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Advanced Virgo design: Preliminary Revision of the Beam Size and the Test Mass Curvatures

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1 Scope of this document

This document is thought to define a consistent preliminary set of beam sizes and test mass curvatures for the Advanced Virgo Gravitational Wave Detector.

2 Introduction

In the Advanced Virgo Conceptual Design document [2] non consistent sizes of the laser beam at the main test masses are used. While throughout most of this document the beam size of 3.5 cm, defined in [1] is used, all noise and sensitivity curves are calculated for a beam size of 6.0 cm. This inconsistency needs to be resolved.

Since the thermal Brownian noise of the test mass coatings increases with decreasing beam size, it is reasonable to increase the beam size to the maximal technically feasible value. This is of special importance, as the thermal noise from the coatings will be one of the noise sources, directly limiting the Advanced Virgo sensitivity.

3 Mirror Size versus Beam Size

In this Section we will give a brief overview of the general procedure of designing the mirror geometry and beam size.

Mirror Weight: The first parameter that needs to be decided on is the weight of the test mass. Bigger weight reduces radiation pressure, but is at the same time more demanding for the suspension.

Aspect Ratio: After choosing the weight of the test mass the next step is to choose the aspect ratio of the mirror. In order to minimize thermal noise the choice of the art is to use mirror diameter to mirror thickness ratio of 7:4.

Coating Area: Usually the mirror surface available for the coating is reduced by flats, necessary for the suspension of the test mass. In addition the potential coating area is further decreased because the coating cannot go exactly up to the rim of the test mass [3].

Beam Size: The diameter of the coating finally determines the maximal possible size of the laser beam. As shown in Figure 1 the power loss from clipping is about a few hundred ppm for a mirror size to beam size ratio of 2. Going to a ratio of mirror size to beam size of 2.5 reduces the power losses to a few ppm, while for a

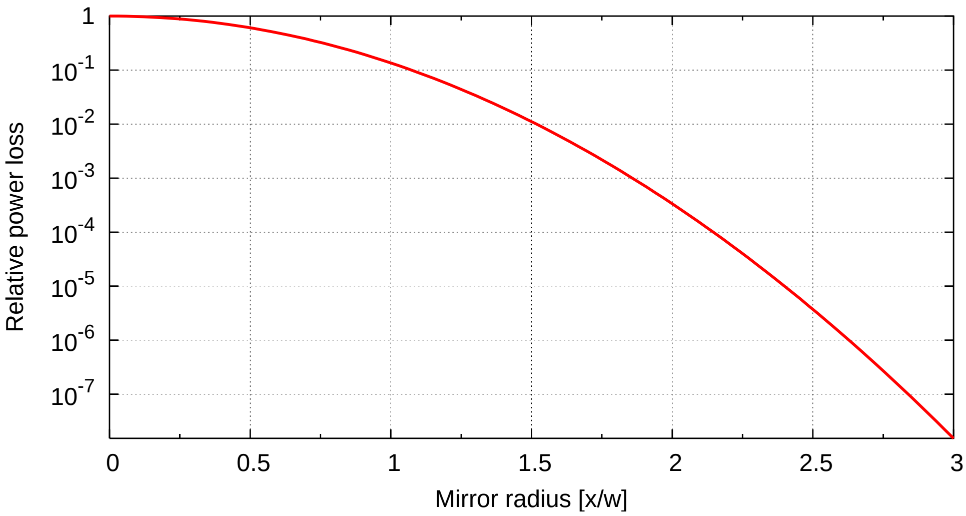

Figure 1: Simple approximation for the power loss experienced by a beam of the radius w on reflection of a mirror with the radius x (this plot should be replaced by a more accurate one).

ratio of 3 the power losses are negligible. In addition clipping loss do not only reduce the power buildup, but may also cause straylight noise. Therefore a careful trade-off of the mirror size to beam size ratio is required. Looking at the numbers given above a mirror size to beam size ratio of 2.5 seems to be safe. However, due to potential mirror imperfections, residual miscentering of the beam in respect to the mirror and avoidable alignment fluctuations we might consider to use a mirror size to beam size ratio of 3.

4 Revised Beam Size at the Main Test Masses

The baseline for the Advanced Virgo test masses design is to use a mirror diameter of 35 cm and a thickness of 20 cm.[1] The geometry of the mirror coating is shown in Figure 2. L_{flat} indicates the length of flats for the Advanced Virgo mirrors, which will probably be between 5 and 12 cm [3], [4].[2] The minimal distance between the mirror rim and the coating is x, which can be as small as 5 mm [3]. Using these values and supposing a circular coating we can derive the maximal radius of the coating area, r_{coat}:

$$r_{\text{coat}} = \sqrt{r_{\text{m}}^2 - \frac{L_{\text{flat}}^2}{4}} - 5\,\text{mm} \tag{1}$$

From r_{coat} we can now calculate the possible beam radii assuming a coating size to beam size ratio of 2.5, $r_{(\epsilon=2.5)}$, and 3, $r_{(\epsilon=3)}$ in dependence of the size of the flats. The corresponding values are depict in Table 1.

5 Revised Test Mass curvatures

Using three exemplary beam radii of 5.5, 6.0 and 6.5 cm we can now calculate the corresponding radii of curvatures of the four main test masses (IMX, EMX, IMY and EMY) and the two recycling mirrors (PRM and SRM). The result is shown in Table 2.

[1] The beam splitter will have a diameter of 55 cm in order to not indroduce further clipping losses. Due to the 45 deg angle of the beam splitter in respect to the arm cavities the effective horizontal diameter of the beam splitter reduces to 55 cm * 0.707 = 38.9 cm

[2] In case the lateral ears are glued to the flats, L_{flat} can be on the smaller end of the given range. In case the lateral ears are machined directly from the mirror substrate flats of larger 10 cm are more likely.

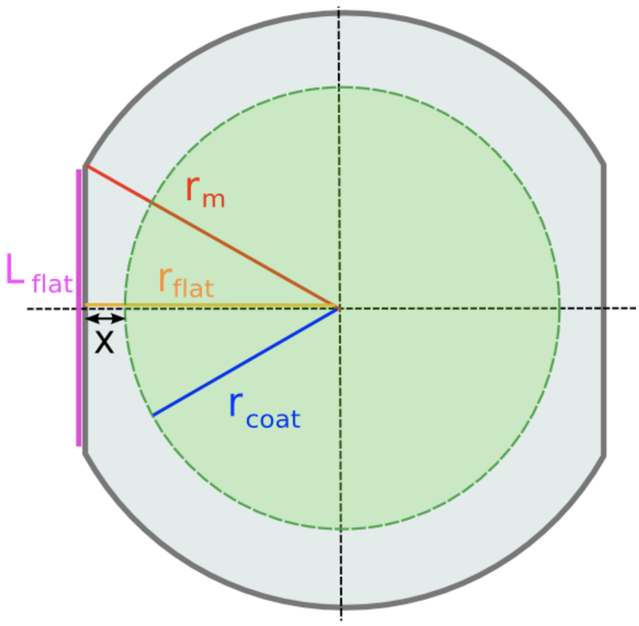

Figure 2: Geometry of the mirror surface of a Advanced Virgo test mass.

L_{flat} [cm]	0	5	6	7	8	9	10	12
$r_{(\epsilon=2.5)}$ [cm]	6.80	6.73	6.70	6.66	6.61	6.56	6.51	6.38
$r_{(\epsilon=3)}$ [cm]	5.67	5.61	5.58	5.55	5.51	5.47	5.42	5.31

Table 1: Beam sizes for Advanced Virgo assuming a test mass diameter of 35 cm. $r_{(\epsilon=2.5)}$ gives the possible beam radius assuming a coating radius to beam radius ratio of 2.5. Analogous $r_{(\epsilon=3)}$ indicates the possible beam radius assuming a coating radius to beam radius ratio of 3.

The values given in Table 2 show, that the beam size in the arm cavities critically depends on the radii of curvature of the main test masses. A 1 percent deviation of the radii of curvature will yield a change of the beam size of 10 percent. This relation will set a strict requirement for the manufacturing accuracy of the mirrors for Advanced Virgo.

The last column of Table 2 displays the waist size (radius $1/e^2$ in power) inside the arm cavities for the three different beam sizes. Such small waist sizes significantly increase the noise from residual gas pressure inside the Advanced Virgo vacuum system. A tradeoff analysis of test mass thermal noise and residual gas pressure noise might be necessary.

beam radius	IMX	EMX	IMY	EMY	PRM	SRM	waist size
r = 5.5 cm	1545	1545	1545	1545	1078	1080	9.4 mm
r = 6.0 cm	1531	1531	1531	1531	1068	1071	8.5 mm
r = 6.5 cm	1522	1522	1522	1522	1062	1064	7.8 mm

Table 2: Radii of curvature of the Advanced Virgo core optics and recycling mirrors in meter.

6 Steps towards the final Beam Size for Advanced Virgo

The investigations presented in this document should be seen as an intermediate step towards the final beam design for Advanced Virgo. The following issues have not been taken into account so far, but need to be considered for the final design:

- Clipping from the actuators and reference masses have not been taken into account, because their geometry is not known at the current stage of the design process.
- The clipped light will contribute to scattered light noise. The actual level of this noise needs to estimated and taken into account.
- So far we did not consider any thermal effects. The influence form thermal lensing onto the actual values of beam size and radii of curvature need to be investigated.

In order to decide on the final beam size used in Advanced Virgo a detailed trade off process is required. This trade off needs to take into account the detector sensitivity, power build-up, residual gas pressure noise and potential scattered light noise.

7 Documentation of Simulation Files

The analysis presented in this document was performed using the numerical interferometer simulation software **Finesse** [?] (available at *http://www.rzg.mpg.de/˜adf/*). Within the context of the Advanced Virgo subsystem for Optical Simulation and Design (OSD) we have developed the **OSD-Tools package**, a collection of Matlab functions for optical design tasks. All relevant scripts and files are stored in a subversion repository which provides backup as well as version control. This svn repository is accessible to everyone without username and password (server: `svn://lnx0.sr.bham.ac.uk`, repository: `adv-osd`).

For further information please see the Advanced Virgo OSD Wiki [5] or contact Stefan Hild (hild@star.sr.bham.ac.uk).

The actual simulations persented here made use of:

- Finesse 0.99.7
- FinesseTools 0.3.1
- The OSD-Tool-function: OSD_ROC.m
- A parameter set derived from: advirgo_base_14062008.kat

References

[1] M. Mantovani, A. Freise, "Initial set of optical parameters for numerical simulations towards Advanced Virgo" Virgo note VIR-002B-07 1

[2] The Advanced Virgo Team, "Advanced Virgo Conceptual Design", Virgo note VIR-042A-07 1

[3] Personal communication with Raffaele Flaminio, LMA. 1, 2

[4] http://wwwcascina.virgo.infn.it/advirgo/biweekly/2008/2008-06/vocca_030608.ppt 2

[5] A. Freise, G, Heinzel, H. Lück, R. Schilling, B. Willke and K. Danzmann: 'Frequency-domain interferometer simulation with higher-order spatial modes', Class. Quantum Grav. **21** (2003)1067–1074.

[6] The Advanced Virgo OSD wiki can be accessed via the Advanced Virgo web page (http://wwwcascina.virgo.infn.it/advirgo/). Please use the link to the 'Adv Wiki' and then proceed to the 'OSD Wiki'. 4