Definitions for the X arm commissioning

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Yutaro Enomoto, Yuta Michimura and Kiwamu Izumi

Contents

1 Purposes of the commissioning test

The main purposes of the X arm commissioning test are to (1) test the key technologies for lock acquisition, in particular ALS (Arm Length Stabilization) and (2) assess the readiness of various critical components and schemes by utilizing an arm cavity of the main interferometer

These tests will allow us for identifyiing what parts of the hardware and software need upgrades/improvements for achieving full lock.

2 Goals of the commissioning test

The below shows a list of goals that we are aiming to achieve during the commissioning period. They are listed in the order of the importance – the top item is the most critical. The derivations and reasoning for the quantities are described in section 4 in great detail.

1. Suppressing length displacement of the X arm cavity to be less than **0.35 nm** in rms, controlled by the ALS system as probed by the main 1064-nm interferometer beam.

2. Engagement of the local damping controls to suppress angular fluctuations of each test mass mirror to be less than **880 nrad** in rms for both the pitch and yaw degrees of freedom without an interferometric global control, as measured by the optical levers.

3. Achievement of a continuous lock stretch held by ALS for a period longer than **2 hours**.

4. Establishment of the hand-over process which switches the control system from ALS to the interferometer common mode control using the infrared transmitted light signal.
5. Establishment and automation of an initial alignment procedure which can be utilized on daily basis.
6. Establishment of control procedure to directly lock the laser frequency of the main interferometer beam to the X arm cavity.
7. Reduction of the mirrors' angular fluctuations down to **10 nrad** in rms as measured in loop with a global control system using the wave front sensors for the main interferometer beam.
8. Full automation of the ALS system, including the auto-locking and monitoring-alerting systems.

3 Parameters to be measured

We will measure several key parameters. The parameters are divided into two different categories; the primary and optional parameters. The primary ones are those we must measure while the optional are those we may measure depending on the progress in the commissioning activities.

Additionally, the necessary experimental arrangement is summarized.

3.1 Primary parameters

- Cavity round-trip loss for the main interferometer beam with an accuracy better than 50 ppm.
- Cavity finesse for both 532 and 1064 nm.
- Mode matching of the main interferometer beam to the arm cavity.
- Mode matching of the green laser beam to the arm cavity.
- Gouy phase separation between the two QPDs on the transmission monitor, as probed by both wave lengths (532 and 1064 nm).
- Distribution map of cavity loss as a function of the mirror spot positions.
- Common mode rejection ratio (CMRR) for the cavity displacement.
- The round-trip Gouy phase of the X arm cavity.

3.2 Optional parameters

- Modulation depths for the f_1, f_2 and f_3 RF sidebands.
- Transfer coefficients from ITM and ETM to the WFSs (wave front sensors) in reflection.
- The cavity length.
- The vertical-to-length coupling of the test mass mirrors.

3.3 Experimental arrangements

(a) Reflectivity measurement

- Cavity round-trip loss.
- Loss distribution map.

(b) The main laser is swept while the green light is resonant

- Cavity finesse.
- Mode matching.
- Cavity round-trip Gouy phase.
- Modulation depths.
- TMS QPD response (without cavity scan).

(c) The green laser is swept while the main laser is resonant.

- Cavity finesse.
- Mode matching.
- Vertical-to-length coupling measurements (without cavity scan).
- TMS QPD response (without cavity scan).
- WFS transfer coefficients (without cavity scan).

4 Some derivations

4.1 Longitudinal residual displacement

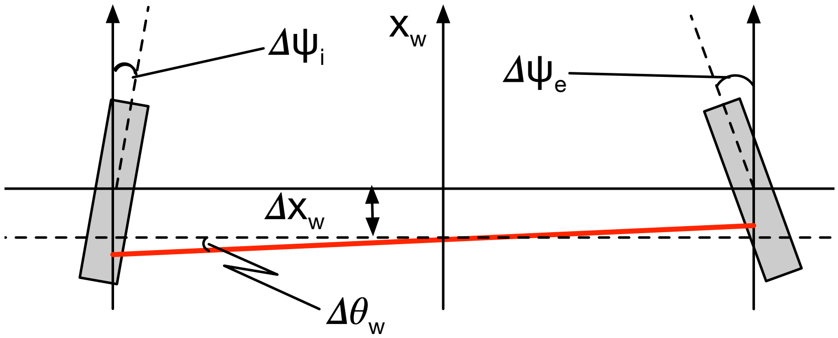

Figure 1: A schematic layout of an arm cavity.

In order to hand over the control from that using the green laser to the infrared main laser, the displacement should be smaller than the full-width-half-maximum (FWHM) of the cavity transmission curve.

Assuming the nominal value for the arm cavity finesse, 1500, one can compute the FWHM as

$$\begin{aligned} \text{FWHM in terms of displacement } &= \frac{\lambda}{2\mathcal{F}}, \\ &= 0.35\,\text{nm} \end{aligned} \tag{1}$$

4.2 Angular fluctuations

The angular fluctuation causes variation in the amount of the cavity power which in turn results in variations in the optical gain of the interferometric readouts. We set the requirement to be **5%** variation in the optical gain or the cavity power in rms. As described below, this corresponds to **880 nrad** rms for each degree of freedom of each test mass.

As the cavity mirrors fluctuate in one of their angles (i.e., either pitch or yaw), the waist of the cavity eigen mode shifts in translation and also tilts in angle. See figure 1 for illustration. Such translation and tilts (Δx_w, $\Delta\theta_w$) can be related to changes in the angles of the cavity mirrors ($\Delta\psi_i$, $\Delta\psi_e$) by

$$\begin{bmatrix} \Delta x_w \\ \Delta\theta_w \end{bmatrix} = \begin{bmatrix} -\frac{R_i}{1+g_i/g_e} & -\frac{R_i}{1+g_e/g_i} \\ -\frac{L}{R_e(1-g_i g_e)} & -\frac{L}{R_i(1-g_i g_e)} \end{bmatrix} \begin{bmatrix} \Delta\psi_i \\ \Delta\psi_e \end{bmatrix}, \tag{2}$$

where L and R_j are the cavity length and the radius of curvature for a mirror j (either ITM or ETM in our case), and where g_x is the g-factor for a mirror X, defined by

$$g_x = 1 - \frac{L}{R_x}. \tag{3}$$

When either Δx_w or $\Delta\theta_w$ has a non-zero value, the cavity power degrades as [1]

$$P \approx P_0 \left(1 - \left(\frac{\Delta x_w}{w_0}\right)^2\right) \left(1 - \left(\frac{\Delta\theta_w}{\theta_0}\right)^2\right), \tag{4}$$

where w_0 and θ_0 are the waist size and cavity's divergence angle. In the case of KAGRA, they are (w_0, θ_0) =(16 mm, 21 μrad).

Figure 2 shows a numerical evaluation of the cavity power degradation. The cavity power reaches 95% of its maximum when the misalignment is as big as 1750 nrad. Note that the numerical values are set as $(R_i, R_e, L) =$ (1900 m, 1900 m, 3000 m) [2]. Since we have four such degrees of freedom (i.e., pitch and yaw for two test masses), the requirement should be that

$$\text{Required rms for each angular dof} = \frac{1750 \text{ nrad}}{\sqrt{4}} \approx 880 \text{ nrad}. \tag{5}$$

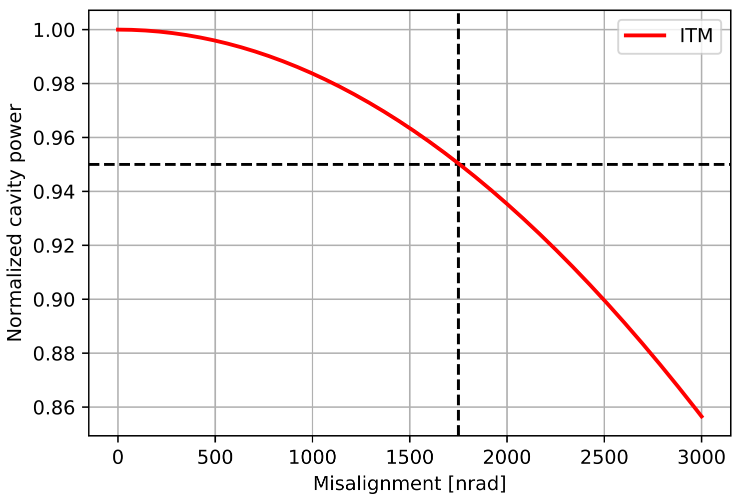

Figure 2: Numerical evaluation of the normalized cavity power as a function of the ITM misalignment.

4.3 Lock stretch

In order to perform the deterministic lock acquisition process, it will be sufficient to hold the cavity by ALS for 10 minutes or so because it is going to be taken over to other control systems in a short period time. However, in practice, one needs to run several measurements in some occasions while holding the system locked. From this point of view, we set the goal as

$$\text{Lock duration} = 2\,\text{hours}. \tag{6}$$

4.4 Control precision for the angular fluctuations

We aim to test out the wave front sensors for the main interferometer beam once the main laser is resonant in the cavity. The goal for this control is set such that the spot position on each test mass doesn't move more than 0.1 mm [3].

The spot positions can be related to the misalignment of the optics as

$$\begin{bmatrix} x_i \\ x_e \end{bmatrix} = \frac{L}{1 - g_i g_e} \begin{bmatrix} -g_e & -1 \\ -1 & -g_i \end{bmatrix} \begin{bmatrix} \Delta\psi_i \\ \Delta\psi_e \end{bmatrix} \tag{7}$$

Plugging the actual numbers, one can get

$$\begin{bmatrix} x_i \\ x_e \end{bmatrix} = \begin{bmatrix} 2613\,[\mathrm{m/rad}] & -4513\,[\mathrm{m/rad}] \\ -4513\,[\mathrm{m/rad}] & 2613\,[\mathrm{m/rad}] \end{bmatrix} \begin{bmatrix} \Delta\psi_i \\ \Delta\psi_e \end{bmatrix}. \tag{8}$$

Apparently the severest coefficients are the off diagonal elements i.e., from the ETM angle to the ITM spot or vice versa. For simplicity, we use the off-diagonal elements only for the rest of our calculation. In order to keep the spot positions smaller than 0.1 mm in rms

$$\text{requirement for angle} = \frac{1 \times 10^{-3}\,\mathrm{m}}{4513\,\mathrm{rad/m} \times \sqrt{4}} \approx 11\,\mathrm{nrad} \tag{9}$$

where the factor of $\sqrt{4}$ comes from the stochastic summation of the four degrees of freedom (pitch and yaw for ITMX and ETMX).

References

[1] K. Dooley "Design and performance of high laser power interferometers for gravitational-wave detection," Dissertation, University of Florida (2011).

[2] MIF wiki page
http://gwwiki.icrr.u-tokyo.ac.jp/JGWwiki/LCGT/subgroup/ifo/MIF/OptParam

[3] Y. Aso *et al.,* "Interferometer design of the KAGRA gravitational wave detector, " Phys. Rev. D **88,** 043007 (2013)