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Advanced Virgo MSRC simulations related to Angular control: EDB suspension requirements - CP tilt requirement - central area pick-off

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M. Mantovani

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VIRGO * A joint CNRS-INFN Project
Via E. Amaldi, I-56021 S. Stefano a Macerata - Cascina (Pisa)
Secretariat: Telephone (39) 050 752 521 * FAX (39) 050 752 550 * Email W3@virgo.infn.it

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1 Introduction

In this note some simulations and computations for the Advanced Virgo configuration angular control are described. The document is divided in three parts which describe three different aspects as:

- External detection benches suspension requirements
- Compensation Plate tilt requirement
- Central area pick-off

2 External detection benches suspension requirements

In the Advanced Virgo configuration important angular modes, such as the Differential and Common End minus modes, have to be controlled with DC signals coming from the external benches in transmission from the Arm cavities [1], thus it requires that the quadrants are suspended under vacuum [1] [2].
In this document the suspension requirements have been computed for the horizontal and vertical directions for the high frequency part, to do not spoil the sensing noise which has to be shot noise limited, and for the low frequency part, in the loop bandwidth, to do not spoil the reference since a DC signal depends on the relative quadrant/beam position.

2.1 Sensing noise

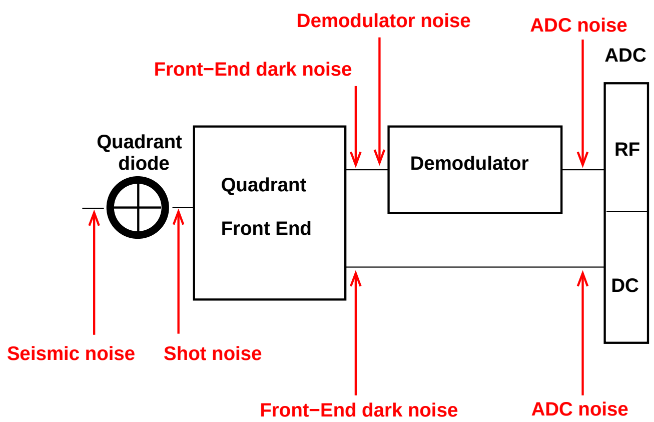

Figure 1: Sensing path for the Automatic Alignment control system. It is formed by the diode, the Front-End electronics, the demodulator board only for the RF path and by the Analog-Digital Converter

The sensing noise of the automatic alignment control system is generated by the contribution of several technical or fundamental noises as: the shot noise, the seismic noise at the level of the diode, the front-end electronic noise, the demodulator noise (only for the RF path) and the ADC (analog-digital converter) noise, as it is shown in Figure 1.
In advanced interferometer controls the sensing noise has to be dominated only by shot-noise (to have the best possible noise performances).
The shot-noise for the Advanced Virgo quadrants can be computed as:

$$\widehat{P}_{shot} = \sqrt{2h_p\nu P} \quad W/\sqrt{Hz} \tag{1}$$

[1] It is important to notice that the control of the (-)-modes with the DC signals coming from the transmission of the Arm cavities is configuration independent, i.e. it is the same for the NDRC and the MSRC configuration

where h_p is the Planck's constant and ν is the frequency of the laser light and P is the impinging light power on the diode. Moreover supposing to have 50 mW quadrant diodes where only half power is impinging on the quadrant, for safety, for each quadrant element the shot-noise is about $4.8 \cdot 10^{-11}\ W/\sqrt{Hz}$ (which is not true for the dark fringe signal which has less impinging power, 2.5 mW and it will be computed separately).
Considering to have all the electronic noises much below the shot-noise an evaluation on the seismic noise requirements at the level of the diode can be done.
This evaluation becomes fundamental since in all the Advanced Virgo optical configuration, NDRC and MSRC, the DC signals of the quadrants placed in transmission of the arm cavity are used to control important angular d.o.f. as the arm cavity (-)-modes. The DC signal is directly affected by the seismic noise because it detects the relative position of the beam with respect to the diode.

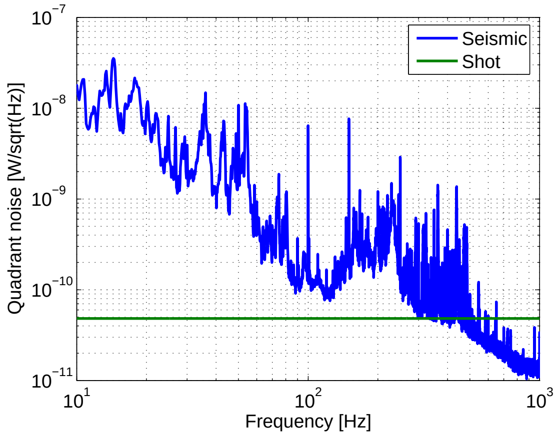

Figure 2: Seismic and Shot noise for one of the Virgo quadrant diode placed on the WE external detection bench.

In this section the requirements for the detection bench vertical and horizontal displacements are computed in the frequency band where the sensing noise is limiting, i.e. above 10 Hz. The analysis is computed by starting from the measured DC signals noise spectra of the quadrant which is actually at the WE bench (q81 quadrant). As it is shown in Figure 2 the sensing noise of the first quadrant element DC signal for the Q81 diode is presently completely dominated by the displacement of the bench, which in this section is called seismic noise [2].

[2] The seismic noise naming means the bench displacement due to the ground seismic noise, of course since the quadrant diodes are placed on a normal optical table the bench displacement is much larger with respect to the ground seismic noise.

2.1.1 Sensing noise requirements evaluation

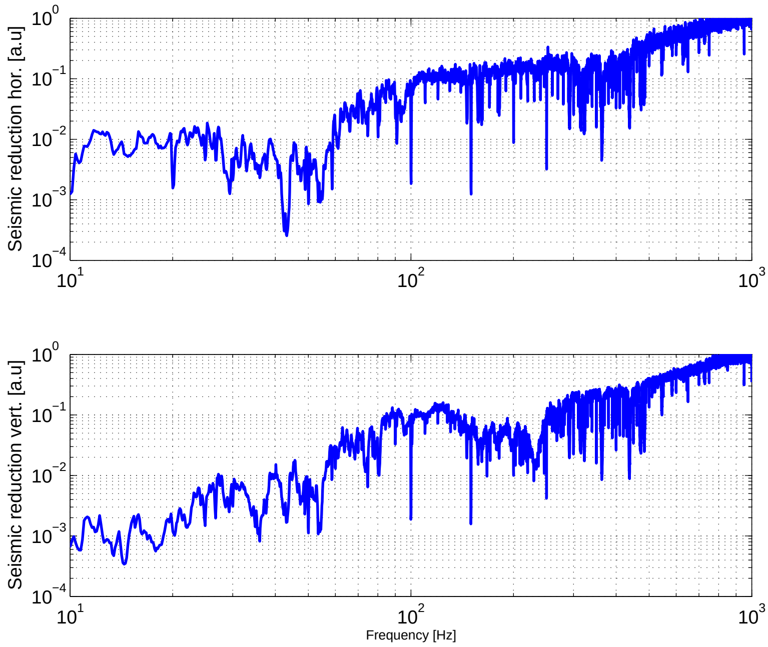

Figure 3: Detection bench seismic noise reduction needed in order to have the seismic noise below the shot noise of a factor 4.

In order to set the requirements for the seismic isolation of the quadrant the present bench displacement effect on the quadrant DC signals has to be evaluated.
It can be done by translating the vertical and horizontal displacements into $W/\sqrt{Hz}$, to be compared with the diode shot-noise level and to be independent from the sensing electronics which is still unknown, and evaluate the seismic noise reduction needed to have the seismic noise four times below the shot noise.
This can be easily done since the present sensing electronics is well known.
From Figure 3 it is clear that the seismic motion at the level of the detection bench has to be reduced of about a factor 100 for the horizontal direction and of about a factor 1000 for the vertical direction at 10 Hz with respect to the present one.

2.1.2 Sensing noise conclusions

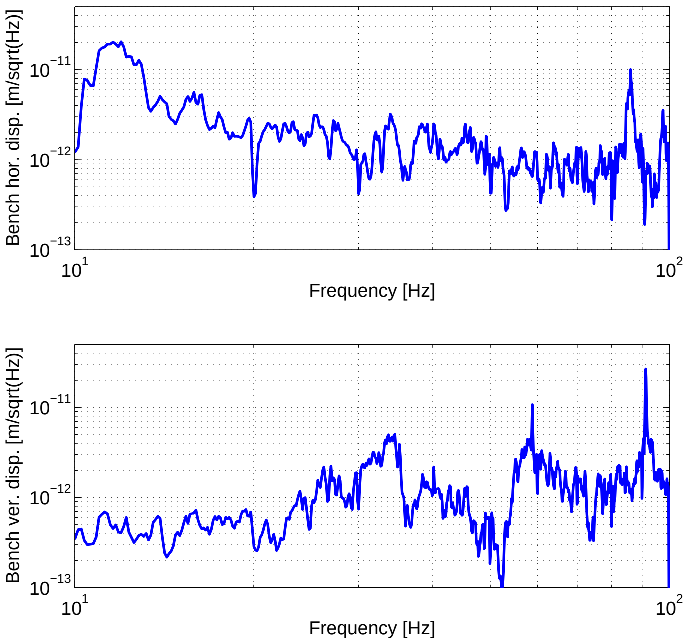

Figure 4: Detection bench displacement requirements to have the seismic noise 4 times lower than the shot noise to do not spoil the error signals .

By using the accelerometer spectra is possible to evaluate the maximum allowed displacement for the vertical and horizontal directions. The requirements for the displacement are shown in Figure 4 and it less than 10^{-12} at 10 Hz for the vertical direction and about 10^{-11}-10^{-12} for the horizontal direction.

2.2 Spectral density requirements

In order to evaluate the whole spectral density requirements the amplitude of the AA error signals on the terminal benches have been evaluated with *Optickle* [3], see the Virgo note [1], for the 25 W and 125 W configurations. The amplitude is ∼ 2.9 W/mrad for 25 W and ∼ 3.8 W/mrad for 125 W of input power, thus in order to be conservative the 25 W configuration has been taken into account.
Considering the present Super-Attenuator performances and considering the terminal quadrant sensing noise limited only by shot noise, with an impinging power of 25 mW, the quadrant DC signal can be extrapolated as:

$$sig_{DC} = \sqrt{(\theta_{mirr} * M_{w/rad})^2 + n_{shot}^2} \qquad (2)$$

where sig_{DC} is the QD signal amplitude, in $W/\sqrt{Hz}$, θ_{mirr} is the angular displacement of the mirror in $rad/\sqrt{Hz}$, the $M_{w/rad}$ is the simulated sensing matrix element and n_{shot} is the shot noise.

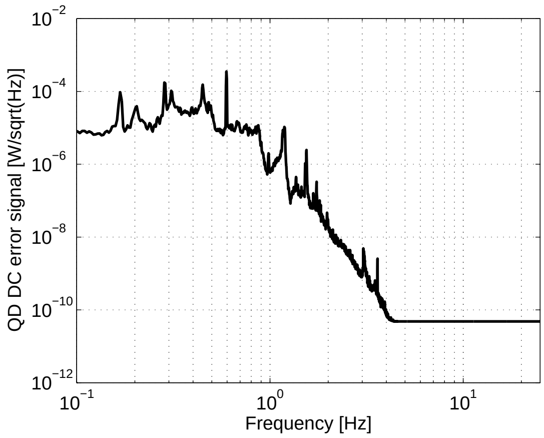

Figure 5: Extrapolated quadrant DC signal.

The requirement have been set, by using the TF between the quadrant signal and the quadrant displacement obtained in the previous analysis which has been considered frequency independent below the Front-End cut off (∼125 Hz), in order to be a factor 10 below the AA error signal in the loop bandwidth and a factor 4 below the sensing noise, as it has been done in the previous section.

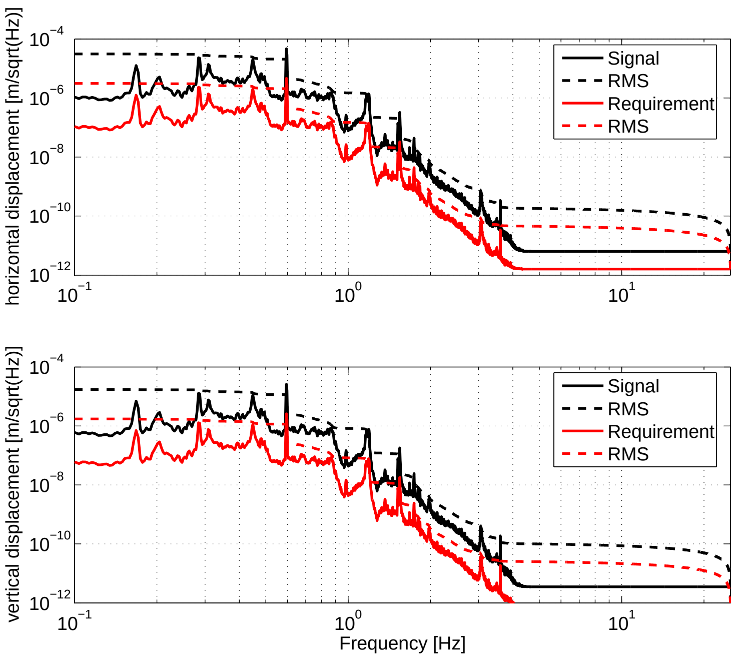

Figure 6: Black curves are the expected error signal amplitude converted in quadrant horizontal and vertical displacement, top and bottom plots, while the requirement spectra for the quadrant displacement are the red curves.

Moreover the spectral density requirement, see Figure 6, gives a requirement on the residual motion [RMS] of about:

2.1e-06 m for the horizontal direction

1.6e-06 m for the vertical direction

2.3 Dark fringe quadrant suspension requirements

As it has been mentioned before on the dark fringe quadrant 2.5 mW of beam power is impinging, a factor ten less than the other diodes, it implies that the suspension requirements for the high frequency part, where the diode sensing has to be limited by shot noise, have to be a factor $\sqrt{10}$ more stringent with respect to the other diodes.
This is not irrelevant since the DC signals from the AP diodes will be used to control the SR mirror.
The RMS suspension requirements can be then calculated as before taking into account the TF between the SR mirror and the AP DC signal, which is about 0.34 W/mrad, and it gives approximately a requirement ten times more stringent as:

	Horizontal direction	Vertical Direction
RMS	2.5e-7 m	1.9e-7 m
sensing noise	6.3e-13 m/$\sqrt{Hz}$	2.5e-13 m/$\sqrt{Hz}$

Table 1: Asymmetric port external bench displacement requirements.

2.4 External detection benches suspension requirements conclusions

The requirements for the bench displacements have been set in order to have the seismic noise ten times below the AA error signal in the loop frequency bandwidth and four times below the sensing noise.
The requirements are then:

	Horizontal direction	Vertical Direction
RMS	2.1e-6 m	1.6e-6 m
sensing noise	2e-12 m/$\sqrt{Hz}$	8e-13 m/$\sqrt{Hz}$
AP	Horizontal direction	Vertical Direction
RMS	2.5e-7 m	1.9e-7 m
sensing noise	6.3e-13 m/$\sqrt{Hz}$	2.5e-13 m/$\sqrt{Hz}$

Table 2: External bench displacement requirements.

3 Compensation plate tilt requirement

The Compensation Plate, which is suspended on IMX back, can create a cavity which would affect the Automatic Alignment error signals. In order to set the requirements the double cavity, CP IMX and EMX, has been simulated with *Finesse* [4] in order to evaluate the effect of the CP misalignment on the cavity alignment error signals. The optical parameters used for the CP simulation are the ones shown in the Virgo presentation VIR-0183B-11, i.e. 100ppm of reflectivity...

3.1 Effect of CP misalignment on the cavity alignment error signals

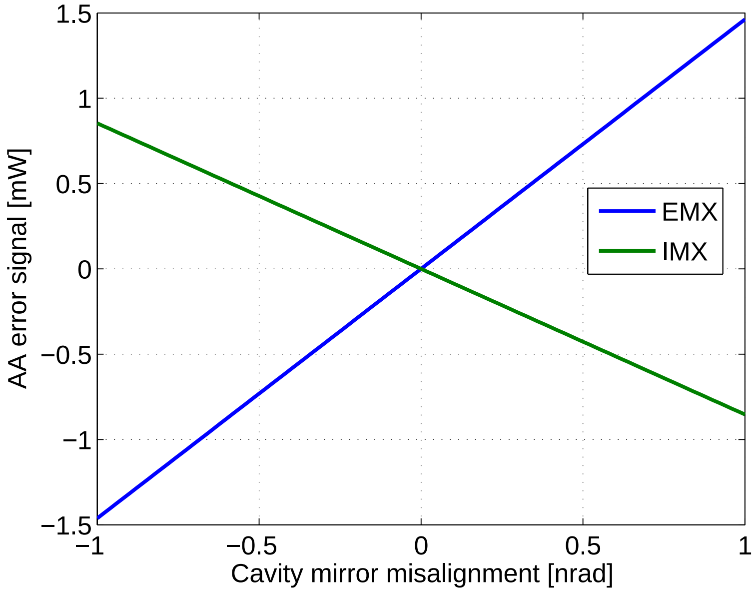

Figure 7: Alignment error signals as a function of the IMX and EMX misalignment.

In order to evaluate the effect of the Compensation plate tilt on the alignment error signals it is important to calibrate them in cavity mirror misalignment to estimate the amplitude of the effect. From Figure 10 the calibrations are:

- 1.46e6 W/rad for EMX
- 8.5e5 W/rad for IMX

Thus it is possible to evaluate the equivalent cavity mirror angular displacement as a function of the CP tilt.

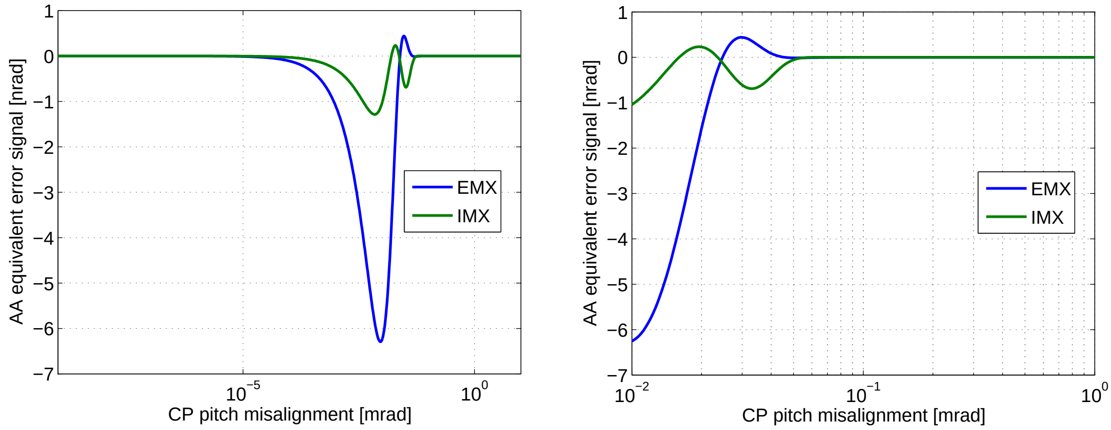

Figure 8: Effect of the CP tilt on the alignment error signals. The CP does not affect anymore the Automatic alignment error signals for tilt of the order of 100 μrad.

As it is shown in Figure 8, the effect of the CP misalignment in the region 0 to 100 μrad is not negligible since it produces an equivalent cavity mirror misalignment of some nrad, up to 6 nrad, which is larger than the angular requirement of 2 nrad, see Virgo note [1]. In order to have the CP plate not interfering with the AA sensing it has to be tilted more than $\sim$ 100 μrad, see Figure 8, which is coherent with the divergence angle of 35 μrad. In the previous computation, done in 2008 [5], the requirement was 1 mrad, 10 time higher than the present results, this discrepancy is due to different cavity design but mostly due to the safety factor chosen.
In this computation a factor 5 of safety factor has been chosen, i.e. a CP tilt 5 time larger with respect the one that gives 2 nrad of equivalent misalignment, while for the old computation a safety factor of $\sim$ 25 had been chosen since it was only a rough evaluation.

3.2 Mode convergence

Since finesse is a modal code it is important to evaluate the results convergence thus it has been simulated the effect of the CP misalignment for increasing number of modes, it has to be considered that for the simulation results shown before the max TEM used in finesse is 6.

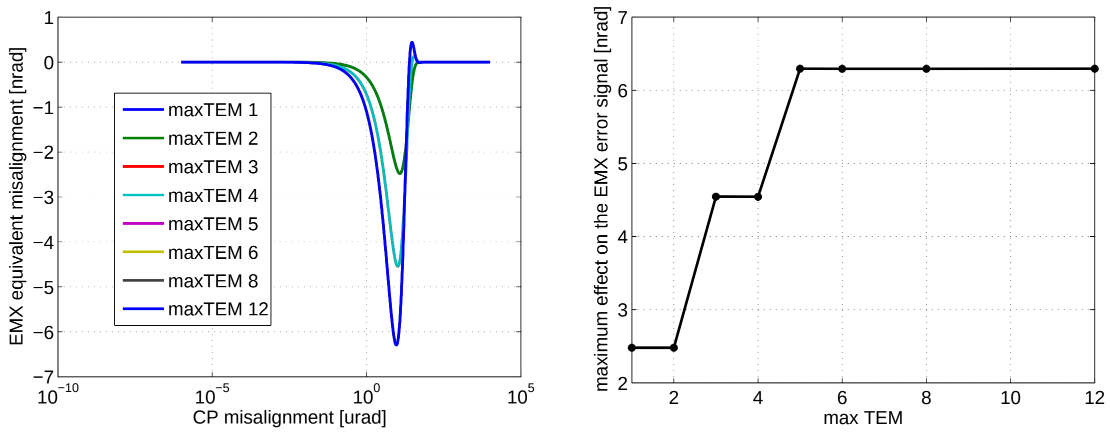

Figure 9: Effect of the CP misalignment on the AA EMX error signal on the left plot. The results obtained with low max TEM are slightly different with respect to the others. On the right is plotted the maximum effect amplitude as a function of the numbers of TEM used. The system converges for max TEM bigger than 5.

As it is shown in Figure 9 the system converge for max TEM bigger than 5, thus the results shown in the previous section, where max TEM 6 have been used, are reliable.

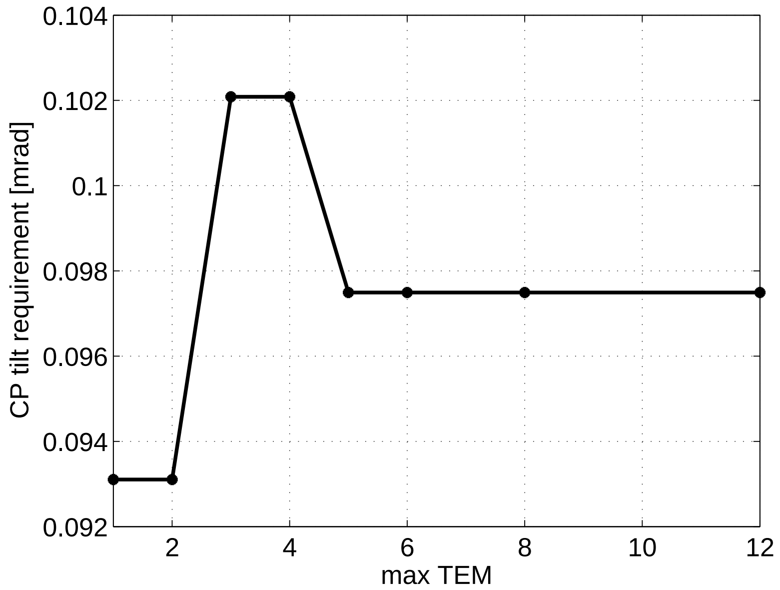

Figure 10: CP tilt requirement, considering a safety factor of 5, as a function of the max TEM used in the simulation. The requirement converges to $\sim 100\ \mu$rad.

4 Central area pick-off beams

In the MSRC design one of the most critical aspects is the pick-off extractions in the central area. It is important then to define which are the pick-off beams to be used for control. In this section the use of the pick-off beams for the angular control is described.

4.1 Pick-off beam

In the Andvanced Virgo Angular control design for MSRC configuration [1], only one pick-off signal is used for the angular control (the POY signal demodulated a the fm2 to control the BS mirror).
In order to evaluate if other pick-off beams could be used for the BS control the complete interferometer, in SRC configuration, has been modeled with *Optickle* in low power regime, with 25 W of input power, and in high power regime, with 125 W of input power, on each diode 25 mW of beam power is impinging.
Thus the error signal for the BS mirror can be simulated by using three different diodes:

- POY - the IMY pick-off beam
- POX - the IMX pick-off beam
- POPR - the pick-off of the pick-off plate in front of the PR mirror (400ppm)

For each signal the Gouy and demodulation phases have been tuned in the usual way (to maximize the BS content in the error signal with respect to the other d.o.f.).

Input Power	diode	D+	D-	C+	C-	PRM	SRM	BS
25 W								
	POY $\phi_G = 75$, $\phi_{dem} = 50$	1.019	**3.917**	-0.678	-2.606	**6.523**	0.071	**11.408**
	POX $\phi_G = 84$, $\phi_{dem} = 57$	1.066	**4.172**	-0.412	-1.609	**4.001**	0.027	**10.086**
	POPR $\phi_G = 77$, $\phi_{dem} = 9$	-0.8976	**-3.4096**	0.6670	2.1579	**-4.9766**	0.0524	**-9.8451**
125 W								
	POY $\phi_G = 72$, $\phi_{dem} = 65$	0.297	**5.629**	-0.207	-2.962	**5.243**	0.026	**10.786**
	POX $\phi_G = 87$, $\phi_{dem} = 90$	0.271	**5.138**	-0.232	-2.987	**5.096**	-0.007	**10.339**
	POPR $\phi_G = 80$, $\phi_{dem} = 0$	-0.285	**-5.176**	0.242	3.179	**-5.450**	0.023	**-10.710**

Table 3: BS error signal with three different diodes. The error signal is almost equivalent for all the three configuration. All of them are demodulated at fm2.

4.2 Central area pick-off conclusions

The BS error signal has been simulated for the 3 pick-off and from Table 3 it is clear that these three are almost equivalent.

5 Conclusions

In this note three different aspects have been described:

5.1 EDB suspension requirements

The quadrant diodes for Advanced Virgo have to be suspended in vacuum in order to reduce the environmental noises which affect the signal. This fact in mostly important for the quadrant placed in transmission to the long arm cavities since the DC signals of that quadrants will be used to control important and sensitive d.o.f. as the long arm cavity (-)-modes and the SR mirror, which is less critical for control noise issues.
The requirements have been set on the quadrant horizontal and vertical displacement starting from the present benches and they are:

	Horizontal direction	Vertical Direction
RMS	2.1e-6 m	1.6e-6 m
sensing noise	2e-12 m/$\sqrt{Hz}$	8e-13 m/$\sqrt{Hz}$
AP	Horizontal direction	Vertical Direction
RMS	2.5e-7 m	1.9e-7 m
sensing noise	6.3e-13 m/$\sqrt{Hz}$	2.5e-13 m/$\sqrt{Hz}$

Table 4: External bench displacement requirements.

The requirements seems to be achievable but DET has to evaluate it.

5.2 CP tilt requirement

The CP tilt requirement has been set in order to do not disturb the Automatic Alignment error signals and it will be transparent for the AA system if it will be misaligned enough to do no create a spurious cavity (larger than the divergence angle which is 35 μrad).
It has been verified also by simulating CP misalignment effect on the angular error signals with finesse and a minimum misalignment requirement of 100 μrad has been set.

5.3 Pick-off beams in the central area

In order to understand which pick-off can be used for the Angular control in the central area, to control the BS mirror, three different pick-off beams have been simulated in the SRC configuration in the low power and high power regime.
The two pick-off from the IMX and IMY AR coating, POX and POY respectively, and the pick-off beam extracted from the pick-off plate in front of the PR, POPR, give equivalent informations thus any of them can be chosen for angular control.

6 Acknowledgements

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References

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