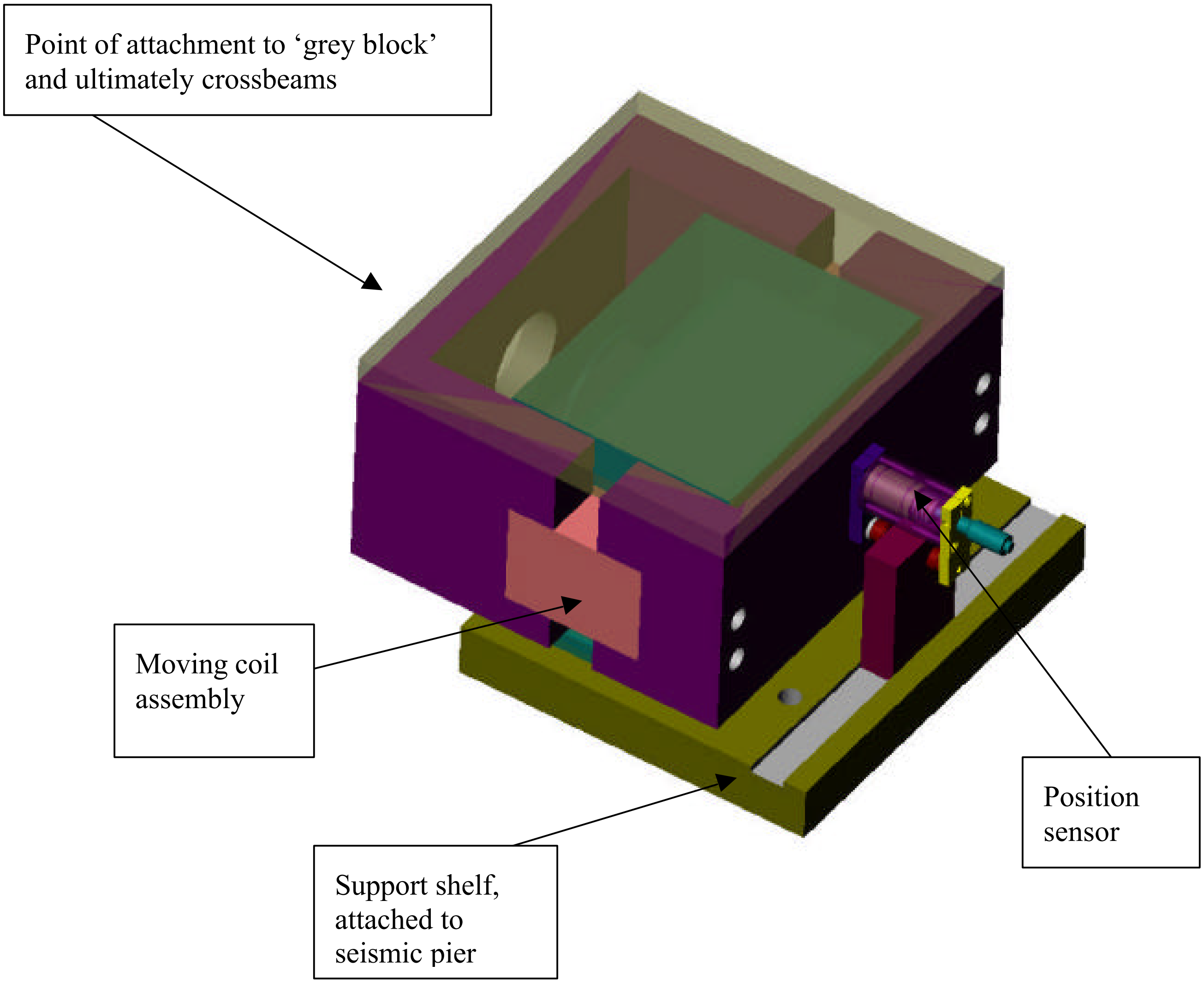
3.1 Description

For each support pier of a BSC or HAM isolation system, a structure equipped with springs is placed between the top of the pier and the external crossbeam. The load of the crossbeams and the seismic isolation stack is supported by the springs, giving ~8 Hz resonant frequencies for the 6 DOF of the crossbeam-stack assembly. The electromagnetic actuator allows forces to be exerted between the crossbeam and the pier, which can compensate for seismic motion of the pier. Sensors integrated into the electroagnetic external pre-isolator (MEPI) allow feedback to be used to reduce the net forces on the stack; in addition ground- or pier-mounted sensors may be used for feedforward and/or sensor correction.

In our baseline concept, the armature (coils) of the electromagnetic (EM) actuator are attached to the external crossbeam and the permanent magnet assembly is (indirectly) attached to the pier, and no flexure arrangement is used to define the axis or alignment of the coils with respect to the magnet.

Referring to Figure 1(from Ken Mason), one sees two spring assemblies at ~30 deg from the vertical. The top of the springs are attached to a rigid structure (called here the V-block), which is supported by the support pier (blue). The springs are left- and right-wound, or otherwise compensated such that no torques are exerted upon extension. The springs support the central gray block, which is attached to the crossbeams (and the seismic isolation stack) through the existing blue external box-frame structure. The EM actuators are seen to the left (for horizontal actuation) and under (for vertical actuation) the grey block. The permanent magnet structure is supported by the pea-green shelf. The geophone sensors are in the gray block, and the position sensor is mounted behind the actuator.

A view of the actuator itself is seen in Figure 2. The magnet assembly is shown in dark green, and is fixed to the pea-green shelf which is supported by the seismic pier. The coil actuator is pink, and is attached to the purple frame which carries the force from the coil to the crossbeams (via the grey block in Figure 1). The force is exerted along the axis from lower right to upper left. The position sensor (Kaman) is shown at the lower right, along the axis of the actuation, with the moving part



attached to the purple frame and the fixed part attached to the pea-green shelf. The L4-C geophone sensor is embedded in the grey block of Figure 1.

Figure 2: View of the electromagnetic actuator assembly.

The magnetic actuator has potential advantages over the hydraulic actuator in the familiarity of the components and their detailed modeling, ease of installation and maintenance, and possibly in the fact that the force exerted is relatively independent of the position of the pier. The lack of hydraulic fluid reduces risk and complexity. Certain and notable disadvantages are the local heat dissipation (which may cause sensor drift or thermal expansion), and the risk of magnetic coupling to nearby sensors and to the test mass. Modeling and prototyping will address both advantages and disadvantages to enable a choice.

3.2 Derived Requirements

We require that the crossbeams of seismic isolation be held stationary (to the limits of the requirements set out in T020033) in inertial space despite local ground motion causing excitation of the support point (the top of the support pier), and despite drifts in the position of the support point (due to thermal expansion or changes in the spring constant, or due to tidal strains, weather conditions, etc.).

We describe the conceptual design for the BSC implementation, with the HAM to follow at a later time; the assumption is that the HAM requirements will be no more difficult to fulfill using the same principal ingredients.

We take as a point of departure the structure and spring specifications determined for the hydraulic actuator approach to the pre isolator. This leads to a net stiffness in the vertical axis of 6e6 N/m, and in the horizontal axis at 45 deg to the optical axis (due to the actuator arrangement) of roughly 2e6 N/m (slightly higher than the simple design stiffness of 1.5e6 to account for the probable increased stiffness of the spring pushed sideways; analysis underway to confirm this number).

3.2.1 Required force

The force is determined by the slow large actuation requirements, rather than the several Hz peaks or the need to have a unity gain frequency of the order of several tens of Hz.

3.2.1.1 Vertical

In the vertical direction, there are 4 actuators, so each actuator must deliver ¼ of the force to compress the net vertical spring. In the vertical, this leads to an equivalent of 1.5e6 N/m Hooke's *k* seen by each actuator. The 40 micron pk-pk requirement leads to a force requirement of 60 N pk-pk per actuator.

This vertical actuation is anticipated to be used principally to correct for the pitch component of the microseismic peak, which the requirements document T020033 tells us to assume will require differential displacements at the fore and aft ends of the seismic isolation system of order 40 microns.

3.2.1.2 Horizontal

In the horizontal direction, there are two actuators for each direction (at 45 deg to the optical axis due to the mechanical design). But this motion is 45 deg to the axis we care about; applying force from all four horizontal actuators to achieve a motion along the optical axis gives v2 times the motion along the optic axis, or net 3.75e5 N/m stiffness seen by each of the 4 horizontal actuators. The 300 micron pk-pk requirement leads to a force requirement of 112 N pk-pk per actuator.

Yaw corrections (and dynamic actuation) are covered by this requirement through differential actuation.

3.2.1.3 Temperature induced forces

An additional requirement for the electromagnetic actuator is to resist the change in force due to temperature fluctuations of the springs. This requires as input the change in length, or k, of the springs, as a function of temperature. As a first estimate, we guess at a net temperature coefficient for the spring of 5e-5 per degree (don't know if CTE or Young's modulus changes more). Given an approximate 50cm spring length gives 25 microns per degree. The temperature stability of the spring/assembly, without a dissipating actuator, is at least a factor of 10 better than this, but the electromagnetic actuator will generate heat and must be able to handle its own effect on the structure. While other arguments may not allow a temperature rise of 1 deg, we require that the electromagnetic actuator be able to execute an additional 25 micron displacement to compensate for heating effects.

When the tides are at the extreme, we can anticipate that the actuator will be required to exert a force of 56 N, sufficient to make a peak excursion of 300/2 = 150 microns, over ~hour long periods. For the target actuator, this would make a power dissipation of 13 W. Resulting temperature distribution and consequent expansion is TBD.

3.2.2 Unintended force (cross terms)

3.2.2.1 Linear

The force perpendicular to the principal axis should be <10%, with a 1 % goal. Logic: There will be cross-coupling due to the imprecision of construction, different spring constants, etc. which will require cross-terms in the servo controller, so the actuator should only be required not to make things worse.

3.2.2.2 Angular

Using the same logic, the torque should be 'small' (1/10 to 1/100) compared to the torque of a given displacement over the baseline of the piers (~3m), so require (1/3) * (1/100 or 1/10) N*m / N, or .03 - .003 N*m / N.

3.2.3 Force as a function of position

The system is in a feedback loop, so absolute calibration of force is not needed and constancy only (!) affects the loop gain and the plant description. Once a control model exists the tolerance can be determined. As a point of departure, we guess that we must have less than 1% variation of the force constant over the throw (300 microns).

3.2.4 Stroke

In operation, the horizontal actuator must accommodate the tidal displacements (up to 260 microns pk-pk) plus the microseismic motion (up to 40 microns pk-pk). We require 300 microns pk-pk of stroke.

3.2.5 Mechanical clearance and alignment tolerance

Would like to allow the installation and operation with no flexible joints built in, so require at least ±1mm clearance and alignment tolerance in all three axes. We require that the operational requirements be met for misalignments of up to 200 microns and 1 mrad.

3.2.6 Output Impedance

We currently place no separate requirements on the open-loop impedance of the actuator and its amplifier, pending a servo model. There may be an advantage to a current (or at least a high-impedance voltage source) for the driving amplifier to allow the passive isolation of the ~8 Hz resonance to be exploited in the GW band. This may be compromised by the bellows ‘short circuit’, so may be illusory.

3.2.7 Safety

A caging mechanism may be needed for powerdown/vacuum cycling/invacuum rework etc.

Earthquake response: A set of safety stops will be needed to reduce the likelihood of damage to the actuator coil in the case of a small earthquake. These should limit, using ‘soft’ stops, motions greater than 1.0 mm pk-pk

Power failure must not result in a dangerous excitation of the stack. Some analysis is needed to be certain, but at first look it seems that a sudden simple loss of current to the coil should not be dangerous (we start at 150 micron peak deviation from the neutral point). A failure of one supply must not ‘rail’ the output amplifier.

3.3 Isolation performance prediction

A model, not yet developed, is needed for any realism in predictions.

Even naïve predictions require that the actuator resonances be measured (UGF upper limit).

The mechanical transmission of the bellows must be measured to determine the effect on the performance of the system in the GW band.

If an upper unity gain frequency of the order of 20-25 Hz can be realized, then the requirements can probably be met.

3.4 Noise performance requirements

3.4.1 Control band (f = 40 Hz)

The self-noise due to the sensors is in common with the hydraulic actuator. Present models indicate that the sensors selected (L4-C geophone and Kaman position sensors) can probably meet the requirements; see that section for discussion. The amplifier output current noise appears to be the only other contribution, and can be made to be negligible at these frequencies.

3.4.2 GW band ($f > 40$ Hz)

The motion of the crossbeams along the optical axis due to the actuator must be < 4e-12 m/vHz for $f = 50$ Hz. We guess that the equivalent mass of the crossbeam at 50 Hz is 500 kg. Thus the allowed force on the support beam end is $F=m?^{2}x$ = 2e-4 N/rHz, or 1e-5 A/rHz at 50 Hz. This is feasible.

We will consider the possibility of exploiting the passive isolation in the GW band due to the ~8 Hz natural frequency of the spring suspension. If the output amplifier driving the actuator is a voltage source, then the attenuation at 30 Hz is ~10, moving the corner frequency with the thermal noise down by ~20%. This would be a weak argument also for lowering the natural frequency of the spring suspension, and will be considered in any spring trades. The bellows (a rather imperfect spring) may compromise the isolation significantly, and will be separately characterized.

3.5 Actuator selection

The evident alternatives to a hydraulic actuator are those based on a piezo-electric transducer (PZT) or an electromagnetic motor. A collection of measures by which one might choose between them is shown in Table 1.

	PZT	**Electromagnetic motor**
Force	>1000 N easy to get	200 N hard to find
Stroke	30 microns hard	1cm easy
Servo similarity to hydraulic actuator	Rather similar	Rather different
Servo limits	High-Q internal resonances	Probably high internal resonances, maybe low Q
Earthquake response	Probably broken	Maybe broken
GW-band character	Probably ‘stiff’	Maybe an 8 Hz double pole
Heat dissipation	Probably negligible	~4 W RMS, 13 W peak
Magnetic field – sensor/TM	Not an issue	TBD, may be significant
Mechanical interface	Requires constraint and flexible coupling for multiple axes	Adequate clearance to allow fixed armature and magnets
Electrical interface	HV amplifiers	Low-voltage systems
Linearity	Requires closed-loop; hysteretic	Linear
Self noise	May create impulsive noise	As quiet as the amplifier
Reliability concerns	Humidity; breakdown; fragility	Good reliability if not overdriven

Table 1: Comparison of PZT and electromagnetic actuators

We have chosen to pursue a solution based on an electromagnetic actuator. The baseline design for the Advanced LIGO isolation system uses an electromagnetic actuator from BEI Kimco, the model Coarse (Model LA50-62-004Z), with the following characteristics:

Peak force	550 N
Continuous stall force	193 N
Mechanical time constant	1.7 msec
Stroke	6.3 mm
Clearance on each side of coil	1 mm
Weight of coil assembly	1.6 lbs (3.5 kg)
Weight of field assembly	23 lbs (51 kg)
DC Resistance (spec)	1.5 ohms +/- 12.5 %
DC Resistance (measured)	1.8 ohms
Force constant (spec)	21 N/A +/-10 %
Max winding temperature (spec)	155 C
Inductance (measured)	1.50 mH
Inductance (spec)	0.78 mH +/- 30 %
Back EMF constant (spec)	2 volts/(m/sec) +/- 10 %

Table 2 Characteristics of the BEI Kimco Model LA50-62-004Z actuator.

This motor has advantages in its high force constant, leading to lower dissipated power, and a well-contained magnetic field. It appears that this actuator meets the derived requirements, in general with a significant safety margin, and presents a reasonable electrical and mechanical interface.

3.5.1 Other electromagnetic motors

There are a range of commercial solutions which can deliver the force (stroke is never the problem). Most commercial linear motors have tight clearances; 0.2 mm is typical. Most use a 3-phase AC drive, which could cause interference with other interferometer components.

One could imagine employing simple solenoids with steel plungers which could be used in opposition, applying current to one or the other to achieve push-pull operation. We –suspect that this could have strong enough cross-coupling to be a problem, but no prototypes have been tested.

Integrated Dynamics Engineering (IDE) Fabricates a series of motors (‘MaxAktiv’) with large (~plus/minus 1.2 mm) clearance in the perpendicular directions (the actuator used in the the TMC

Electro-Damp isolators look similar in design). The largest one (LM200) has a quoted force of 250 N at 100% duty cycle (1600 N at 15% duty cycle), cost $2800/each in small quantities, have 8-10 week delivery. A smaller unit, the LM-80 delivering 130 N at 100% duty cycle is more readily available. It is a DC (not AC) system, using permanent magnets and coils. Other characteristics of the LM-80 are found in Table 3

Force constant	100 N/amp
Peak force, 15% duty cycle	800 N
Peak force, 100% duty cycle	130 N
Heat dissipation	11 W
temperature at 100% duty cycle	80 C
Coil resistance 30 Ohms	30 Ohms
Coil inductance	35 milliH
Gap on each side of the coil	1.14 mm per side

Table 3: Integrated Dynamics Engineering (IDE) MaxAktiv LM80 characteristics

3.6 Implementation

The objective is to have as much in common as possible with the design of the hydraulic system (servo principles, servo sensors, mechanical aspects). There are inevitably some differences.

3.6.1 Sensors

The same sensors and electrical interface are planned as for Hydraulic Actuator: the Sercel L4-C geophone for high frequencies, and the Kaman displacement sensor for low frequencies. Sensitivities for these sensors can be found in the HEPI documentation.

3.6.2 Mechanical design

The ‘V-block’, or main structural system, will be used with minor modifications. The central block will be bored to receive the L4-C geophones. A new optimization for the spring stiffness should be performed, but the point of departure is that the same stiffness will be used (at least for the prototype effort).

The permanent magnet field assembly will be supported on a ‘shelf’ as for the hydraulic actuator; the smaller size of the electromagnetic actuator requires either a different placement or an adaptor plate. The position, height and angle of the field assembly will be fine-aligned through shims to center the coil in the field with ~0.1 mm precision using feeler gauges or the equivalent.

The moving coil assembly is held in a rigid box structure to carry the force from the coil assembly to the central block. This box structure is bolted with an initial pre-alignment to the central block to establish the coil axis parallel to the desired force vector.

3.6.3 Servo control design

The servo control design for the MEPI has not been started. It will be based on the combined heritage of the 'rapid' prototype one-stage servo design and results, and also the common elements with the hydraulic design.

It appears that the sensor modeling, and sensor blending, should be similar or identical for the MEPI and HEPI.

The modeling of the load, spring suspension, and the pier dynamics should all be able to be incorporated directly into a model for the MEPI from the HEPI.

The techniques for dealing with the over-monitored and over-controlled system (8x2 sensors, 8x actuators, for 6 DOF) should be transportable from the HEPI to the MEPI.

The actuator description, and any consequences of the completely different passive impedance of the electromagnetic actuator, will need to be integrated into the HEPI model basis, hopefully with carryover from the 'rapid' prototype effort results.

4 Pending issues to be resolved in the PD phase

4.1 Prototype and test

There has been no prototype test to date, although many of the issues have been investigated in the first prototype for the Advanced LIGO isolation system. Both stand-alone actuator tests, and simple servo tests, are a high priority. The test plan presently is just an outline.

4.2 Controls paradigm, feasibility study

Not enough information yet to even know where the problems are, but we will look at

?? Tilt-horizontal coupling?
?? Internal resonances?
?? Sources of instability due to nature of force actuator?

4.3 Issues around heat dissipation

?? Is there a problem?
?? Can it be solved using convective airflow and deflectors to keep heat away from sensitive components?
?? Forced cooling of some kind?

4.4 Issues around magnetic coupling

?? Is there a problem, either for coupling to nearby sensors or to the test masses?
?? Magnetic shielding possible with close collocation?
?? Separation of actuator and geophone needed – mechanical consequences?

5 Test Plan

5.1 Stand-alone actuator/sensor tests

5.1.1 Amplifier/actuator/sensor requirements test

?? Set up actuator in frame with stiff spring, position sensor to check force/amp

?? Measure amplifier noise, bandwidth

?? Measure back-to-back geophones with buffer amplifier for noise characterization

5.1.2 Thermal testing

?? Set up actuator in frame, airflow as for final design with stiff spring; put in current at 100 N force

?? Measure temperatures, look at airflow, design, fab, iterate heatsinking/deflectors/chimney

?? Measure final spring thermal properties – change in length or *k* with temperature

?? Measure displacement sensor thermal sensitivity

?? Measure geophone temperature sensitivity

?? Estimate impact on system stability, iterate design

5.1.3 Stray magnetic field testing

?? Set up actuator in frame, geophone in steel box as per design – but not mechanically coupled

?? Measure xfer function to characterize coupling to geophone, calculate impact, iterate on design as needed

?? Check for perpendicular geophone position sensitivity as well

?? Measure magnetic field with loop antenna at various distances, predict field at test mass

?? Determine if cross coupling is acceptable

5.1.4 Servo element characterization

?? Set up actuator in frame, coil on stiff spring, instrument coil with accelerometers

?? Measure transfer function to high frequencies, understand first few resonances, assure that these are intrinsic

?? measure dF/dx (variation of AC on a DC background)

?? measure torques and perpendicular forces enough to assess importance of problem

?? iterate with model to determine if acceptable

5.2 One-axis subsystem tests

5.2.1 Actuation testing

?? set up one corner in final configuration, vertical actuation only

?? apply DC currents, monitor displacements with displacement sensor

5.2.2 Open-loop servo characterization

?? measure transfer function of actuation to geophone over broad range of frequencies

5.2.3 Closed-loop servo characterization

?? set up dspace, blend, and control

?? set up witness seismometer

?? measure in-loop and out-of-loop performance, reconcile with model, requirements

5.2.3.1 Feed-forward characterization

?? set up ground seismometer

?? test, reconcile with model, requirements

5.3 Complete system tests

5.3.1 Sensor and witness calibration

?? place all geophones together, check for similarity of response, noise levels

?? check witness calibration with geophones

?? check functionality, calibration of position sensors (dial gauge), noise level

5.3.1.1 Actuation testing

?? with all systems installed,

?? close loops around individual sensors; check for limiting resonances, phase shifts, get it working right

?? check/calibrate position sensors using geophones

?? execute DC translations and tilts, check with dial gauges

?? calibrate position sensors

?? reconcile with spring uniformity, mechanical tolerances

?? execute translations and tilts at higher frequencies

?? develop pure translation and rotation matrices (trusting geophones)

?? make it all work

5.4 Installation plan exercise

The installation procedure will resemble closely that for the HEPI.

?? Remove initial prototype materials, replace dummies

?? Instrument optics table (HAM, BSC) with retroreflectors/theodolites, mirrors and optical levers, and electronic levels as needed to determine alignment to ~<10 microrads

?? Instrument optics table (HAM, BSC) with geophones etc. as needed to monitor excitation of table during installation

?? Install ‘first-article’ (might be recycled prototype hardware if close enough to first article) mechanical systems according to protocol

?? Monitor both alignment accuracy and shock history (from optics platform geophones)

?? Iterate as needed to meet installation requirements