LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

LIGO Laboratory / LIGO Scientific Collaboration

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Commissioning the Advanced LIGO L1 Input Mode Cleaner

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1 Introduction

The first integration phase for the Advanced LIGO L1 interferometer is the commissioning of the Input Mode Cleaner (IMC), the Faraday Isolator (FI), the auxiliary input optics (IO), and the power recycling cavity optics located in the HAM2 and 3 vacuum chambers, using the light beam from the Pre-Stabilized Laser (PSL). The integrated testing of the PSL/IMC/IO is expected to begin in June of 2012. This document describes the plans and goals of this phase.

2 Motivation and context

The IMC is a three-mirror ring cavity with two optics (MC1 and MC3) located in HAM2 and one optic (MC2) located in HAM3 vacuum chambers (T060269). The main function of the IMC is the spatial filtering of the light going from the PSL to the interferometer. The filtering is provided by the IMC high finesse cavity (F~500) with mirrors isolated by triple pendulum suspensions with vertical blade springs. Additionally, before the arm cavities are locked, the IMC cavity length serves as the PSL frequency reference at high frequencies, owing to the seismic isolation and triple suspensions, while at low frequencies the IMC length is slaved to the laser frequency.

The control loop topology of the IMC length and angular control servos, and of the laser frequency stabilization, are the same as the ones used for the Initial and Enhanced LIGO. The main difference between initial and Advanced LIGO's IMC performance (T020020, T0900142) is the improved isolation from the ground motion, which will make low noise operation possible down to 10 Hz.

The Advanced LIGO laser will deliver up to 165 W into the IMC and comparable power through the FI. The initial LIGO IMC and the enhanced LIGO FI were tested with the enhanced LIGO laser, which is also the Advanced LIGO front end, at an input power level up to 30 W. Based on the enhanced LIGO experience and lab testing with the high power lasers, the thermal effects in the FI and IMC are expected to be small at 30 W input power but could be significant at 165 W.

The main objectives of the PSL/IO/IMC integration phase are:

1. Achieving the robust operation and verifying the integrated performance of the PSL/IO/IMC, at the level required for full interferometer locking.
2. Characterizing the thermal effects in the FI and IMC at the maximum input laser power.

These, and other secondary objectives, are discussed later in Section 4.

3 Components of the PSL/IO/IMC integration phase

The optical layout of the main beam path in the HAM2 and HAM3 is shown in Figure 1. The laser beam from the PSL passes the HAM1 chamber and enters the HAM2 chamber through the septum plate. It is brought down to the HAM2 optical table level by a periscope inside of the HAM2 chamber and steered into the IMC by two mirrors rigidly attached to the table. The beam transmitted through the IMC is steered though the FI and mode matched into the recycling cavity by four suspended mirrors – SM1, PMMT1, PMMT2, SM2. The beam reflected by the IMC (not shown) is steered out of the vacuum chamber by relay mirrors, which are rigidly attached to the HAM2 optical table. The IMC length and angular sensing photo-detectors are located outside of the vacuum chamber. A fraction of the IMC transmitted beam is picked off in the transmission of SM1 and steered out of the vacuum chamber by relay mirrors rigidly attached to the table (not shown).

The IMC reflected and transmitted beam optical benches are placed on the opposite sides of the HAM2 chamber. The power recycling mirror (PRM) is the input coupler for the power recycling cavity, and together with PR2 and PR3 forms a mode-matching telescope, providing a non-degenerate solution for this cavity. The beam reflected by the interferometer is rejected by the FI and directed to the HAM1 by rigidly mounted steering mirrors.

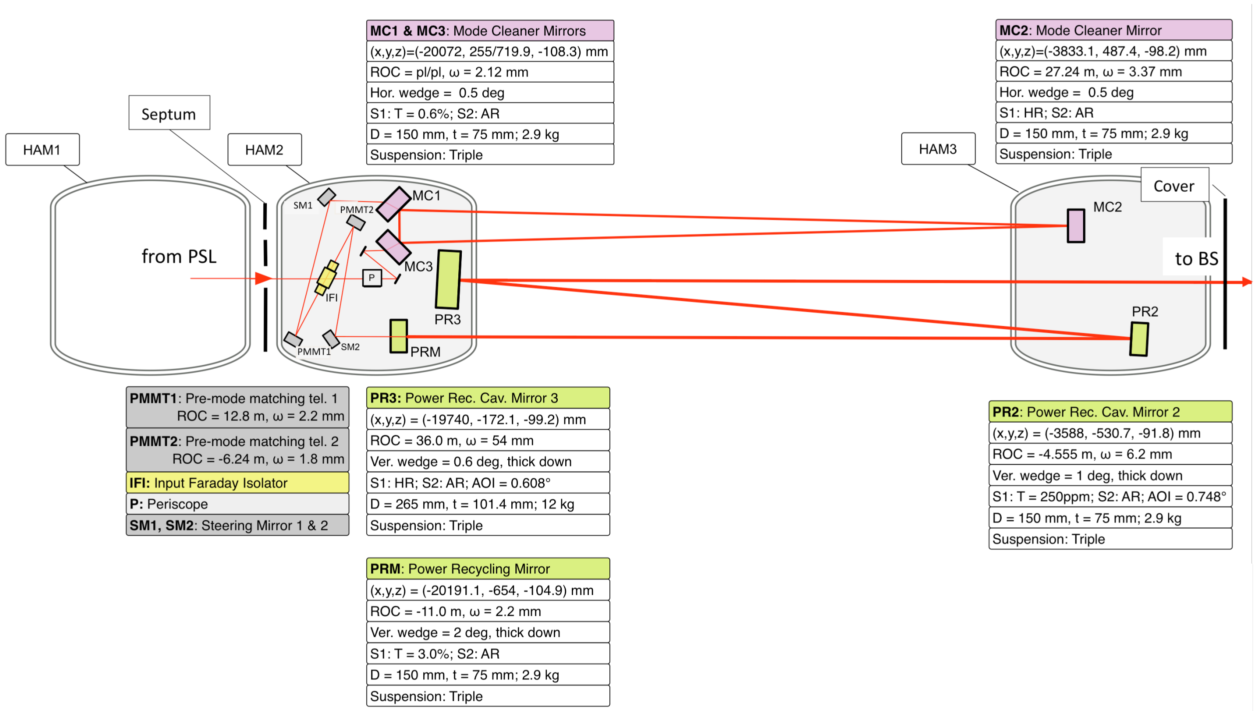

Figure 1. The optical layout shows the IMC, the FI with relay optics, and the first three optics of the power-recycling cavity. The in-air IMC detection table is not shown in the diagram. A septum and a temporary cover plate will be installed to isolate the HAM2 and HAM3 vacuum chambers from the HAM1 and BSC2 vacuum chamber respectively. The cover plate will be removed after the first integration phase.

3.1 Optics components

The integration phase requires: 3 Input Mode Cleaner mirrors; 2 pre-mode matching mirrors; 2 suspended steering mirrors; 3 power recycling mirrors; 1 Faraday Isolator; 1 input beam periscope; 2 IMC reflected beam periscopes; ~15 fixed mount steering mirrors.

3.2 Suspensions

From SUS, the setup requires: 1 large triple suspensions; 5 small triple suspensions; 4 input optics single suspensions; control electronics for all suspensions.

3.3 Seismic isolation

This integration phase requires 2 full HAM seismic isolation systems: HEPI and ISI for each chamber, including control electronics. The HAM1 seismic isolation is not required at this step, but the HEPI stage, the passive stack, and the in vacuum optical table are planned to be installed before this phase.

3.4 IMC length and angular sensing and control

The IMC length and angular sensing and control are accomplished by using the standard reflection locking scheme with 24 MHz phase modulation frequency. The advanced LIGO readout electronics, digital system, and video camera diagnostics are required for this integrated testing. The number of video cameras needed for the integrated commissioning (T1000632) is: HAM2 - 11; HAM3 - 3; input optics in-air tables (IOT) - 4. The PSL has 20 cameras, which will be installed before the integrated testing. The location of the video cameras is shown in the Figure 2.

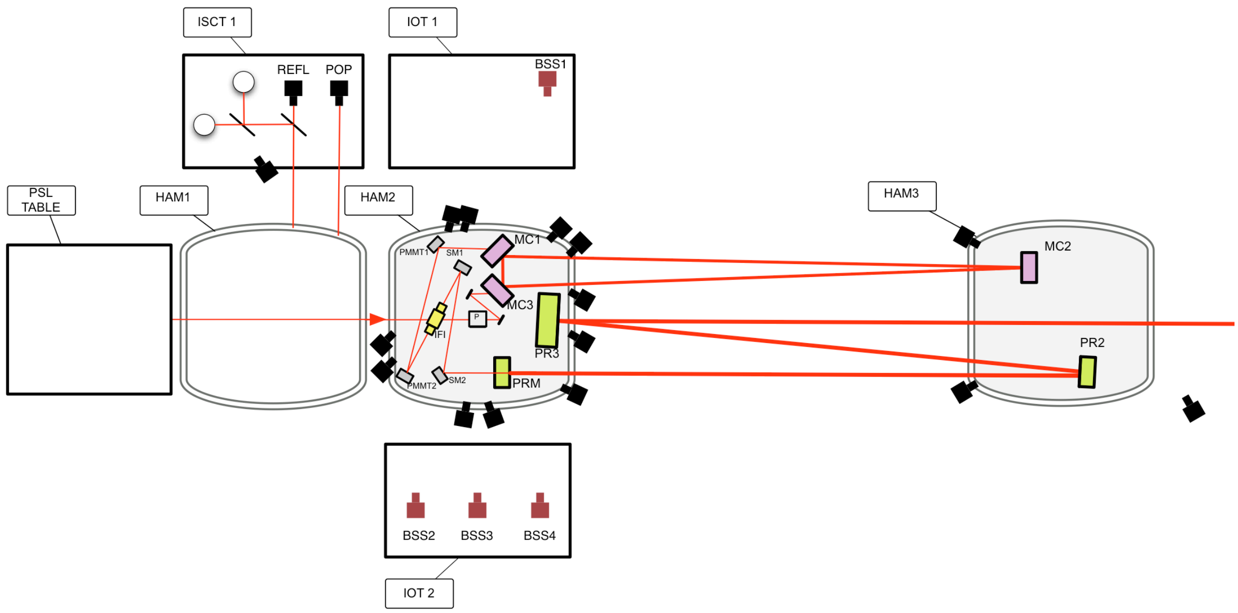

Figure 2. Diagram shows the location of the video cameras for IMC/IO and ISCT1, IOT1, and IOT2 (from T1000632).

3.5 Stray light control

The HAM2, HAM3, and input tube stray light control baffles, wire protection baffles, and beam dumps will be installed before this testing phase.

3.6 Optical levers

Both the HAM2 and HAM3 optical tables will be outfitted with an optical lever. These optical levers will provide the angular motion diagnostics and the DC references for the HAM optical tables. The PR3 optic will also be outfitted with an optical lever. No other optics in HAM2 and HAM3 will have optical levers.

3.7 Viewports

This integration phase requires the HAM1, HAM2 and HAM3 viewports to be in place. The viewport final design is in T1000746.

3.8 PSL

This integration phase requires a fully operational PSL at maximum power. The phase modulator for the IMC and the interferometer sensing and control RF sidebands, the power control, including the wave plate, polarizer, and beam dump, will be installed and commissioned before this integration phase. The commissioning of the PSL outer loop laser amplitude stabilization servo is part of this integration phase.

3.9 DAQ

The full L1 DAQ system is planned to be functional by the start of this phase.

4 Objectives

As noted earlier, the main objectives of the PSL/IO/IMC integration phase are:

1. Achieving the robust operation and verifying the integrated performance of the PSL/IO/IMC, at the level required for full interferometer locking.
2. Characterizing the thermal effects in the FI and IMC at the maximum input laser power.

These objectives, as well as various secondary objectives, are further discussed below.

4.1 IMC initial alignment and in air locking

The objective of this step is to align the IMC optics and input beam to allow the IMC cavity locking and the alignment of the optical components downstream of the IMC (T0900267). During the in-air alignment and locking the PSL power will be reduced below 100 mW to avoid damaging the IMC optic coating (additionally the input polarization can be rotated from S to P to achieve lower cavity finesse). The HAM2 and HAM3 vacuum chambers will be accessible to make the manual adjustments to the input beam periscope and steering mirrors and to the IMC suspended optics. Once fundamental cavity mode flashes are obtained, the IMC reflected light optical table can be aligned and the IMC can be locked in air. The block diagrams of the IMC sensing and control are shown in Figure 3.

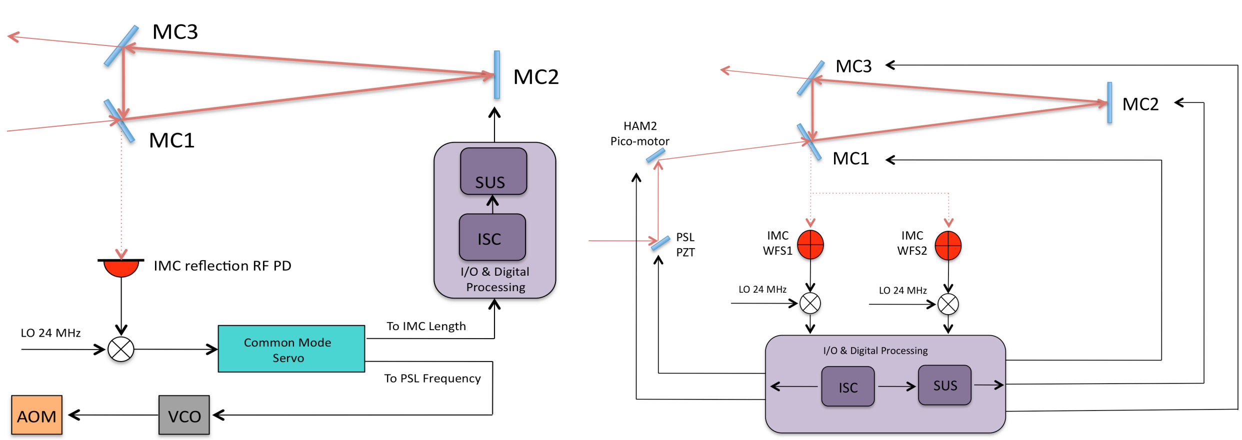

Figure 3. Diagram for the IMC length (left) and angular (right) sensing and control before the interferometer common arm is locked. In this state the length actuation is split between the PSL frequency (analog path) and the IMC length (digital path). The crossover frequency is expected to

be a few times lower than the initial LIGO 50 Hz crossover frequency, which was determined by the HAM passive isolation stack. After full interferometer lock is attained, the PSL frequency and the IMC length follow the laser common arm length (at very low frequencies <0.1 Hz the control signal will eventually go back to the arm cavities via the tidal servo). Two quad RF photo-detectors provide the error signals for the angular control servo. The angular control signals are sent digitally to the IMC mirror suspensions with bandwidth of ~1 Hz. The IMC input beam is tracking on a ~day-long time scale the IMC cavity axis by offloading the control signals to the steering mirrors (the PZT actuated mirror on the PSL periscope and the pico-motor actuated mirror on the HAM2 in vacuum table) when the IMC is locked at low power.

4.2 IO initial alignment and in air characterization

The objectives of this step are:

- Align the beams through the FI, onto the power recycling mirrors, reflected by the PRM, and IMC2, PR2, SM1, and SM2 pick-offs.
- Optimize the wave-plate angles to maximize the transmission and isolation ratio of the FI. The goals for the FI are >95% power transmission and the isolation ratio of 40 dB in air at low power and 30 dB in vacuum at full power.
- Measure the power levels in various places in the optical chain. The goal for IO is >75% power transmission from the PSL to the PRM.

4.3 IMC optimization and automation

On this step the IMC will be locked in vacuum. The following optimization tasks will be performed to achieve stable cavity operation:

- Mode matching >98%. The adjustment to the IMC input beam waist size and position can be made using two lenses on the PSL optical table.
- Length control bandwidth of >40 kHz with the IMC length/PSL frequency split paths crossover frequency of ~10 Hz.
- Angular control bandwidth of ~1 Hz.
- Length/Angle decoupling and suspension damping will be tuned to minimize the low frequency motion 0.1-1 Hz and to roll off the sensor noise above a few Hz.

The IMC lock acquisition and transition between states will be automated using Guardian scripts (T1000131). The Guardian scripts for the IMC and various components (HEPI, ISI, SUS) will be developed before the beginning of this phase, but will have to be tested and optimized during the PSL/IO/IMC integration phase.

4.4 PSL/IO/IMC performance testing

The in vacuum locking of the IMC will allow for the PSL/IO/IMC commissioning, and achieving operation at the designed noise performance and full input power. The preliminary performance test plan and the noise requirements for the IMC were outlined in E0900341. In this section we present the objectives and the updated test plan.

4.4.1 IMC characterization

The following cavity parameters will be measured with the IMC locked in vacuum with an input power of ~10 W:

- Transmission, losses, and visibility by doing the power budget
- g-factor by performing the mode scan
- Cavity pole or line width by taking the transfer function from the IMC input to output power
- Mechanical mode frequencies and quality factors
- Scattering from the IMC optics by measuring the amount of scattered light at various angles using photo-detectors and CCD cameras.

4.4.2 Frequency noise

The frequency noise on the PSL light can be measured with the IMC locked in the low noise state by calibrating the frequency control signal through the known VCO actuation coefficient. The frequency noise on the IMC transmitted light in this state can be estimated from the measurements of the IMC sensing noise, the IMC control loop suppression, and the residual IMC motion.

4.4.3 Amplitude noise

The laser amplitude noise will be stabilized by the outer loop of the Intensity Stabilization Servo (ISS) to the level of RIN=2×10^{-9} $Hz^{-1/2}$ at 10 Hz using a low noise in vacuum photo-detector array, which will receive a sample of the IMC transmitted light (the SM2 pick-off). The laser amplitude stabilization at this level has been demonstrated in the test setup by the PSL group at AEI, but not in an IMC size suspended cavity. The effect of the photo-detector beam centering on the amplitude noise stabilization will be investigated. This testing will require high input power. The performance of the outer loop ISS will be evaluated at later commissioning stages when the interferometer low noise readout (OMC) will become available.

4.4.4 Angular noise

The angular beam motion after the IMC couples into the interferometer directly via the residual arm cavity angular motion (T0900142) and through the beam motions at the output ports: the Output Mode Cleaner and the Interferometer Sensing and Control photo-detectors. The coupling of the input beam motion to the interferometer output is a non-linear effect and analytical calculations provide only an order of magnitude estimates. During the first integration phase the angular motion after the IMC will be characterized at the frequencies below ~10 Hz using the IO/IMC photo-detectors. At the frequencies above ~10 Hz the Output Mode Cleaner or other interferometer cavity low noise readout will be used during later commissioning stages to evaluate the IO/IMC angular noise.

4.4.5 RF noise

The laser RF noise is filtered by the pre-mode cleaner cavity with a pole at ~1 MHz. The remaining amplitude noise can be measured before and after the IMC using a broadband low noise RF photo-detector. The 9 and 45 MHz modulation sideband frequencies will be set to match the IMC length to avoid phase to amplitude modulation conversion. The relative drift of the IMC length and the modulation frequencies will be monitored during this phase.

4.4.6 VCO range

The common mode servo actuation on the PSL frequency is accomplished by shifting the frequency of the light using the AOM driven by a VCO at 80 MHz. In initial LIGO the VCO was the limiting noise source for the PSL phase noise. The VCO phase noise can be improved by reducing the VCO actuation range. The needed VCO range will be determined during this testing phase.

4.5 High power testing

The objectives of this step are:

- Operate the IMC at high power. The light level on the photo-detectors and the IMC sideband modulation index will be adjusted during this test to avoid saturations. The control signals due to the radiation pressure will be offloaded using hierarchical control scheme. The high power beam dumps, baffling, and shutters will be installed and tested.
- Characterize the thermal effects in the FI. The FI transmission, isolation ratio, thermal drift, and mode distortion will be measured as a function of the input power.
- Characterize the thermal effects in the IMC. The cavity transmission, absorption, and mode distortion will be measured as a function of the input power. The absorption will be measured by tracking the optics' internal mode frequencies.

4.6 Interaction between subsystems

The interaction between subsystems, that are difficult to evaluate without having the full system, will be examined throughout this integration phase. The coupling mechanisms could be electromagnetic, mechanical, or optical such as:

- Electrical pick up
- Stray magnetic fields either from coil actuators or permanent magnets
- Mechanical resonances of the components on the optical table (cages, periscopes, baffles) modifying the response of the seismic isolation stages
- Scattered light from the main beam entering into local damping sensors

4.7 Adaptive feed-forward for IMC cavity length

The active seismic isolation system, which consists of HEPI and ISI, and the triple suspensions will be commissioned for each chamber and optic independently using the relative motion of the optics and the suspension cage as a figure of merit. The IMC cavity control signal provides information for the relative motion of IMC optics and HAM optical tables. The feed-forward filtering can be adjusted adaptively to minimize the IMC control signal to remove the remaining correlation between the ground motion, as measured by seismometers, and the relative motion of the mirrors. The adaptive filtering technique has been tested on the Caltech 40m lab IMC (P1100037) but the advanced LIGO control allocation will be very different.

5 Quantitative goals for the PSL/IO/IMC integration phase

Parameter	Goal
IMC availability with automated relocking	> 90%
Mean lock duration (limited by seismic excursions e.g. earthquake)	> 4 h
PSL to PRM power transmission	> 0.75
Measurement error on PSL to PRM power transmission	3%
IMC longitudinal control bandwidth	~40 kHz
IMC frequency/length feedback crossover frequency	~10 Hz
IMC transmitted beam angular motion rms	$< \theta_{IMC}/100 = 1.6\text{x}10^{-6}$ rad
IMC transmitted power fluctuation rms	< 1%
IMC transmitted light RIN above 10 Hz	$< 1\text{x}10^{-7}\ \text{Hz}^{-1/2}$
IMC visibility	> 95%
FI isolation ratio at full power	30 dB

6 Prioritization of objectives

Objective	Duration
Top priority	
Cavity locking / automation	Throughout test phase
Alignment optimization and control	Throughout test phase
Mode matching	1 week
IMC cavity characterization	1 week
High power operation	2-3 weeks
Thermal effects in FI and IMC optics	1 week + data mining
Secondary priority	
IMC noise characterization	1 week + data mining
Suspension damping optimization	Throughout test phase
Adaptive feed-forward on cavity length	1-2 weeks
Outer loop ISS commissioning	1-2 weeks
Reducing PSL VCO range	1 week

7 Timeline

The total time for this integrated testing is 60 working days.

	10 days	10 days	10 days	10 days	10 days	10 days
Initial alignment						
In air locking						
In vacuum locking						
IMC mode matching and characterization						
Control optimization						
High power testing						
Adaptive feed-forward						
ISS outer loop						
VCO range						