LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

LIGO Laboratory / LIGO Scientific Collaboration

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Jitter Attenuation Cavity (JAC) Design

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1 Introduction

This document describes the design considerations for a Jitter Attenuation Cavity (JAC) that will be needed to meet the Advanced LIGO requirements for pointing stability.

2 Requirements

2.1 Pointing

The Advanced LIGO pointing requirement is described in T0900142. The requirement for the arm misalignment was set to 10^{-9} rad rms which is rather stringent, especially at higher laser powers. We reduce this assumption by a factor of 3 and tighten the overall requirement by a factor of 2 to account for the planned improvements envisioned by the A+ upgrade. The jitter out of the pre-stabilized laser (PSL) is about a factor 3-5 above the original requirement which leads to a requirement for additional pointing suppression of 20-30.

Quantity	New	Old	Unit
Assumption on differential arm cavity alignment	$< 3\times10^{-9}$	$< 10^{-9}$	rad rms
Target sensitivity envelope Ref: P1400164	$1.5\times10^{-24}\sqrt{1+\left(\frac{40\text{ Hz}}{f}\right)^4}$	$3\times10^{-24}\sqrt{1+\left(\frac{40\text{ Hz}}{f}\right)^4}$	$1/\sqrt{\text{Hz}}$
Jitter requirement at input of interferometer	$1.7\times10^{-9}\sqrt{1+\left(\frac{100\text{ Hz}}{f}\right)^4}$	$1\times10^{-8}\sqrt{1+\left(\frac{100\text{ Hz}}{f}\right)^4}$	$1/\sqrt{\text{Hz}}$
Jitter requirement at input of input mode cleaner (IMC)	$4\times10^{-7}\sqrt{1+\left(\frac{100\text{ Hz}}{f}\right)^4}$	$2.5\times10^{-6}\sqrt{1+\left(\frac{100\text{ Hz}}{f}\right)^4}$	$1/\sqrt{\text{Hz}}$
	$7\times10^{-11}\sqrt{1+\left(\frac{100\text{ Hz}}{f}\right)^4}$	$4\times10^{-10}\sqrt{1+\left(\frac{100\text{ Hz}}{f}\right)^4}$	$\text{rad}/\sqrt{\text{Hz}}$
Jitter requirement at input of jitter attenuation cavity	$1.6\times10^{-5}\sqrt{1+\left(\frac{100\text{ Hz}}{f}\right)^4}$	Same as above	$1/\sqrt{\text{Hz}}$
Jitter requirement at input of pre-mode cleaner	$1\times10^{-3}\sqrt{1+\left(\frac{100\text{ Hz}}{f}\right)^4}$	$1.6\times10^{-4}\sqrt{1+\left(\frac{100\text{ Hz}}{f}\right)^4}$	$1/\sqrt{\text{Hz}}$

With the following assumptions:
1. Dimensionless jitter requirements are given in units of beam divergence angle or spot size.
2. The jitter attenuation of the IMC is ~250, the waits size is 2.1 mm and the Rayleigh range is 13.3 m. This leads to a divergence angle of 0.16 mrad. Ref: T0900386.
3. The jitter attenuation of the JAC is ~40 (see next section).
4. The jitter attenuation of the pre-mode cleaner is ~60.

2.2 Higher Order Modes

TBD.

A quick estimate can be done as follows: During the 50 W commissioning test at H1 a broad noise hump was seen around 500 Hz, which in the worst case was about a factor of 3 above shot noise. If we attribute this noise to second order higher order mode fluctuations, an additional suppression of second order higher order modes of about 60 would be required to meet the A+ requirement.

2.3 Polarization

Four mirror cavities tend to have both polarization states resonating within the cavity bandwidth. The resonance separation for the Advanced LIGO PMC is approximately one 10^{th} of the cavity line width. A slightly off-resonance mode will introduce intensity noise couplings from both frequency noise and length fluctuations. We therefore require the new jitter attenuation cavity to be an odd mirror configuration to separate the two polarization states.

The polarization of the input mode cleaner is vertical, whereas the polarization of the Advanced LIGO PMC is horizontal. The current IO EOM also requires horizontal polarization. Using the most standard material and design for the JAC input mirrors and coatings, a 2.48% transmission for s-polarization would give an estimated p-polarization transmission of about 9.4%. If it is designed for 2.48% transmission of p-polarization, then the s-polarization transmission would be 0.05%. But it will depend significantly on the materials used, and somewhat on the details of the design as well. To avoid high finesse modes in the wrong polarization, a design using s-polarization would be preferred. In turn, this would require the EOM design to be flipped over by 90º. It would also require the polarization to be rotate by 90º between the JAC and the IMC.

2.4 RF Filtering

The current PMC provides a factor of 15 filtering at the main modulation frequency of 9.1 MHz. We do not require that the new jitter attenuation cavity provides additional filtering. This allows the cavity length to be chosen arbitrarily.

However, any filtering provided by jitter attenuation cavity could relax the requirement put on the PMC. One interesting idea would be to make both cavity of identical configuration. This would mean that each cavity needs to provide a factor of 4 or more of RF filtering at 9.1 MHz. If the Finesse of the PMC is kept the same at 125, the minimum round-trip length is then 0.5 m.

3 Parameters

3.1 Cavity Parameters

The initial LIGO PMC had a short triangular configuration with a relatively high finesse and a target Gouy phase separation of 55.3º. This gives good attenuation of higher order modes and filtering of laser noise at the RF modulation frequencies. For Advanced LIGO the finesse had to be lowered to avoid very high internal power. To have sufficient filtering of RF laser noise, the cavity length had to increased. To stay compact a bow-tie configuration was employed. In turn this also increased the Gouy phase separation to 100º. Both Gouy phase solution are good in avoiding accidental resonances of higher order optical modes. For the jitter attenuation cavity, we want a triangular configuration and a power build-up like the Advanced LIGO PMC. A reasonable design can be achieved by using the same curved mirror as the Advanced LIGO PMC, but other options exist with smaller mirror curvature.

A set of possible parameters for the jitter attenuation cavity are shown below:

Parameters	iLIGO PMC	aLIGO PMC	JAC			Units
Mirrors	3	4	3			
Mirror curvature	1.00	3.00	3.00	2.00	1.00	m
Input/output reflectivity	1.4	2.48	2.48			%
Finesse	380	125	125			
Power build-up	120	40	40			
Round-trip length	0.42	2.02	1.29	0.86	1.17	m
FSR	710	150	232	348	255	MHz
Cavity pole	0.95	0.6	0.93	1.38	1.02	MHz
Attenuation at 9.1 MHz	~10	~15	~10	~7	~9	
Waist size	0.37	0.5/0.7	0.65	0.53	0.41	mm
Rayleigh range	0.40	0.85/	1.23	0.82	0.49	m
Divergence angle	0.92	0.63/	0.52	0.64	0.83	mrad
Round-trip Gouy phase	55.3	100	55.3	55.3	100	°
TEM01 attenuation (parallel to pol.)	0.9	1.6	2.7	2.7	2.0	%
TEM10 attenuation (perp. to pol.)	0.5	1.6	1.6	1.6	1.5	%
TEM20 attenuation	0.5	1.3	1.4	1.4	1.3	%

If the cavity round-trip length is set to 1 m, the new cavity will take a footprint very like the Advanced LIGO PMC, which uses a bow-tie configuration to achieve a round-trip length of roughly 2 m.

3.2 Beam Propagation

TBD.

4 Electronics

4.1 Block Diagram

A block diagram is located in LIGO-D1700001.

4.2 Modulators

The triple frequency IO modulator currently located on the PSL table has to move into the beam path after the JAC. A new vacuum compatible design is required. A new single frequency EOM has to replace the old IO modulator to provide the RF sidebands for locking the JAC.

4.3 Sensors and Photodetectors

The HAM1 table implements a QPD sled to monitor the jitter of the incoming light. It implements an RF detector in reflection of the JAC to lock the resonator. Two DC photodetectors are used to monitor the power build-up inside the cavity and the power after the cavity.

Name	Location	Description/Comment
JAC-QPD_A	HAM1	LIGO in-vacuum quad photodetector Former POP_A and POP_B detectors
JAC-QPD_B	HAM1	
JAC-REFL_A	HAM1	Single frequency in-vacuum LSC RF PD
JAC-TRANS_A	ISCT1	DC monitor photodetector for transmitted light
JAC-PWR_A	HAM1	DC monitor photodetector for light after JAC
JAC-CAM_TRANS	ISCT1	Camera for transmitted light

4.4 Actuators

An additional in-vacuum steering mirror, in combination with the periscope steering mirror, aligns the incoming beam into the JAC, whereas the two QPDs serve as the alignment reference. Two additional steering mirrors are located after the JAC to steer the beam into the IMC. One or two PZT actuators control the length of the cavity.

Name	Location	Description/Comment
JAC-LENGTH1	HAM1	In-vacuum longitudinal PZTs to control the cavity length.
JAC-LENGTH2	HAM1	
IO-PZT_B	HAM1	Second input steering mirror
JAC-PZT_A	HAM1	In-vacuum steering mirrors after the JAC
JAC-PZT_B	HAM1	

4.5 Equipment

The following electronics chassis are required to control the JAC:

Name	Location	Description/Comment
Angle PZT driver	ISC-R5	3 units are required for the PZT steering mirrors
Dewhitening	ISC-R5	TBD, for angle PZTs
Length PZT driver	ISC-R5	1-2 units are required for the JAC length PZTs
LSC RFPD interface	ISC-R1	Use spare channel in existing IMC unit
2-chn demod	ISC-R1	Use spare channel of IMC 2-chn demod
Delay line	ISC-R1	Use spare channel of IMC delay line
RF source	ISC-C4	Propose to use divide-by-3 from 71 MHz
RF distribution amp	ISC-C4	New unit
EOM drivers	ISC-R5	Use the two existing PSL units
Dual QPD transamp	ISC-R5	Used freed POP_A/B unit
Whitening	ISC-R5	Used freed POP_A/B unit
DCPD transamp	ISC-R5	TBD, 2 channels required
AA/AI chassis	ISC-C1	Quantity as required

4.6 Data Acquisition

A preliminary ADC and DAC channel list is shown below:

Card	AA/AI conn.	ADC/DAC Chs.	Signal		
ASC ADC	DB9_1	1-4	JAC-QPD_A		
	DB9_2	5-8	JAC-QPD_B		
ASC DAC	DB9_1	3-4	IO_PZT_B		
	DB9_2	5-6	JAC-PZT_A		
		7-8	JAC_PZT_B		
LSC ADC	DB9_1	1	LSC-IMC_REFL_A	RF24	Q-phase
		2			I-phase
		3	JAC-REFL_A	RF23	Q-phase
		4			I-phase
	DB9_2	3	JAC_REFL_A_DC		
	DB9_3	1	JAC_TRANS_A_LF		
		2	JAC_PWR_A_LF		
LSC DAC	DB9_1	1	JAC_L		
		2	JAC_SCAN		