Estimation of clipping losses in a Fabry-Perot cavity

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- added the cryostat 270 mm aperture.

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1 Overview of this document

This document attempts to estimate the size of optical losses due to various apertures clipping the resonating laser field in a Fabry-Perot cavity of KAGRA. This study was motivated by the fact that the upcoming X-arm commissioning [1] will take place with both ITM and ETM intentionally kept at the room temperature. This leads to an involved situation where the mirror's vertical positions as well as that of WAB will not be at the final cryogenic positions and hence possibility of increased clipping losses.

2 Setup

2.1 Oveview

Figure 1 illustrates the setup under consideration. Because of the symmetry between the setup around the ITM and that for the ETM, we consider the baffles around the ITM only. As seen in the figure, the tightest aperture

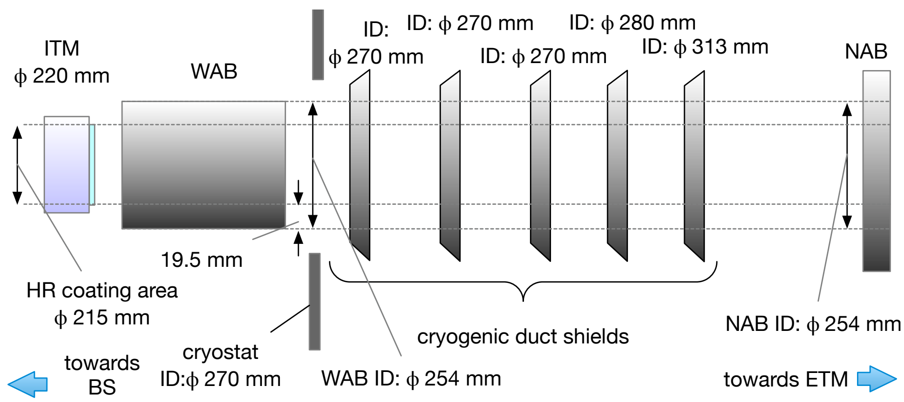

Figure 1: A schematic view of the baffle setup around the ITM. Not to scale.

is given by the HR coating of the ITM which is 215 mm in diameter [2]. The second tightest aperture is given by the WAB, NAB and the cryostat all of which have an inner diameter of 254 mm [3, 4]. Finally there are five cryogenic duct shields [5] that are installed between the WAB and NAB. The smallest aperture size among the five is 270 mm in diameter as annotated in the figure.

2.2 Assumptions

For simplicity, we assume all the optical components to be well aligned in their angles so that the interferometer beam will propagate through them orthogonally. Also we assume that the interferometer beam does not have any misalignment in its angular degrees of freedom i.e., the interferometer beam is always normal to the ITM surface, but can move in its position translationally.

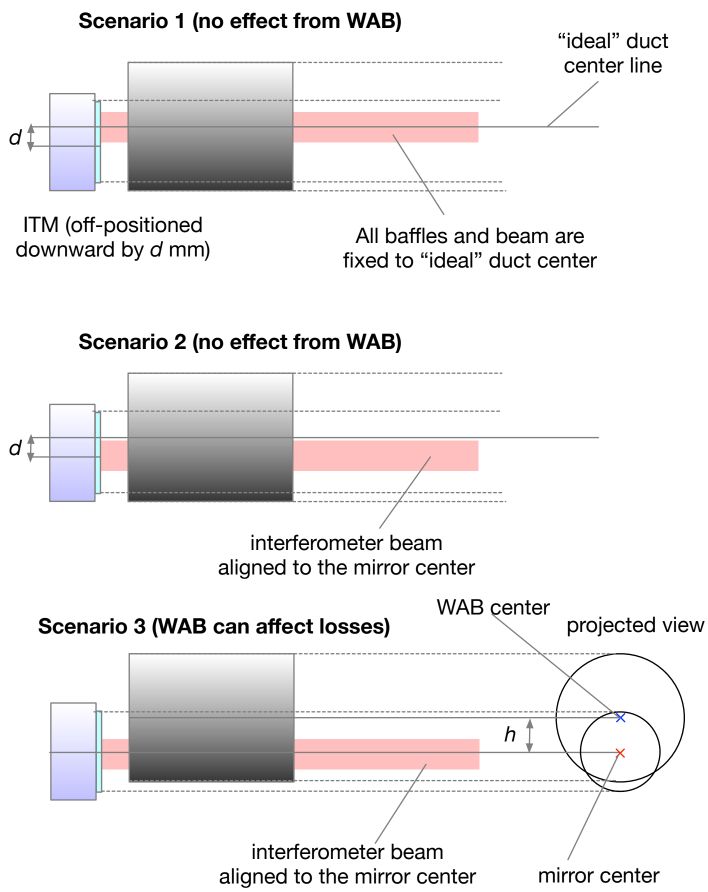

Figure 2: Graphical summary of the scenarios under consideration in this document. The cryogenic duct shields and NAB are not considered in this document as described in section 2.3.

2.3 Scenarios

Even though many of the components shown in figure 1 can be either intentionally or unintentionally installed to a point off from the "ideal" location, we restrict ourself to three scenarios for now to obtain an idea of how big losses would be. In all the scenarios, we only consider the interferometer beam propagating through an ITM and a WAB. However, the same argument should be directly applicable to the NABs which have the same inner diameter as the WABs. The cryogenic duct shields are also excluded from the discussion for now to reduce the number of possible scenarios.

- **Scenario 1:** Only the ITM is off-positioned by d in the vertical direction. The rest of the components as well as the interferometer beam are fixed to their final cryogenic positions. As described in the next section 3.1 in detail, the WAB does not contribute to optical loss.
- **Scenario 2:** This is a variant of scenario 1 and only different by the point that the interferometer beam is now repositioned so as to center the beam to the ITM.
- **Scenario 3:** The relative placement of the WAB with respect to the ITM is off by an arbitrary amount h. Both the HR coating and WAB can contribute to the resulting optical loss.

Additionally, the scenarios are graphically summarized in figure 2.

3 Estimating clipping losses

In order to evaluate cavity round trip loss caused by clipping losses, we follow the estimation technique that H. Yamamoto suggested [6]. The technique is quite simple. It integrates the optical power of the interferometer beam (assumed to be a perfect Gaussian beam) across the area that is occulted by some apertures. This optical loss is directly interpreted as cavity round trip

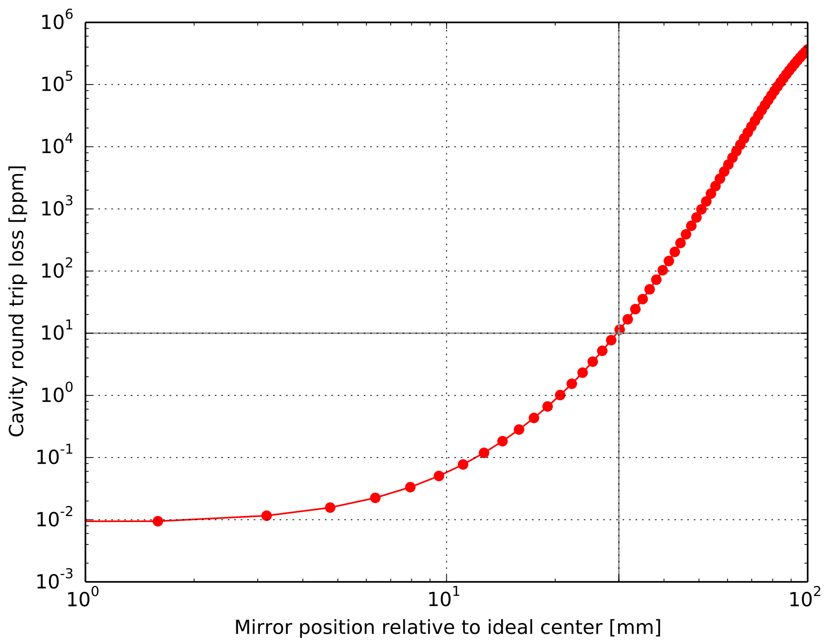

Figure 3: Simulated cavity round trip loss as a function of the mirror's vertical position relative to the ideal duct center in scenario 1.

loss. This should give us a relatively precise order estimation [7]. The beam size in radius is assumed to be the nominal value of 35.3 mm [8] in all the computations.

3.1 Scenario 1

Under scenario 1, the only parameter we control is the vertical position of the mirror center with respect to the ideal duct center, characterized by d. Remember that the rest of the baffles and the interferometer beam are virtually fixed to the ideal duct center as described in the previous section.

In this case, optical loss will be dominated by the clipping of the ITM HR coating. So for the reason, the effects from other apertures are explicitly omitted in the calculation. The estimated loss as a function of the mirror position relative to the ideal duct center is given in figure 3.

When the mirror position is off by 30 mm, round trip loss becomes as large as 10 ppm which is comparable to typical round trip losses (on the order of several tens of ppm).

3.2 Scenario 2

This is a special case of scenario 1 in which the loss is minimized by repositioning the interferometer beam. In this situation, clipping loss is negligibly small (on the order of 0.01 ppm) as can be seen at the leftmost end of the plot in figure 3.

3.3 Scenario 3

In this scenario, we parameterize the relative distance of the centre of the mirror and WAB, h. The simulation result is shown in figure 4. As expected, the WAB does not contribute to the overall loss until h becomes as large as 19.5 mm that is the difference in the radii of the HR coating and WAB's aperture size (see figure 1).

As the relative distance becomes as large as 50 mm, it reaches 10 ppm, a comparable value to ordinary cavity round trip losses.

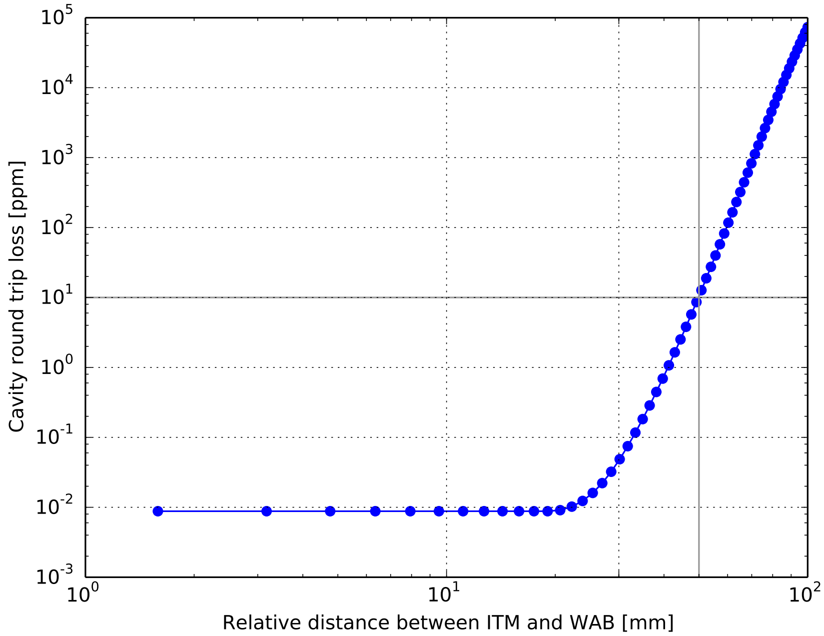

Figure 4: Simulated cavity round trip loss as a function of the relative distance between the mirror center and WAB center for scenario 3.

4 Conclusion

The narrowest aperture size is given by the HR coating area of the ITM and ETM. In order to make their clipping losses subdominant compared to other cavity losses, the interferometer beam must be centered to both mirrors with an accuracy better than 30 mm. This holds true as long as the relative position of each mirror and the nearest WAB (and NAB too!) is controlled with an accuracy better than ~ 20 mm.

In case the relative distance between a WAB and its closest mirror is off from the ideal value by more than 50 mm, such situation can introduce optical loss as significant as other cavity round trip losses.

References

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[2] E. Hirose, private communication (2018)

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[5] N. Kimura has a chamber CAD layout which was drawn by Jecc Torisha Co., Ltd. The drawing itself was made in 2014.

[6] L. Tsukada et. al., "Loss Dependence on Beam Position in the Arm Cavities of aLIGO," LIGO-P1400198-v2 (2014)
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[7] According to Hiro, this technique might exhibit a bias as big as a factor of two. (2018)

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