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Summary of the L1 Input Mode Cleaner Testing

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1 Executive summary of the Input Mode Cleaner testing

Testing of the L1 Input Mode Cleaner (IMC) was the first aLIGO integration phase at LIGO Livingston Observatory. It took place from the beginning of August 2012, until the second week of February 2013. This period included one vent of the HAM2/3 volume, which interrupted the IMC testing for the months of November and December. The applicable integration planning document can be found in T1100201.

The IMC testing was quite successful. The control system for the IMC was implemented with little trouble, and its performance goals were met. High power testing, though not as complete as possible, did not uncover any barriers to high power operation. Below is a summary of the specific goals, as outlined in T1100201.

2 Quantitative goals

IMC availability. *Goal: > 90%*
Achieved. The IMC will remain locked indefinitely; no unintended source of lock-loss were discovered.

Mean lock duration. *Goal: > 4 hrs*
Achieved.

PSL to PRM power transmission. *Goal: >0.75*
Achieved. Measured transmission of 86% from the base of the PSL/IO table periscope to the parking beam dump on top of HAM2; see LLO alog entry 5764.

IMC longitudinal control bandwidth. *Goal: ~40 kHz*
Achieved. Unity gain frequency of 61 kHz with a phase margin of 62 deg; see LLO alog entry 5865.

Frequency/length crossover frequency. *Goal: ~10 Hz*
Achieved. See LLO alog entry 4178.

Transmitted power fluctuations, rms. *Goal: <1%*
Achieved. Relative RMS fluctuations of 0.5%, down to 20 mHz; see entry 4304.

Transmitted beam angular motion. *Goal: <1.6 urad rms*
Achieved. 0.4 urad in pitch, and 0.07 urad in yaw; see entry 4896.

IMC visibility. *Goal: >95%*
Achieved. Visibility of 97-98%; see, e.g., entry 5834.

Transmitted light RIN. *Goal:* $<10^{-7}\ /\mathrm{Hz}^{1/2}$ *above 10 Hz*
Not achieved. This remains an issue; see section 3.2.3.

Faraday isolation at full power. *Goal: > 30 dB*
Not measured in-situ. Faraday was tested to this level at high power before installation into HAM2.

3 Further discussion of testing objectives

The following addresses the objectives laid out in Section 4 of T1100201.

3.1 IMC optimization and automation

The goals for the mode-matching and length/frequency controls were met as mentioned above. For stability, the length feedback path required notches at the highest roll and vertical modes of the MC2 suspension. This may need to be investigated further, if higher bandwidth for the length path is desired for Common Mode servo operation.

Angular control was also implemented, using both the WFS and in-vacuum QPD. It was found that the inherent angular stability of the IMC was very good (see numbers above), and the global alignment control was only necessary for long term stability (times scales of several hours or more). The design for the angular sensing and actuation was found to be adequate, and it seems unlikely that even longer term operation (longer than several days) will need anything additional.

An auto-locker script was implemented that automates the IMC acquisition and controls optimization; the auto-locker was controlled by a systems guardian set up for the IMC.

3.2 Performance testing

3.2.1 IMC characterization

The cavity transmission, g-factor, and pole-frequency were all measured and found to agree well with their design values. Frequencies and Q-factors of the IMC suspension wires were measured. The frequencies were in good agreement with calculations, once accounting for differing tensions between wires. The violin mode Q-factors can be related to the suspension thermal noise. Though the Q's are determined largely by thermo-elastic loss (which is not significant for the low-frequency thermal noise), the measured values are consistent with the expected suspension wire internal loss. This implies that the double-prism suspension technique is successful. See log entry 5407 and T1200418.

Scattering from the IMC mirrors was looked at using video cameras; nothing anomalous was seen, though no quantitative results were generated.

3.2.2 Frequency noise

The IMC feedback controls signals were calibrated to provide a measure of the frequency noise coming from the PSL. Below 100 Hz, the frequency noise is close to or is better than the requirements. Above 1.5 kHz, the performance is a bit better than the noise requirement. Between 100 Hz and 1.5 kHz, the spectrum is dominated by a large collection of acoustic peaks, and the measured noise is broadly speaking about an order of magnitude above the requirement; see log entries 4132 & 5992. This excess noise may not be as problematic as this appears, as the IMC and Common Mode loops may provide sufficient suppression. However, this is an issue that needs to be investigated. Compared to eLIGO, the frequency noise is a bit worse (factor of 2-3) below 100 Hz, and worse by a factor of 10 or more above 100 Hz due to all the acoustic peaks.

3.2.3 Amplitude noise

The inner loop of the PSL Intensity Stabilization Servo (ISS) was operational, and it performed to requirements. The outer loop detectors were installed in HAM2 during the commissioning break; however, the detector array was later found to be non-functional, so there was no outer loop stabilization. The main finding was that the intensity noise gets worse going downstream of the inner loop detector box. For example, the IMC transmitted light has about 1000x higher RIN at 10Hz than the light at the inner loop output. See log entry 4680.

3.2.4 Angular noise

The rms angular fluctuations of the IMC transmitted beam are quite small; see the numbers reported in the previous section. Beam pointing noise in the GW band has also been measured using a misaligned cavity technique; see log entry 6033. This measures the angular beam jitter of the input beam to the IMC, and can be compared to the requirements given in T0900142 (v2). The yaw jitter meets requirements at low frequencies (< ~100 Hz); above 100 Hz there are many peaks that exceed the requirement by a factor of a few to 10. The pitch jitter is generally higher than yaw by a factor of 5-10. We note that the requirement given in T0900142 is a simplified envelope that is fairly conservative above 60 Hz. Nonetheless the acoustic peaks observed bear further investigation.

3.2.5 RF noise

The RF amplitude noise on the beam transmitted by the IMC was not measured.

3.2.6 VCO range

The new aLIGO low-noise VCO was found to have adequate range for IMC lock acquisition and operation (2 MHz range; 5x smaller range than the iLIGO VCO); see log entries 4645 and 4446. The VCO range used in-lock is ~10 kHz rms, while acquisition transients are typically a few hundred kHz. On the other hand, the low-noise VCO did not reduce the frequency noise as seen by the IMC—it was masked by some other noise.

3.3 High power testing

The IMC was operated successfully at an input power of 120 W, with the following findings:

- The IMC was locked at 120 W input for 2-3 hours, with no significant changes measured in the cavity pole frequency or transmission efficiency.
- Absorption in the IMC mirrors was measured by two methods: g-factor shift, and mirror acoustic mode shift. MC3 appears to absorb the nominal level of 0.6-0.7 ppm, whereas MC1 and MC2 each absorb about 2 ppm. Thus the MC1/2 absorption appears to have increased since they were measured prior to installation.
- Beam sizes and positions were monitored with video cameras to look for thermal effects. These measurements need further work to get reliable results, but the gross conclusion can be made that the IMC output beam is moving by less than ~1/3 the beam radius at the PRM location.
- Isolation of the Faraday was not measured since the retro-reflected beam was not directed through the Faraday during this integration phase.

3.4 Interaction between subsystems

One issue that arose is vibrations on the PSL/IO table, which appear to lead to excess frequency noise and excess beam jitter. No other problematic subsystem interactions were identified.

The active seismic isolation system was found to perform quite well for IMC operation. Seismic motion above 1 Hz is suppressed below other IMC noises. Isolation at the lowest suspension eigenfrequencies is sufficient to provide very stable output beam pointing. There is some amplification of differential motion at low frequencies, but it posed no problem for IMC operation. See log entry 6148.

3.5 Adaptive feed-forward for IMC length

This was not implemented in this integration phase, and is being studied off-line for potential future use.

4 Action items

- Excess laser noise. Laser frequency noise, amplitude noise, and beam jitter are all in excess of requirements at some frequencies. None of these excesses are yet deemed 'show stoppers', but they need further investigation.
- The PSL ISS outer-loop detector array requires some re-engineering, including a technical review of the re-design.
- Characterization of the beam stability at high power—i.e. thermal lensing and thermal-induced pointing—will need to be revisited once the PRM is installed and there is a better understanding of the digital camera signals.
- The digital (GigE) cameras that monitor the beam positions and scatter of the IMC mirrors need to be installed and commissioned.
- Absorption in the IMC mirrors should be measured periodically in the future to look for changes.
- The IO laser power control system was under development throughout this integration phase, and was not quite completely functional at the end. The final design of this component will need to be reviewed for functionality and safety.
- RF amplitude noise (static and dynamic) of the IMC transmitted beam needs to be measured (at 9 and 45 MHz).