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Test Plan for the Input Mode Cleaner

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1 Introduction

This document presents a preliminary test plan for the Advanced LIGO Input Mode Cleaner (IMC) with the purpose of verifying that all design requirements for the IMC are met.

1.1 Scope

The principal function of the IMC test plan is to define the test requirements for the performance of the input mode cleaner. Test plans for other IO components are in separate documents.

1.2 Applicable Documents

1.2.1 LIGO documents

[1] LIGO-T020020, "Input Optics Subsystem Design Requirements Document", IO group.

[2] LIGO-T010075, "Advanced LIGO Systems Design", P. Fritschel, et al.

[3]LIGO-M990288, "LIGO 2 Conceptual Project Book"

[4] LIGO-T010076, "Optical Layout for Advanced LIGO", D. Coyne.

[5] LIGO-T0900142-v1, "Pointing Requirements in Advanced LIGO", G. Mueller.

[6] LIGO T020027-00-D, "Advanced LIGO Input Optics Conceptual Design Document," IO group

[7] LIGO T060629-00-D, "Advanced LIGO Input Optics Preliminary Design Document," IO group.

[8] LIGO-T080075-01-D, "Input Optics Procurement Readiness," IO group.

[9] LIGO-T080078-06-D "Stable Recycling Cavity Mirror Coordinates and Recycling Cavity Lengths," Michael Smith and Dennis Coyne.

2 General Description

2.1 IO subsystem

The IO is shown in Figure 1

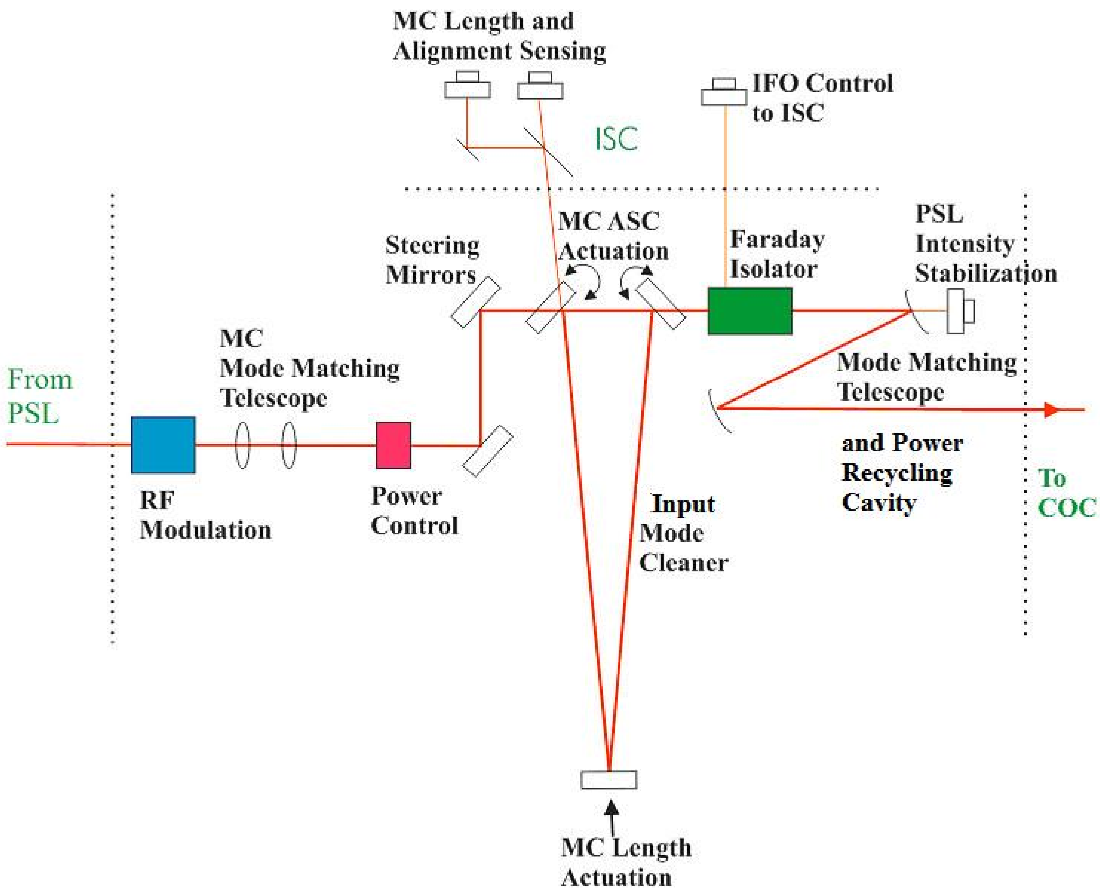

Figure 1. IO schematic

3 IMC Requirements and Tests

The mode cleaner provides frequency and spatial stabilization of the laser light, as well as intensity stabilization above its pole frequency.

3.1 Mode Cleaner Frequency and Intensity Stabilization

The frequency noise requirement of ~3×10^{-6} Hz/Hz$^{1/2}$ for DC readout on the light at the IFO input requires a mode cleaner frequency stability consistent with ISC loop gains and expected PSL frequency noise. We require (at 165 W input power):

- $\delta\nu(f) < 5 \times 10^{-2}$ Hz/Hz$^{1/2}$ at 10 Hz
- $\delta\nu(f) < 1 \times 10^{-3}$ Hz/Hz$^{1/2}$ at 100 Hz

This limits the changes in the mode cleaner half-length to be below:

- $\delta L(f) < 2.5 \times 10^{-15}$ m/Hz$^{1/2}$ at 10 Hz
- $\delta L(f) < 5 \times 10^{-17}$ m/Hz$^{1/2}$ at 100 Hz

The half-length changes caused by technical radiation pressure noise are:

- $\delta L(f) = 5.7 \times 10^{-17}$ m/Hz$^{1/2}$ (RIN(f)/[2x10^{-9}/Hz$^{1/2}$]) ([10Hz]/f)^2

TEST:

- Use the mode cleaner error signal to measure the frequency noise as limited by that sensing system.
- Measure intensity noise after the MC using a broadband photodiode at its maximum allowed photocurrent with a RF spectrum analyzer to establish an upper limit with the frequency dependence of the excess noise to allow an extrapolation to actual modulation frequencies.

3.2 Output Beam In-band Alignment Stability (Jitter)

Alignment fluctuations at the input of the COC couple to angular motion of the test masses to give in-band displacement signals. The (in-band) alignment stability of the entire IO subsystem shall not compromise that achieved directly after the mode cleaner, including the mode-matching telescope. For the output beam alignment stability requirement for the DC readout scheme we find that contributions from the carrier jitter coupled to ITM differential tilts dominate the noise contribution. This leads to:

$$\varepsilon_1(f) < 1.0\text{x}10^{-8} \sqrt{1+\left(\frac{100Hz}{f}\right)^4} \frac{\left[2\times 10^{-9}\right]}{\Delta\Theta_{ITM}} \frac{1}{\sqrt{Hz}}$$

where ε_1 is the amplitude of the 10,01 modes, and $\Delta\Theta_{ITM} = \Theta_{ITM1} - \Theta_{ITM2}$ is the total differential tilt of the ITMs.

TEST:

- Coarse: Using a Quadrant photodiode (to be shot-noise limited at 10 mA of photocurrent per segment) and a spectrum analyzer, mounted on IOT7 table, with measurements done at two distances from the output of the mode cleaner a measurement can be done to verify that the jitter noise is limited by the Quadrant diode and where it is mounted.
- Fine: Using a single arm cavity of the IFO (by misaligning PRM and BS) the remaining beam jitter with respect to the arm cavity can be measured.

3.3 Mode Cleaner Alignment

The MC alignment requirement is given by:

- Low frequency – the frequency stability of the laser field must not be compromised by beam jitter, giving:

  $\Delta\Theta_{MC} < 10^{-7}$ rad(rms)

These requirements can be viewed as a trade off between alignment of the MC and beam jitter. Relaxing the requirements on mode cleaner alignment will reduce our sensitivity, especially in the high frequency GW band, or require tightening the requirements on beam jitter in that frequency region. However, we note that a better mode cleaner alignment then the one given above would not result in relaxed beam jitter requirements unless we also tighten the requirements on the alignment of the core optical components.

- In-band - the MC jitter rejection must not be compromised by MC mirror angular fluctuation noise, giving:

$$\delta\Theta_{MC}(f) < 2\times10^{-14}\sqrt{1+\left(\frac{100Hz}{f}\right)^4}\,\frac{\left[2\times10^{-9}\,rad\right]}{\Delta\Theta_{ITM}}\,\frac{rad}{\sqrt{Hz}}$$

TEST:

- Low frequency: Monitor DC control input voltage to pitch and yaw control coil actuators.
- In-band: use spectrum analyzer to monitor control input voltage to (summed) length control coil actuators

3.4 Mode Cleaner FSR stability

The requirements for oscillator phase noise and modulation amplitude stability presented above assume that the mode cleaner FSR matches the modulation frequency. Detuning of the modulation frequency from the mode cleaner FSR couples oscillator phase noise to produce modulation index instabilities. This will increase the intensity fluctuations in the carrier through the intensity feedback loop and would lead to even more stringent requirements for the modulation amplitude variations. The calculated requirements presented above are valid as long as the detuning between the FSR and the modulation frequency is below 14 Hz .

In addition, the optimum demodulation phases will depend on the relative phases between carrier and sidebands. Changes in the FSR require in principle a readjustment of the demodulation phases to zero offsets in the error signals. The effect on the signal cannot be evaluated without a detailed length sensing and control scheme (TBR).

Test: Use RF photodiode to monitor the amount of excess noise at the modulation frequency on the transmitted MC light. An optimal value can be found by tuning the MC length or varying the RF oscillator frequency.

3.5 Mode Cleaner Mirror Loss

The mode cleaner mirrors are specified to have absorption of less than 1 ppm/mirror. Scatter losses are supposed to be below 30 ppm/mirrir

Test: Measure cavity ringdown. Measure thermal effects in mirror mechanical properties.

3.6 Mode Cleaner Beam Centering

The beam spot must be centered in the mode cleaner mirrors to a precision of 1 mm to avoid length-misalignment couplings.

TEST: Use CCD cameras to monitor MC1, MC2, MC3 and the beam spot on those.

3.7 Optical efficiency of Input Optics

The net efficiency of IO TEM_{00} optical power transmission from PSL output to COC input shall be 0.75 or greater, determined by the requirement that at least 125.0 W of TEM_{00} light be coupled into the COC assuming > 165 W in TEM_{00} coming from the PSL. The output power is the sum for the carrier used for GW detection and sidebands on that carrier.

TEST: Calibrated power measurements and laser beam profiler measurements at the input of the IO and at the input to the mode matching telescope (directed out of vacuum via steering mirror to IOT7). This test will be done a variety of input powers: 1, 6, 30, and 165 W. Losses from the MMT mirrors will be accounted for by separate measurements of reflectivity subsequent to vacuum installation. Final verification of coupling will be measured using the bullseye diode on the locked recycling cavity.

3.8 Availability

The IO availability will be limited by the lock acquisition time of the mode cleaner, and any degradation in performance due to thermal stress or optical contamination. We require:

- Lock acquisition time to fully operational state < 20 sec

TEST: Lock Acquisition: statistics (~10 cycles) for the time to lock the system from cold start and from warm start; statistics for time between loss of lock (or evidence that lock exceeds 40 hours regularly); demonstration of ability to lock, unlock, and to determine the state of the sub-system via remote control functions stability of performance (pointing, intensity) over a 40 hour period. Stored Light Intensity: DC PD input power monitor; periodic cavity ringdown measurements to determine finesse.

3.9 Modulation frequencies

We require a frequency which resonates in the recycling cavity and an additional frequency which is not resonant in the IFO. Both frequencies (chosen by LSC) must be passed by the mode cleaner and therefore be integral multiples of the mode cleaner free spectral range.

TEST:

1) Optical spectrum analyzer (OSA) measurements of the phase modulated laser light and frequency counter measurement of the residual RFAM using a broadband RF photodiode on the PSL table to verify frequencies.
2) Optical spectrum analyzer measurements of the transmitted mode cleaner light to verify transmission.
3) Measurement of the mode cleaner FSR using optical vernier technique.

3.10 Suitability of In-Vacuum components

The in-vacuum components of the IO must be contained in the current LLO and LHO vacuum envelopes (subject to the replacement of the HAM1,2 and 7,8 beam tube with a LIGO beam tube) and within the footprints of the Advanced LIGO seismic platforms.[1]

TEST: All in-vacuum components are checked for vacuum compatibility. RGA data from vacuum bake-outs; cavity ringdown and mode-spacing changes from optical contamination studies

[1] LIGO-T010076, “Optical Layout for Advanced LIGO”, D. Coyne