*LIGO Laboratory / LIGO Scientific Collaboration*

LIGO-T1600595-v3 Advanced LIGO 4/6/2017

Jitter Attenuation Cavity (JAC) Design

Daniel Sigg, etc.

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# 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.

# Requirements

## Pointing

The Advanced LIGO pointing requirement is described in [T0900142](https://dcc.ligo.org/LIGO-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 | < 3×10–9 | < 10–9 | rad rms |
| Target sensitivity envelopeRef: [P1400164](https://dcc.ligo.org/LIGO-P1400164) | $$1.5×10^{-24}\sqrt{1+\left(\frac{40 Hz}{f}\right)^{4}}$$ | $$3×10^{-24}\sqrt{1+\left(\frac{40 Hz}{f}\right)^{4}}$$ | 1/√Hz |
| Jitter requirement at input of interferometer | $$1.7×10^{-9}\sqrt{1+\left(\frac{100 Hz}{f}\right)^{4}}$$ | $$1×10^{-8}\sqrt{1+\left(\frac{100 Hz}{f}\right)^{4}}$$ | 1/√Hz |
| Jitter requirement at input of input mode cleaner (IMC) | $$4×10^{-7}\sqrt{1+\left(\frac{100 Hz}{f}\right)^{4}}$$ | $$2.5×10^{-6}\sqrt{1+\left(\frac{100 Hz}{f}\right)^{4}}$$ | 1/√Hz |
| $$7×10^{-11}\sqrt{1+\left(\frac{100 Hz}{f}\right)^{4}}$$ | $$4×10^{-10}\sqrt{1+\left(\frac{100 Hz}{f}\right)^{4}}$$ | rad/√Hz |
| Jitter requirement at input of jitter attenuation cavity | $$1.6×10^{-5}\sqrt{1+\left(\frac{100 Hz}{f}\right)^{4}}$$ | Same as above | 1/√Hz |
| Jitter requirement at input of pre-mode cleaner | $$1×10^{-3}\sqrt{1+\left(\frac{100 Hz}{f}\right)^{4}}$$ | $$1.6×10^{-4}\sqrt{1+\left(\frac{100 Hz}{f}\right)^{4}}$$ | 1/√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](https://dcc.ligo.org/LIGO-T0900386).
3. The jitter attenuation of the JAC is ~40 (see next section).
4. The jitter attenuation of the pre-mode cleaner is ~60.
 |

## 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.

## 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 10th 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.

## 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.

# Parameters

## 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.

## Beam Propagation

TBD.

# Electronics

## Block Diagram

A block diagram is located in [LIGO-D1700001](https://dcc.ligo.org/LIGO-D1700001).

## 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.

## 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 photodetectorFormer 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 |

## 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 |

## 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 |

## Data Acquisition

A preliminary ADC and DAC channel list is shown below:

|  |  |  |  |
| --- | --- | --- | --- |
| Card | AA/AI conn. | ADC/DAC Chs. | Signal |
| ASCADC | DB9\_1 | 1-4 | JAC-QPD\_A |
| DB9\_2 | 5-8 | JAC-QPD\_B |
| ASCDAC | DB9\_1 | 3-4 | IO\_PZT\_B |
| DB9\_2 | 5-6 | JAC-PZT\_A |
| 7-8 | JAC\_PZT\_B |
| LSCADC | 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 |
| LSCDAC | DB9\_1 | 1 | JAC\_L |
| 2 | JAC\_SCAN |