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Advanced LIGO

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

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 waist 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 90° . It would also require the polarization to be rotate by 90° 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 55.3° . 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 be increased. To stay compact a bow-tie configuration was employed. In turn this also increased the Gouy phase separation to 100° . 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 | mrاد |
| 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