LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

LIGO Laboratory / LIGO Scientific Collaboration

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Photon Calibrator Conceptual Design

Mike Smith, Phil Willems

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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/

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1 Introduction

1.1 Purpose

The purpose of this document is to describe the Conceptual Design of the Photon Calibrator subsystem. In accordance with document M950090-A-D, "Guidelines for Detector Construction Activities," the Conceptual Design is intended to flesh out a subsystem sufficiently to develop a complete set of requirements that the final design must satisfy. This document presents the design of a Photon Calibrator subsystem at this level.

1.2 Scope

The Photon Calibrator is a laser that reflects an intensity-modulated beam from a test mass, along with the necessary optics to condition and deliver the beam and monitor the delivered power. Radiation pressure provides the force to the test mass. In Advanced LIGO the Photon Calibrator will act only on the ETMs.

2 Physics of Photon Calibration

A photon of wavelength λ has momentum h/λ, so when it reflects off the surface of an optic with incident angle θ, its momentum normal to the surface changes by $2h\cos(\theta)/\lambda$. The optic recoils with the opposite momentum. As each photon has energy hc/λ, a beam of photons with power $P = Nhc/\lambda$, where N is the number of photons per second, will exert a force upon reflecting from the optic of $F = 2Nh\cos(\theta)/\lambda = 2P\cos(\theta)/c$. The force on the optic can be varied in time by modulating P. Note that the laser wavelength does not affect the relationship between force and power.

Note also that radiation pressure can only push an optic, never pull it. The desired calibration force is a sinusoid, so the laser power must be sinusoidal around a mean power equal to at least half the amplitude of power oscillation. This results in a DC force which is balanced by the ISC servo and which does not contribute to the calibration.

3 Photon Calibrator Design

3.1 The Laser

The Photon Calibrator for initial LIGO uses a Crystal Laser 500 mW Nd:YLF laser operating at 1047 nm. There has been some question about the reliability of this laser, although the past year of operation, including specific power tests[1], has found no problems. Therefore, the baseline Advanced LIGO Photon Calibrator laser will be a Crystal Laser 500 mW Nd:YLF laser. This 500 mW is well in excess of the 14.2 mW requirement in section 2.1.1 of the Photon Calibrator DRD. This will allow the Photon Calibrator to operate at much higher force levels than nominal, for example early in commissioning of the detector when the noise levels are higher, or when operating at higher frequencies or in alternative IFO configurations (narrowband, low power). Additional SNR can be simply gained also by longer integration of the Photon Calibrator signal. However, at these higher force levels the noise requirements may not be met, see section 3.2.

The 500 mW laser can run reliably for >10,000 hours without maintenance and not need forced air or water cooling, satisfying the MTBF of one year in section 2.3.1 of the Photon Calibrator DRD.

3.1.1 Nd:YLF Design

The advantage of using a Nd:YLF 1047 nm laser for the photon calibrator is that it is completely incoherent with the main interferometer laser by virtue of their wide frequency separation. This means that risk of noise due to scattered light is only through Photon Calibrator light fluctuations making their way to the ASP and causing audiofrequency fluctuations in the DC readout level. This possibility will be largely mitigated by dividing the Photon Calibrator beam into two or four weaker beams that are directed toward the outer regions of the ETM face, away from the main IFO beam. In order for the light to reach the dark port, it then must scatter off both the ETM and ITM surfaces. If necessary, laser line filters can be used at the output tables to further attenuate the 1047 nm light while passing the 1064 nm light.

The main disadvantage of using a 1047 nm laser is that the ETM HR coatings are optimized for 1064 nm, and the possibility exists that 1047 nm light is reflected or absorbed significantly differently. The ETM coating generally has very high reflectivity at 1047 nm, and the reflection coefficient is better than 99%; however, questions have arisen as to whether the absorption of 1047 nm light by the coating could be ~100x larger than that for 1064 nm light, causing photothermal effects which create systematic errors in the calibration signal. This too would be mitigated by keeping the photon calibrator beams outside the main IFO beam profile to minimize overlap. Even at this high level the increased absorption will not change the recoil of the ETM by more than 0.1% (see Section 3.3.5.4 below).

3.2 Intensity Modulation and Stabilization

The Photon Calibrator may not ever need to operate while the interferometer is collecting data in science mode. If so, the noise requirement on the Photon Calibrator need only be low enough not to make the calibration uncertain to more than 5%.

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[1] Rick Savage, private communication, 12/20/2006.

The Photon Calibrator will use an acousto-optical modulator to produce the desired calibration waveforms. At 14.2 mW optical power, the applied force is 94.7 pN. In Section 2.1.3 of the Photon Calibrator DRD the noise force is required to be less than the upper limit of $7.9\text{x}10^{-16}$ N/√Hz at 10 Hz, rising linearly with frequency, and $1.6\text{x}10^{-15}$ N/√Hz, independent of frequency. This is equivalent to a RIN of $\sim 10^{-5}$/√Hz, which is easily achievable using AOMs (see Figure 1 below). However, at higher force, meeting the noise requirements could require a more stringent RIN. Since the higher net force would only be used early in commissioning before the interferometer reaches design sensitivity and/or not during data collection, this does not impact the design.

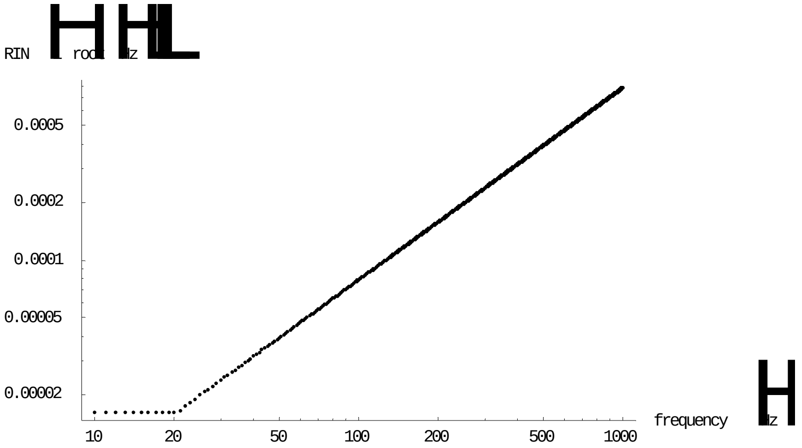

Figure 1:Intensity stability requirement for the Photon Calibrator when run during data collection.

3.3 Optical Layout

3.3.1 Test Mass Illumination Pattern

Given the modest power required, multiple bounces of the Photon Calibrator laser beam to increase the radiation pressure are not necessary. However, it is desirable to direct the Photon Calibrator beam away from the center of the test mass, to minimize scattering into the IFO beam and to prevent elastic deformation of the mirror surface by the Photon Calibrator from injecting additional apparent recoil into the calibration. In order that there be no resultant torque on the test mass, it is necessary to use multiple beams with counterbalancing torques on the test mass.

Two beams of equal power, equidistant from the center of the test mass face and on a line through it,[2] are sufficient for this purpose. The offset from center can be horizontal, vertical, or anything in between. The baseline design assumes horizontal offset.

The recoil of the test mass does not depend upon the spot size of the incident beams, so long as none of the light is lost around the edges of the mirror surface. It is convenient for the spot size not

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[2] Strictly speaking, since the angles of incidence on the ETM will in general be different for two spots, the beams should be slightly unequal.

to change significantly from the Photon Calibrator breadboard to the ETM, a distance of ~6 m. Therefore, the Rayleigh range of the beam must be greater than 6 m, which implies a waist size greater than 1.4 mm. This spot size is consistent with the laser source and with standard 1” optics. This will also allow the Photon Calibrator beam powers to be verified in the BSC with an absolute radiometer before evacuation without additional lenses.

3.3.2 In-vacuum Beam Paths

The in-vacuum layout of the Photon Calibrator is shown in Figure 2. Note that the in-vacuum dumps for the reflected beams are not shown. The Photon Calibrators for the unfolded IFOs will inject their laser beams through the –p2 viewports on the beam tube adapters.

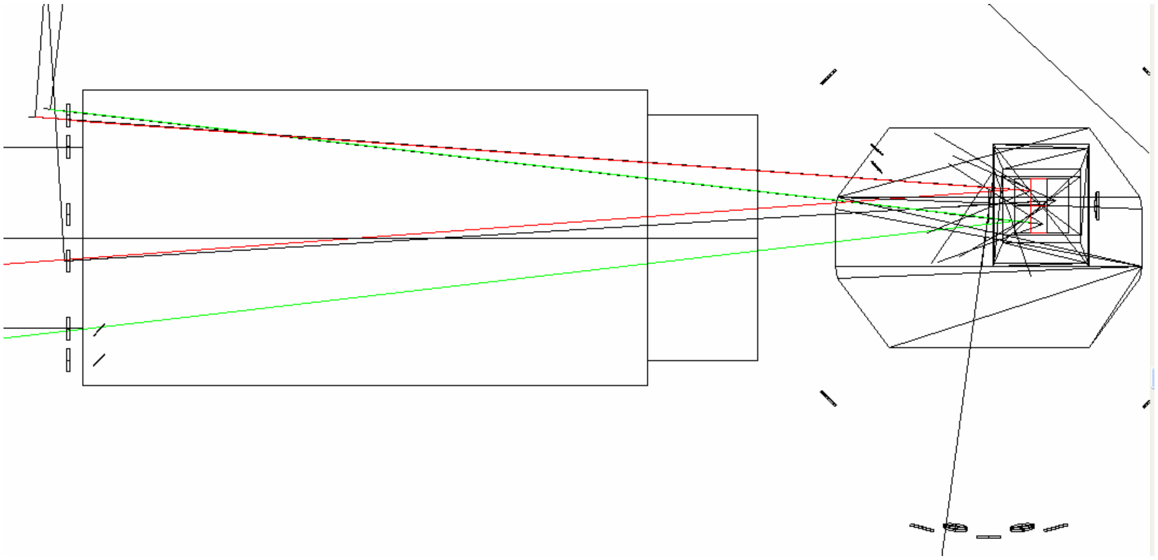

Figure 2: In-vacuum layout of the Photon Calibrator beams for H1 ETMx.

The viewport layout for the folded IFO is not finalized as of the writing of this document. It will be necessary to move BSC chambers from the mid stations to the end stations at the Hanford site, and facility restrictions will require construction of some new vacuum hardware. The currently proposed vacuum layout is shown in Figure 3. The ETM for the folded IFO would reside in the right-hand BSC chamber. Between the two BSC chambers are, from left to right, a bellows, a spool piece, a ring adapter, and a short section of beam tube. The ring adapter would contain the viewports used by AOS to interrogate the ETM of the folded IFO. No detailed layout has yet been made, but this approach is optically workable. Any baffles in the unfolded IFO BSC chamber will have no effect on the folded IFO AOS beams.

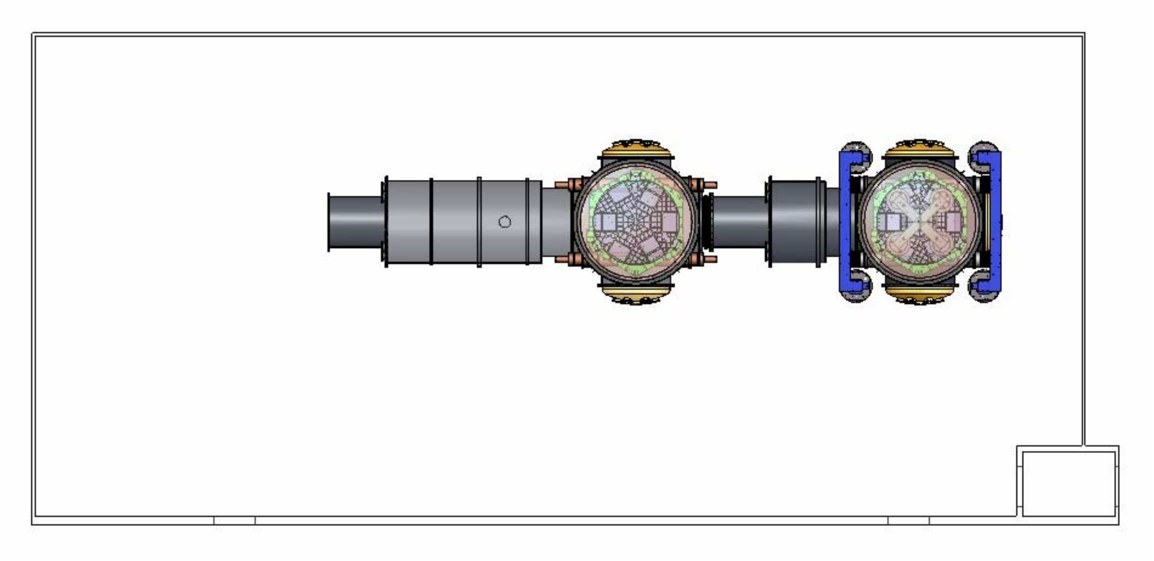

Figure 3: Proposed vacuum layout of the LHO end station, with the laboratory walls as shown.

3.3.3 Out-of-vacuum Beam Paths

The optical breadboard will mount on a pier attached to the ground near the adapter plate, near the –p2 viewport flange for the onfolded IFOs. No connection to the optical lever piers will be required.

As far as is practical all electronics are located off the Photon Calibrator optical breadboard in a separate rack, to simplify the optical layout, reduce noise and waste heat, and allow access to the electronics without interfering with the optics or opening the beam enclosure and creating a laser safety hazard.

Figure 4 shows the conceptual layout of the Photon Calibrator optical breadboard. The red lines represent the Nd:YLF beam paths and the blue lines represent the aiming laser beam path.

The polarizer at the laser output guarantees the Nd:YLF laser polarization before delivery to the AOM and folding mirrors, which are polarization sensitive. The lenses in the Photon Calibrator beam path create a waist at the AOM and set the spot sizes at the ETM. The fast PD monitors the Photon Calibrator power. The PD before the AOM is used during initial calibration of the Photon Calibrator fast PD. The three radiometer locations show where the absolute radiometer is placed during initial and subsequent calibrations of the Photon Calibrator power. The chopper wheel is used for AC calibration of the fast PD. The aiming laser is used to align the Photon Calibrator onto the ETM during installation.

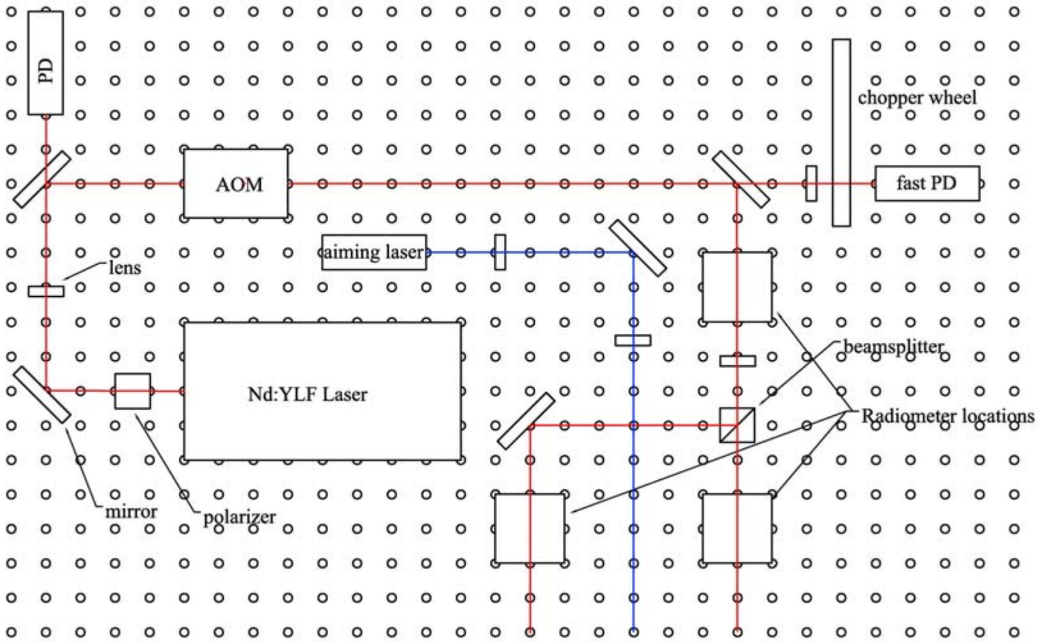

Figure 4: Optical layout of the Photon Calibrator breadboard.

3.3.4 Calibration of Photon Calibrator Beam Delivery Efficiency

The absolute calibration of the Photon Calibrator depends upon well-characterized efficiency of the beam delivery optics from the point where the power is reflected from the ETM. These include the steering mirrors on the Photon Calibrator breadboard, the viewports into the vacuum, and the ETM itself.

Dielectric mirrors are commercially available with reflectivities better than 99.97% in visible and near-infrared wavelengths.[3] Simply by using them within their angular and polarization specifications will therefore guarantee better than 0.03% accuracy in reflectivity. These reflectivities can be verified by direct measurement of the mirror.

Commercial antireflection coatings are available with reflectivities less than 0.2% for appropriate wavelengths, polarizations, and incident angles.[4] With these coatings on the viewports, and careful characterization during installation, the error in transmittance of the viewports can be held to less than 0.1%.

The reflectivity of the ETM HR coating is expected to be >99.9% for the Photon Calibrator beam at its wavelength, polarization, and angle of incidence. This can be validated in the ETM metrology by measurement of the transmission and absorption of the HR coating. We therefore adopt a precision of 0.1% for the ETM reflectivity.

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[3] For example, from Newport Corp.

[4] Newport Corp.

Diffraction at the various optics in the beam delivery path can scatter power into angles which miss the ETM. Optics will be chosen large enough that this is not a significant issue.

The force on the optic depends upon the incident angle of the Photon Calibrator beam. We assume for concreteness that the beam enters through the center of the –p2 viewport (coordinates in the Zemax Advanced LIGO optical layout: X=0 mm, Y=762 mm, Z=-5752.98 mm, radius 68.3 mm, normal axis along Z) and irradiates the ETM at the center of its HR surface (X=80 mm, Y=200 mm, Z=161 mm, radius 170 mm, normal axis along Z). The angle of incidence onto the center of the ETM HR face is 5.48°. This reduces the force by 0.46% from the maximum value, obtained at normal incidence. Assuming very conservatively that the Photon Calibrator beam could enter the vacuum at any position in the –p2 viewport and irradiate the ETM at any point on its HR face, the range of incident angles is 3.19-7.76°, for a range of forces 0.16-0.92% below the normal incidence value. The Photon Calibrator alignment procedure will place the beam spots within 1 cm of their nominal positions, which sets the incident angle force error at the 0.02% level. The curvature of the ETM surface is too small to appreciably affect this calculation.

Leaving aside thermoelastic effects, any absorption of the Photon Calibrator beam will alter the recoil force from that in section 2, reducing the force component along the arm axis from $2P\cos(\theta)/c$ to $P\cos(\theta)/c$ for the part of the power that is absorbed, and adding a force component transverse to the arm axis with magnitude $P\sin(\theta)/c$. The normal force adjustment will be small given the small uncertainty in the reflectivity. The transverse force will not be aligned with the ETM center of gravity and will cause a torque. This torque is dealt with in Section 3.3.5.3 below, but is also negligible.

Summing all the above uncertainties in quadrature gives an overall beam power delivery efficiency of 0.15%.

3.3.5 Test Mass Displacement Uncertainty

3.3.5.1 Mirror Mass Uncertainty

Strictly speaking, what is desired from the Photon Calibrator is not a known force, but a known displacement of the test mass. Thus the mass of the ETM must be precisely known. Commercially available scales can weigh 40 kg masses with 0.02% precision.[5] To convert weight to mass, the gravitational acceleration must be divided out. Given the latitudes of Kennewick, WA (46.211N) and Livingston, LA (30.51N), the resulting difference in the gravitational acceleration is 0.12% between the two sites. This difference is well characterized, so if properly accounted for the mass measurement accuracy will be that of the scale, 0.02%.

3.3.5.2 Calibrator Frequency Uncertainty

The recoil displacement of a free mass to a sinusoidally varying force falls inversely with the frequency squared. Therefore, the relative uncertainty in the displacement is twice the relative error in the drive frequency. In order that the frequency uncertainty of the drive force not cause more than 0.1% error in the test mass displacement, the frequency uncertainty must be less than 0.05%. This is almost trivially obtained given LIGO’s GPS-based timing standard.

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[5] Omega Scientific Corp.

Related to the frequency uncertainty is the error due to digitization of the waveform provided to ISC from the Photon Calibrator. The power to the ETM, even if perfectly recorded by the fast PD, must be digitized and transmitted down the arm to be received by ISC. This can contribute both amplitude and phase error, especially at high frequency. These uncertainties lie outside the scope of the Photon Calibrator. The ADC gain is calibrated along with the fast PD and so can be accounted for.

3.3.5.3 Photon Calibrator Beam Offset-Induced Torque on the ETM

Ideally, the Photon Calibrator force is directed along the arm axis and through the ETM center of mass. The ETM HR surface must be normal to the arm cavity if the interferometer to lock, so the equal angles of incidence and reflection of a reflected beam guarantee that the force due to the reflected beam will be along the arm axis, wherever the beam is incident.

If there is a net offset in the force relative to the ETM center of mass, then the Photon Calibrator will torque the ETM. If the arm cavity mode is centered on the optic, this torque produces only second-order displacement of the ETM face and is not observed. However, in general the arm cavity mode is offset. Assuming the arm cavity mode and photon calibrator are offset along the same line from the ETM center (the worst case), the correction to the expected displacement is abM/I, where a and b are the arm cavity mode and photon beam offsets, and $M = 40\,\mathrm{kg}$ and $I = .42\,\mathrm{kg\ m^2}$ are the ETM mass and moment of inertia. Assuming the arm cavity mode offset to be no more than 1 mm, the torque-induced error is no more than 0.095%/cm of Photon Calibrator offset. Thus, for 1 cm offset the torque-induced error is 0.1%.

Absorbed photons impart their transverse momentum to the ETM. This moves the ETM transversely (which the interferometer does not see) and torques the ETM, since the momentum is imparted 10 cm away from the center of the optic along the arm cavity axis. With the conservative assumption of 100 ppm absorption, the resultant torque is equivalent to that of 10 µm offset of the Photon Calibrator beam and is negligible.

3.3.5.4 Elastic and Thermal Effects in the ETM

The Photon Calibrator force is not applied uniformly to the body of the ETM, but to a few small regions on the HR surface. Therefore, along with the recoil of the center of mass there will also be an elastic deformation of the test mass, changing the position of the surface sampled by the IFO arm cavity mode relative to the mirror center of mass.

The first plot in Figure 5 shows an FEM of how the surface of the ETM will distort if the Photon Calibrator beam has 3 mm spot size and is centered on the optic. The applied force in the model is 0.1 nN, but since we are concerned with deformation relative to the overall recoil of the ETM the particular value of the force is unimportant. Averaged over the arm cavity mode, the net displacement is 1.43×10^{-20} m, and is nearly independent of frequency in the quasistatic approximation that the applied frequency is much less than the lowest resonant mode of the ETM. It is also in phase with the applied force. The recoil of the test mass due to this same force is 6.33×10^{-16} m at 10 Hz, falling as the frequency squared, and is 180° out of phase with the applied force. So, at 250 Hz the elastic deformation would cause a 1.4% correction to the calibration signal. The net displacement is only weakly dependent upon the Photon Calibrator spot size for spot sizes much smaller than the arm cavity mode.

Naturally, the correction will be smaller the more the beam spot is moved from the center of the optic to its periphery, although due to flexure of the mirror the optimum is not at the outermost limit. The second plot in Figure 5 shows the effect if the central spot is replaced with an annulus of 14 cm radius. The overall force is still 0.1 nN. In this case, the dimple is less deep because the incident power is spread over a larger area. In addition, it is well outside most of the arm cavity mode. However, due to flexure of the optic the net displacement is positive. For some distribution of beams at the periphery the net displacement due to deformation can be nulled. In the case of the annulus modeled here, this may be necessary, since the elastic net displacement is $7.7\text{x}10^{-22}$ m and presents greater than 1% correction to the calibration signal above 900 Hz.

Needless to say, these corrections will only produce errors in the calibration to the extent that they are not accounted for, and they are quite predictable.

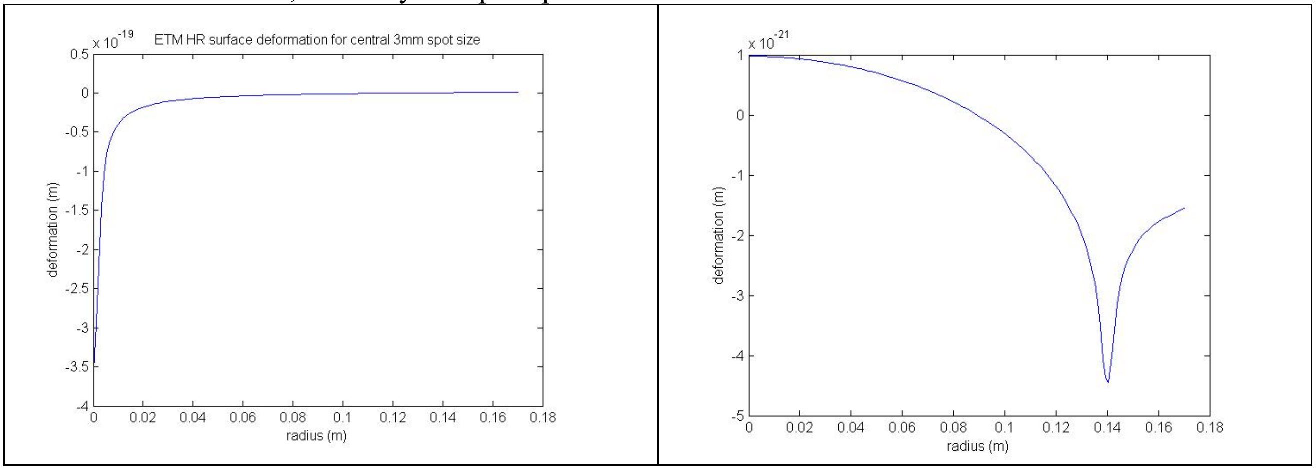

Figure 5: deformation of the ETM HR surface due to a 3 mm spot size central photon calibrator beam, and for an annulus beam with 14 cm radius.

Thermal deformations are less predictable because the absorption of the ETM HR surface for the Photon Calibrator beam is uncertain and could change during Advanced LIGO's operation. However, assuming some level of absorption for the coating, we can calculate the observed net displacement in the same manner as we calculate the noise couplings due to thermal compensation. We assume a conservative value of 100 ppm absorption. The optical power required to exert 0.1 nN of force is 15 mW, so this corresponds to 1.5 μW of fluctuating heat power.

Adapting Equation 2.39 of Stefan Ballmer's thesis, we find that the thermoelastic deformation rapid fluctuations in surface heating is

$$\Delta z(x,y) = (1+\eta)\alpha \frac{p(x,y)}{2\pi i f C \rho}$$

where we assume for now that the test mass thermal flexure is relatively small. The net displacement is obtained by averaging $\Delta z(x,y)$ over the arm cavity mode intensity profile. Assuming a central 3 mm spot as before, the net displacement is $1.66\text{x}10^{-18}$ m at 10 Hz, and is 90° out of phase with the force. Again comparing to the recoil of $6.33\text{x}10^{-16}$ m at 10 Hz, falling as frequency squared, this will introduce a >1% correction to the calibration at 38 Hz and above.

However, by moving the spot 14 cm away from the optic center, the net thermoelastic displacement drops to 3.2×10^{-23} m at 10 Hz and becomes negligible at all relevant frequencies.

There remains the matter of thermal flexure. Using the same FEM approach employed for TCS flexure noise coupling, two spots of size 1 cm each were placed 14 cm on either side of the center of the HR face and allowed to thermally stress the optic. The displacement of the center of the face was $\sim 3 \times 10^{-20}$ m at 10 Hz. The resulting correction to the calibration is thus below 1% up to 2150 Hz.

It is worth noting that so long as the photon calibrator beams are kept away from the center of the optic they introduce a fairly small correction, assuming 100 ppm absorption of the incident light. A more likely absorption is <10 ppm, in which the thermal correction for offset beams can be completely ignored.

3.3.6 Photon Calibrator Power Uncertainty

By far the dominant source of uncertainty is in the power of the Photon Calibrator beam itself. This ultimately relates to the accuracy with which its DC power can be measured.

The ultimate standard for radiometric power measurement is the cryogenic electrical substitution radiometer. This device measures the temperature rise of a blackbody radiation absorber under illumination and compares it to the temperature rise of the same absorber when heated by an embedded resistor with precisely measured current and voltage applied. Accuracy at the 0.01% level can be achieved. However, these devices are very large and expensive and are generally found only in national standards laboratories, and are not feasible for direct use in LIGO. All NIST-traceable radiometers are ultimately calibrated back to such devices.

The usual specified accuracy of commercial laser power meters is at the 2.5-3% level, and it is reasonable to expect to measure the DC power of the Photon Calibrator at this level with careful technique and periodic recalibration of the sensor and meter as needed (typically annually).

With more care, it should be possible to achieve <1% power accuracy. The UDT Instruments Model 370 Radiometer with a Model 221 Silicon Sensor Head mounted in a Model 2525 6” integrating sphere has a typical accuracy of about 1.6%. By slight modification and precise current calibration of the radiometer input electronics, and special calibration of the sensor head at the UTC Instruments laboratories, accuracy at the 0.8% level can be achieved.[6] Scientech, Inc. produces an electrical substitution radiometer that also can achieve better than 1% absolute power accuracy.[7] These instruments cost less than $10,000 and are not bulky.

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[6] Riccardo Vargas, UTC Instruments optical engineer, private communication.

[7] Tom Campbell, VP of Scientech Inc., private communication.

4 Commissioning and Operation

4.1 Initial Calibration and Alignment

This section elaborates the procedures by which the calibration errors described in the previous section will be obtained in practice.

4.1.1 Component Calibration

The transmittance and absorption of the end test mass HR coating will be measured for radiation with the wavelength, polarization, and incident angle of the Photon Calibrator beam (either 1047 nm or 1064 nm) during the metrology of the ETMs. Measurements upon witness samples will be considered adequate.

The transmittance of the viewports and reflectance of the mirrors passing the Photon Calibrator beams will be measured as they are received using the Photon Calibrator laser in a test setup on site prior to installation of the viewports.

The masses of the ETMs will be measured using a commercial scale to within 0.02%.

4.1.2 Breadboard Alignment

Precise and accurate calibration of the Photon Calibrator’s delivered beam must follow the initial assembly and alignment of the Photon Calibrator optical breadboard.

The Photon Calibrator optical breadboard is assembled. The Photon Calibrator optical breadboard conceptual design allows the calibrator beams and visible steering beam to be directed across the end station floor to a target positioned at the distance of the end test mass (6 m). The relative positions of the calibrator spots relative to the aiming laser crosshairs can then be adjusted using the steering mirrors and beamsplitter on the breadboard. The visible aiming laser is then turned off for initial power calibration.

4.1.3 Initial Power Calibration

The radiometer is positioned to capture the reflected beam from the pickoff mirror to the fast PD. Using the AOM to set a range of laser powers, the pickoff mirror/fast PD are calibrated for absolute power at a variety of levels, to account for any nonlinearity in the fast PD. This provides DC calibration of the fast PD.

While the radiometer continues to monitor the stability of the laser beam delivered by the AOM, the chopper wheel is then rotated at various frequencies and the AC response of the fast photodetector signal is measured. The chopper wheel has the advantage over the AOM of providing a well-defined on-off modulation of the laser power that cannot vary with frequency, and also allows the radiometer to continue to monitor a DC laser power level during the calibration. With the chopper holes large relative to the beam size, the transmitted power will take the form of a square wave with transitions approximating error functions and will therefore not be a sinusoid. The fast PD signal can be digitally filtered to obtain the fundamental harmonic of the transmitted power. The variation of the amplitude of the fundamental harmonic with frequency yields the rolloff of the fast PD. The bandwidth of the New Focus 2033 photodetector used in the initial

LIGO Photon Calibrator is nominally 30 kHz, and if it is used in Advanced LIGO the signal reduction at the 2 kHz maximum frequency of the chopper will be only 0.5%.

It may be prudent at this point to measure the temperature sensitivity of the calibration by heating the environment a few degrees and rechecking the measurement.

The calibration of the AOM may be accomplished at this stage by assuming the laser power to be stable and using the fast PD to monitor the power through the AOM as its drive voltage is varied. If necessary, a photodetector positioned at the pre-AOM pickoff can monitor the relative laser power stability.

Lastly, the radiometer is moved to sample each of the two delivered beams independently to verify their power balance and delivery efficiency while the fast PD monitors the laser power stability. If needed, the power balance can be tweaked by minute adjustments of the beamsplitter angle. If so, the initial alignment is then rechecked.

4.1.4 Alignment to the ETM

At this point, the breadboard as a whole is hoisted onto the shelf below the viewport and directed to the ETM using the visible aiming laser crosshairs. Once the alignment is satisfactory, the breadboard and is clamped into position onto the shelf with dog clamps and the enclosure is closed. The visible aiming laser is then turned off until it is needed for any subsequent realignment. The locations of the reflected spots are checked to ensure that they safely dump to the chamber walls within the vacuum.

4.2 Recalibration and Realignment

The breadboard design allows the power at the points used during the initial calibration to be accessed *in situ* without removing the Photon Calibrator from the viewport. This procedure requires the enclosure to be removed.

Realignment of the Photon Calibrator to the ETM can be performed at any time by unclamping the breadboard from the shelf and using the visible aiming laser to redirect the beams to the ETM, and reclamping. Again, this requires removal of the enclosure.

Realignment of the visible aiming laser with the Photon Calibrator beams will require the Photon Calibrator to be removed from the shelf and the initial alignment procedure to be repeated.

The absolute radiometer should be recalibrated by the manufacturer annually as recommended.

4.3 Operation

The Photon Calibrator drive waveform (nominally, a sinusoid) is delivered to the Photon Calibrator AOM by DAQS. Variations in the AOM diffraction efficiency caused by alignment drift or nonlinear response will be observed as variations in power in the fast PD and so will not affect the calibration. The fast PD signal is sensed by DAQS, is analyzed digitally to yield the sensed amplitude and phase, and the phase corrected by the phase shift of the electronics after the fast PD.