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Specifications for longitudinal and quadrant photodiodes: Version 1

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Contents

1 Introduction

In this note, we present specifications for the photodiodes and quadrants of the DET sub-system based on the powers expected on the sensors. These specifications can be used as first basis for the design of the photodiode electronics.

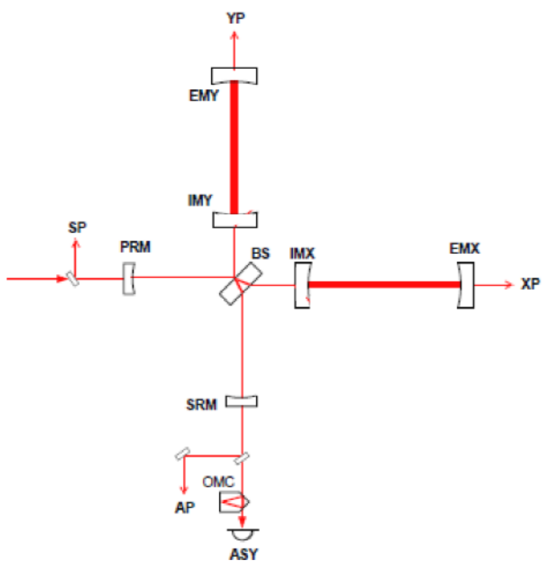

Figure 1: Beams in Advanced Virgo.

2 Beams and photodiodes inventory in Advanced Virgo

The naming convention for the beams is explained below and illustrated in Fig.1. Names in parenthesis refers to the corresponding Virgo beams:

- ASY (B1): This refers to the beam transmitted by the second Output Mode Cleaner at the Anti Symmetric Port. The DC channels of the ASY photodiodes will provide the gravitational wave channel.
- AP (B1p): This refers to a pick-off of the Anti Symmetric Port before the beam passes through the Output Mode Cleaner.
- OMCR1 (B1s): This is the beam reflected by the first Output Mode Cleaner.
- OMCR2: This is the beam reflected by the second Output Mode Cleaner.

- PO: This is the pick-off beam extracted inside the power recycling cavity with the PR plate.
- B5: As in Virgo this is the beam created by the reflection on the AR coating of the BS. This beam will be extracted at the level of the first suspended detection bench and sent on DC quadrants to provide error signals for the OMC alignment. We shall foresee the possible extraction of secondary beams coming from spurious reflections on the CPs surfaces, but this is not yet included in the baseline.
- SP (B2): This refers to the Symmetric Port (reflection from the interferometer towards the laser lab).
- XP (B7): This refers to the beam transmitted by the North End mirror.
- YP (B8): This refers to the beam transmitted by the West End mirror.

The list of requested photodiodes is presented in Table 1. The baseline is to have two longitudinal and two quadrant photodiodes on AP, PO, SP, XP and YP. On the ASY beam, 2 longitudinal photodiodes will be used at nominal power to extract the DC signal, while one extra photodiode is foreseen for the readout of the demodulated signals for monitoring purposes only. An extra longitudinal photodiode is also foreseen on the Symmetric Port to be used at high power during the lock acquisition. For the sake of completeness Table 1 includes 2 OMC quadrants that will extract a small fraction of the Anti Symmetric Port before the Output Mode Cleaner and will be used to align the beam on the OMC.
As shown in Table 1 the standard beam size at the level of the sensors will range between 300 and 400μm.

3 Set of demodulation signals

The list of modulation frequencies proposed by ISC [3] is reported in Table 2.

The list of frequency components (DC signals or demodulated signals) to be extracted for each longitudinal photodiodes is presented in Table 3. Two different sublists are provided: the list of signals potentially used in science mode with low noise requirements, and a list of complementary signals used only during the lock acquisition or for monitoring purposes without stringent noise constraints.
The following considerations have been taken into account when filling Table 3:

- The double demodulation signals ($2f$) will be provided on most of the ports in order to monitor the power in the Side Bands. Extracting the double demodulation signals from one photodiode per port is sufficient.
- The f_3 demodulated signals will be provided only on the Symmetric Port as this side band does not resonate in the recycling cavity.

Port Name	Photodiodes	Beam size on the sensor	Comments
ASY (B1)	Longitudinal: $2+1$	$300-400\mu m$	2 photodiodes at nominal power, 1 photodiode for AC signals
AP (B1p)	Longitudinal: 2 Quadrant: 2	$300-400\mu m$ $300-400\mu m$	1 photodiode on S polarisation 1 photodiode on P polarisation
OMCR1 (B1s)	Longitudinal: 2	$300-400\mu m$	1 photodiode on S polarisation 1 photodiode on P polarisation
OMCR2	Longitudinal: 2	$300-400\mu m$	1 photodiode on S polarisation 1 photodiode on P polarisation
B5	Longitudinal: 2 Quadrant: 2	$300-400\mu m$ $300-400\mu m$	Used for OMC alignment
PO	Longitudinal: 2 Quadrant: 2	$300-400\mu m$ $300-400\mu m$	
SP (B2)	Longitudinal: $2+1$ Quadrant: 2	$300-400\mu m$ $300-400\mu m$	1 for lock acquisition
XP (B7)	Longitudinal: 2 Quadrant: 2	$300-400\mu m$ $300-400\mu m$	
YP (B8)	Longitudinal: 2 Quadrant: 2	$300-400\mu m$ $300-400\mu m$	
OMC quadrants (B1)	Quadrants: 2	$300-400\mu m$	Used for OMC alignment

Table 1: List of requested photodiodes for Advanced Virgo as in baseline.

f_1	f_2	f_3	f_4
6.27 MHz $[5-8MHz]$	56.44 MHz $[50-70MHz]$	8.36 MHz $[8-10MHz]$	131 MHz $[120-140MHz]$

Table 2: Proposed modulation frequencies in Advanced Virgo. The most probable values are given when known, and a range of possible values is also quoted. Recently the collaboration has started investigating a fourth modulation frequency f_4 that would be used for lock acquisition.

- Four ASY photodiodes will be delivering the DC signal at a nominal power of 20 mW per photodiode. As their electronic chain will be optimized for DC detection, it is anticipated to send a small fraction of the dark fringe beam (1 mW) to an extra photodiode monitoring the demodulated signals.

- An extra modulation frequency f_4 would be useful for lock acquisition. Its noise requirements will be relaxed by a factor 10 or so with respect to other side bands. But further investigations have to performed in order to verify which electronic performances are achievable at 131 MHz.

Port Name	Signals used in science mode	Signals for lock acquisition or monitoring
ASY	DC	f_2, $2f_1$, $2f_2$
AP	-	DC, f_1, f_2, $2f_1$, $2f_2$, f_4
B1s	-	DC, f_1, f_2, $2f_1$, $2f_2$
PO	f_1, f_2	DC, $2f_1$, $2f_2$, f_4
SP	f_1, f_2, f_3	DC, ($2f_1$, $2f_2$, $2f_3$)?, f_4
XP	-	DC, f_1
YP	-	DC, f_1

Table 3: List of signals to be extracted for the Longitudinal Photodiodes.

The list of frequency components (DC signals or demodulated signals) to be extracted for each quadrant is presented in Table 4. The $2f$ signals will be used as input for the driving of the galvanometers. For the end bench quadrants (XP and YP) it is anticipated that only the DC signals will be used in science mode while the demodulated signals at f_1 might be useful during lock acquisition. For the Anti Symmetric Port in the final Advanced Virgo configuration ($125W$ with SR) it is anticipated that one quadrant will provide the DC signal for SR drift control while the second quadrant will provide the f_2 demodulated signals involved in the full bandwidth Automatic Alignment [1].

Port Name	Signals used in science mode	Signals for monitoring or galvometer driving
AP	DC, f_1, f_2	$2f_2$
PO	f_1, f_2	DC, $2f_1$, $2f_2$
SP	f_1, f_2, f_3	DC, $2f_1$, $2f_2$, $2f_3$
XP	DC	f_1
YP	DC	f_1
OMC quadrants	-	DC

Table 4: List of signals to be extracted for the Quadrants.

4 Electronic specifications for the longitudinal photodiodes

The goal of this section is to set electronic specifications for the longitudinal photodiodes, for each of the following configurations:

- Advanced Virgo with 25 W of injected power and power recycling;

- Advanced Virgo with 25 W of injected power and dual recycling;
- Advanced Virgo with 125 W of injected power and power recycling;
- Advanced Virgo with 125 W of injected power and dual recycling.

An estimation of the expected DC and AC powers will be presented in each scenario, and noise specifications will be derived.

4.1 Advanced Virgo with 125 W of injected power and dual recycling

4.1.1 DC and 2f powers

Specifications on DC powers for the longitudinal photodiodes are presented in Table 5. Whenever possible the nominal DC power on each longitudinal photodiode will be set to $50mW$ (which corresponds to half of the maximum power that a photodiode can stand) and two photodiodes will be placed on the path of each beam. Thus the total amount of power that will be sensed is $100mW$ per beam. However there are several exceptions as shown in Table 5:

- The total amount of power expected on the dark fringe after the OMC is about $80mW$. In order to minimize the readout noise of the ASY photodiodes, 2 photodiodes will be placed on the path of the ASY beam. Each of them will receive about $40mW$ of nominal power.
- An extra photodiode receiving about $1mW$ will be placed at the ASY port to monitor the side bands frequencies.
- For what concerns the dark fringe beam before the OMC (AP, B1p), only $2.5mW$ will be sent on each phototiode.
- An extra photodiode will be placed at the Symmetric Port to be used during the lock acquisition only. This photodiode will receive about $50mW$ during lock acquisition and less than $5mW$ during science mode.

Powers expected in the side bands (obtained after demodulating at twice the modulation frequencies) are also indicated in Table 5. The powers at the pick-off and at the symmetric ports have been deduced from an Optickle simulation of Advanced Virgo provided by [4] assuming $125W$ of injected power and modulation indexes equal to 0.1. For what concerns the dark fringe beams, the situation is a bit more tricky as powers depend strongly on the amount of High Order Modes that will be transmitted at the dark port and this is more difficult to predict. Some assumptions on the powers at the dark fringe are presented in Table 6. These assumptions have been used to estimate the powers expected on the ASY, AP, and B1s photodiodes.

Port Name	Photod. Num.	Signals	Nominal and Maximum powers
ASY	2	DC	$P_{nom} = 40mW$ / $P_{max} = 100mW$
	1	DC	$P_{nom} = 1mW$ / $P_{max} = 2.5mW$
		$2f_1$	$P_{nom} = 3 \times 10^{-3}mW$
		$2f_2$	$P_{nom} = 3 \times 10^{-3}mW$
AP	2	DC	$P_{nom} = 2.5mW$ / $P_{max} = 5mW$
		$2f_1$	$P_{nom} = 0.05mW$
		$2f_2$	$P_{nom} = 0.8mW$
B1s	2	DC	$P_{nom} = 50mW$ / $P_{max} = 100mW$
		$2f_1$	$P_{nom} = 1.1mW$
		$2f_2$	$P_{nom} = 17mW$
PO	2	DC	$P_{nom} = 50mW$ / $P_{max} = 100mW$
		$2f_1$	$P_{nom} = 0.5mW$
		$2f_2$	$P_{nom} = 0.4mW$
SP	2(+1)	DC	$P_{nom} = 50mW$ / $P_{max} = 100mW$
		$2f_1$	$P_{nom} = 1.1mW$
		$2f_2$	$P_{nom} = 0.8mW$
		$2f_3$	$P_{nom} = 1.1mW$
XP	2	DC	$P_{nom} = 50mW$ / $P_{max} = 100mW$
YP	2	DC	$P_{nom} = 50mW$ / $P_{max} = 100mW$

Table 5: Expected DC/2f powers on the longitudinal photodiodes.

	Carrier	SB at $6.27MHz$	SB at $56.44MHz$
$TEM00$	80 mW	2.5 mW	160 mW
Alignment HOMs	200 mW	6.2 mW	60 mW
Laguerre Gauss HOMs	500 mW	16 mW	160 mW

Table 6: Assumptions about the power at the dark fringe for $TEM00$ and High Order Modes.

4.1.2 AC powers

In order to characterize the expected AC powers in Advanced Virgo, the following parameters will be estimated:

- $P_{pp,nom}$: Nominal peak to peak amplitude of the demodulated signals in Watts
- $P_{pp,max}$: Maximum peak to peak amplitude of the demodulated signals in Watts
- P_{max}: Maximum absolute power (if offset is not zero)

Port Name	Signals	Powers measured during VSR4
B1p	DC	SM: $P_{nom} = 4\ mW$ ($0.02mW$ on carrier $TEM00$)
	$2f_1$	SM: $P_{nom} = 0.4\ mW$
	f_1	SM: $P_{pp,nom} = 0.1mW$ / $P_{pp,max} = 0.3mW$ / $P_{max} = 1mW$ LA: $P_{pp,nom} = 0.1mW$ / $P_{pp,max} = 1mW$ / $P_{max} = 2mW$ Maximum at unlock: $P_{max} = 10mW$
B5	DC	SM: $P_{nom} = 36\ mW$
	$2f_1$	SM: $P_{nom} = 1.6\ mW$
	f_1	SM: $P_{pp,nom} = 0.001mW$ / $P_{pp,max} = 0.1mW$ / $P_{max} = 0.1mW$ LA (above step 5): $P_{pp,nom} = 0.2mW$ / $P_{pp,max} = 0.5mW$ / $P_{max} = 2mW$ Maximum at unlock: $P_{max} = 5mW$
B2	DC	SM: $P_{nom} = 10\ mW$ LA: From $90mW$ (step 2) to $10mW$ (above step 5.5)
	f_1	SM: $P_{pp,nom} = 0.003mW$ / $P_{pp,max} = 0.01mW$ / $P_{max} = 0.04mW$ LA (above step 5): $P_{pp,nom} = 0.05mW$ / $P_{pp,max} = 0.2mW$ / $P_{max} = 0.2mW$ Maximum at unlock: $P_{max} = 5mW$
	f_3	SM: $P_{pp,nom} = 0.001mW$ / $P_{pp,max} = 0.004mW$ / $P_{max} = 0.002mW$ LA: $P_{pp,nom} = 0.001mW$ / $P_{pp,max} = 0.004mW$ / $P_{max} = 0.01mW$ Maximum at unlock: $P_{max} = 0.04mW$

Table 7: Typical powers measured on longitudinal photodiodes with Virgo+. Initials SM stands for Science Mode and LA for Lock Acquisition.

Estimation with Virgo+ AC powers

A first estimation have been made by measuring the typical AC powers in VSR4 both during science mode or lock acquisition. These AC powers are reported in Table 7.
In order to extrapolate the AC powers measured with Virgo+ to the expected powers with Advanced Virgo, one has to rescale them according to the DC powers in the carrier and the side bands. A general formula to evaluate the AC power in Advanced Virgo $P_{AC}(AdV)$ from the measured AC power in Virgo+ $P_{AC}(V)$ is given by:

$$P_{AC}(AdV) = P_{AC}(V) \times \sqrt{\frac{P_{car}(AdV)}{P_{car}(V)}} \times \sqrt{\frac{P_{sb}(AdV)}{P_{sb}(V)}} \quad (1)$$

where P_{car} and P_{sb} refers to the DC powers in the carrier and side bands for Virgo or Advanced Virgo. The corresponding values can be found in Table 7, Table 5 and Table 6.
The previous formula has been applied to $B1p$ (ASY) and B5 (PO) to estimate the expected AC powers in Advanced Virgo. The AC powers at the end mirror transmission (EX, EY) have been deduced from the B5 powers. The B1s AC powers have been obtained by multiplying the

B1p powers by a factor 20 (DC ratio).
For what concerns the symmetric port (B2), no precise measurement of the power in the side bands was available for VSR4, thus the AC signals have simply been rescaled according to the total DC power (×5).
The estimated powers for Advanced Virgo are reported in Table 8.

Port Name	#N	Signals	Nominal and Maximum Powers
ASY	2	DC	$P_{nom} = 40mW$
	1	DC	$P_{nom} = 1mW$
		$2f_1$, $2f_2$	$P_{nom} = 3 \times 10^{-3} mW$
		f_1	SM: $P_{pp,nom} = 0.04mW$ / $P_{pp,max} = 0.1mW$ / $P_{max} = 0.4mW$ LA: $P_{pp,nom} = 0.04mW$ / $P_{pp,max} = 0.4mW$ / $P_{max} = 0.5mW$
		f_2	SM: $P_{pp,nom} = 0.07mW$ / $P_{pp,max} = 0.2mW$ / $P_{max} = 0.7mW$ LA: $P_{pp,nom} = 0.07mW$ / $P_{pp,max} = 0.7mW$ / $P_{max} = 1mW$
AP	2	DC	$P_{nom} = 2.5mW$
		$2f_1$	$P_{nom} = 0.05\ mW$
		$2f_2$	$P_{nom} = 0.8\ mW$
		f_1	SM: $P_{pp,nom} = 0.08mW$ / $P_{pp,max} = 0.2mW$ / $P_{max} = 0.8mW$ LA: $P_{pp,nom} = 0.08mW$ / $P_{pp,max} = 0.8mW$ / $P_{max} = 1mW$ Maximum at unlock: $P_{max} = 8mW$
		f_2	SM: $P_{pp,nom} = 0.3mW$ / $P_{pp,max} = 0.9mW$ / $P_{max} = 3mW$ LA: $P_{pp,nom} = 0.3mW$ / $P_{pp,max} = 3mW$ / $P_{max} = 5mW$ Maximum at unlock: $P_{max} = 30mW$
B1s	2	DC	$P_{nom} = 50mW$
		$2f_1$	$P_{nom} = 1.1mW$
		$2f_2$	$P_{nom} = 17mW$
		f_1	SM: $P_{pp,nom} = 1.6mW$ / $P_{pp,max} = 4mW$ LA: $P_{pp,nom} = 1.6mW$ / $P_{pp,max} = 16mW$
		f_2	SM: $P_{pp,nom} = 6mW$ / $P_{pp,max} = 18mW$ LA: $P_{pp,nom} = 6mW$ / $P_{pp,max} = 60mW$
PO	2	DC	SM: $P_{nom} = 50mW$ LA: From $1mW$ to $50mW$
		$2f_1$	SM: $P_{nom} = 0.5mW$ LA: From $0.01mW$ to $0.5mW$
		$2f_2$	SM: $P_{nom} = 0.4\ mW$ LA: From $0.01mW$ to $0.4mW$

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Port Name	#N	Signals	Nominal and Maximum Powers
		f_1	SM: $P_{pp,nom} = 0.0007mW$ / $P_{pp,max} = 0.07mW$ / $P_{max} = 0.07mW$ LA: $P_{pp,nom} = 0.2mW$ / $P_{pp,max} = 0.4mW$ / $P_{max} = 1.4mW$ Maximum at unlock: $P_{max} = 3.5mW$
		f_2	SM: $P_{pp,nom} = 0.0006mW$ / $P_{pp,max} = 0.06mW$ / $P_{max} = 0.06mW$ LA: $P_{pp,nom} = 0.1mW$ / $P_{pp,max} = 0.3mW$ / $P_{max} = 1.2mW$ Maximum at unlock: $P_{max} = 3mW$
XP/YP	4	DC	$P_{nom} = 50mW$
		f_1	SM: $P_{pp,nom} = 3 \times 10^{-6}mW$ / $P_{pp,max} = 3 \times 10^{-4}mW$ $P_{max} = 3 \times 10^{-4}mW$ LA (PRCL locked): $P_{pp,nom} = 7 \times 10^{-4}mW$ / $P_{pp,max} = 0.0015mW$ / $P_{max} = 0.005mW$ With PRCL unlocked: need amplification $\times 5$
SP	2(+1)	DC	$P_{nom} = 50mW$
		$2f_1$	$P_{nom} = 1.1mW$
		$2f_2$	$P_{nom} = 0.8mW$
		$2f_3$	$P_{nom} = 1.1mW$
		f_1, f_2	SM: $P_{pp,nom} = 0.015mW$ / $P_{pp,max} = 0.05mW$ / $P_{max} = 0.2mW$ LA (PRCL locked): $P_{pp,nom} = 0.25mW$ / $P_{pp,max} = 1.0mW$ / $P_{max} = 1.0mW$
		f_3	SM: $P_{pp,nom} = 0.005mW$ / $P_{pp,max} = 0.02mW$ / $P_{max} = 0.01mW$ LA (PRCL locked): $P_{pp,nom} = 0.005mW$ / $P_{pp,max} = 0.02mW$ / $P_{max} = 0.05mW$

Table 8: Estimated power on longitudinal photodiodes for Advanced Virgo, $125W$, with Dual Recycling - Version 1.

Estimation with Optickle simulation

In order to increase our confidence in the previous estimations of photodiode AC powers, an independent cross check has been performed by using the results of an Optickle simulation reported in [3]. In this simulation the sensing matrix for the longitudinal control has been calculated. This sensing matrix can be used to translate the expected residual mirror motions into photodiode AC signals.

Nominal displacements correspond to the residual mirror motions reached in Virgo, except for DARM for which the smallest displacements that can be measured with $SNR \approx 7$ given the expected shot noise are of the order of $5 \times 10^{14}m$. Maximum displacements in science mode are based on the requirements given for each degree of freedom in [3] multiplied by a margin factor of 10 (to allow the possibility for injecting large signals). The sensing matrix obtained in simulation for Advanced Virgo, $125W$, with dual recycling, is shown in Table 10. This matrix can be used to convert the mirror displacements reported in Table 9 into the corresponding AC signals during science mode. The results are shown in Table 11.

DoF	Nominal displacements	Maximum displacements
DARM	$5 \times 10^{-14} m$	$6 \times 10^{-12} m$
MICH	$3 \times 10^{-11} m$	$2 \times 10^{-9} m$
PRCL	$5 \times 10^{-12} m$	$2 \times 10^{-10} m$
SRCL	$3 \times 10^{-12} m$	$3 \times 10^{-10} m$
CARM	$7mHz$	$70mHz$

Table 9: Requirements on residual longitudinal displacements in science mode.

DoF	Channel	Optical Gain
DARM	ASY DC	4.65×10^3 W/m
MICH	SP f_1	1.756×10^4 W/m
PRCL	SP f_1	1.951×10^7 W/m
SRCL	PO f_2	8.1684×10^4 W/m
CARM	SP f_3	4.9×10^{-5} W/Hz

Table 10: Longitudinal Sensing Matrix (at 0 Hz) for Advanced Virgo with 125 W and Dual Recycling. The numbers are based on the assumption of 100 mW per beam, except on the Antisymmetric Port where 80 mW are expected. The column "channel" indicates the photodiode signals which are used for measuring each degree of freedom.

Table 11 also contains an estimation of the maximum peak to peak amplitudes during the lock acquisition. They have been obtained by assuming that the maximum AC signal to be measured in science mode corresponds to the line-width of the cavities.

For instance the line-width of the Power Recycling Cavity is $2 \times 10^{-9} m$. According to the sensing matrix shown in Table 10 this corresponds to a peak to peak AC signal of $40mW$ for an input power of $50mW$. This is the amount of signal to be expected on the extra SP photodiode that will be dedicated to lock acquisition.

The line-width of the Signal Recycling Cavity is $10^{-8} m$ which corresponds to a peak to peak amplitude on the PO photodiode of 0.8 mW.

The estimations shown in Table 11 have been merged with the previous power estimates shown in Table 8. In order to be conservative we will set specifications on the AC ranges that include the various estimated powers obtained from the two different methods. The final version of the estimated powers in the longitudinal photodiodes for Advanced Virgo with $125W$ and dual recycling is presented in Table 12. While in the previous tables the expected maximum peak to peak amplitudes ($P_{pp,max}$) were given for a nominal DC power, Table 12 shows the maximum peak to peak amplitudes when the DC power will reach the maximum allowed value (i.e. all $P_{pp,max}$ values have been multiplied by a factor 2, except for channels where a factor 10 margin had already been foreseen for injections).

Port Name	#N	Signals	Nominal and Maximum powers
PO	2	DC	SM: $P_{nom} = 50mW$
		f_2	SM: $P_{pp,nom} = 10^{-4}mW$ / $P_{pp,max} = 10^{-2}mW$ LA: $P_{pp,max} = 1mW$
SP	2(+1)	DC	$P_{nom} = 50mW$
		f_1ACp f_1ACq	SM: $P_{pp,nom} = 5 \times 10^{-2}mW$ / $P_{pp,max} = 2mW$ LA: $P_{pp,max} = 40mW$ SM: $P_{pp,nom} = 3 \times 10^{-4}mW$ / $P_{pp,max} = 2 \times 10^{-2}mW$
		f_3	SM: $P_{pp,nom} = 2 \times 10^{-4}mW$ / $P_{pp,max} = 2 \times 10^{-3}mW$ LA: $P_{pp,max} = 4mW$

Table 11: Photodiodes power estimated from the simulated sensing matrix.

Port Name	#N	Signals	Nominal and Maximum Powers
ASY	2	DC	$P_{nom} = 40mW$ / $P_{max} = 100mW$
	1	DC	$P_{nom} = 1mW$ / $P_{max} = 2.5mW$
		$2f_1$, $2f_2$	$P_{nom} = 3 \times 10^{-3}mW$ / $P_{max} = 7.5 \times 10^{-3}mW$
		f_1	SM: $P_{pp,nom} = 0.04mW$ / $P_{pp,max} = 1mW$ LA: $P_{pp,nom} = 0.04mW$ / $P_{pp,max} = 1.3mW$
		f_2	SM: $P_{pp,nom} = 0.07mW$ / $P_{pp,max} = 1.8mW$ LA: $P_{pp,nom} = 0.07mW$ / $P_{pp,max} = 2.5mW$
AP	2	DC	$P_{nom} = 2.5mW$ / $P_{max} = 5mW$
		$2f_1$	$P_{nom} = 0.05mW$ / $P_{max} = 0.1mW$
		$2f_2$	$P_{nom} = 0.8mW$ / $P_{max} = 1.6mW$
		f_1	SM: $P_{pp,nom} = 0.08mW$ / $P_{pp,max} = 1.6mW$ LA: $P_{pp,nom} = 0.08mW$ / $P_{pp,max} = 2mW$ Maximum at unlock: $P_{max} = 8mW$
		f_2	SM: $P_{pp,nom} = 0.3mW$ / $P_{pp,max} = 6mW$ LA: $P_{pp,nom} = 0.3mW$ / $P_{pp,max} = 10mW$ Maximum at unlock: $P_{max} = 30mW$
B1s	2	DC	$P_{nom} = 50mW$ / $P_{max} = 100mW$
		$2f_1$	$1.1mW$ / $P_{max} = 2.2mW$
		$2f_2$	$17mW$ / $P_{max} = 34mW$
		f_1	SM: $P_{pp,nom} = 1.6mW$ / $P_{pp,max} = 8mW$ LA: $P_{pp,nom} = 1.6mW$ / $P_{pp,max} = 32mW$
		f_2	SM: $P_{pp,nom} = 6mW$ / $P_{pp,max} = 36mW$ LA: $P_{pp,nom} = 6mW$ / $P_{pp,max} = 120mW$
PO	2	DC	SM: $P_{nom} = 50mW$ / $P_{max} = 100mW$ LA: From $1mW$ to $50mW$
		$2f_1$	SM: $P_{nom} = 0.5mW$ / $P_{max} = 1mW$ LA: From $0.01mW$ to $0.5mW$
		$2f_2$	SM: $P_{nom} = 0.4mW$ / $P_{max} = 0.8mW$ LA: From $0.01mW$ to $0.4mW$
		f_1	SM: $P_{pp,nom} = 7 \times 10^{-4}mW$ / $P_{pp,max} = 0.14mW$ LA: $P_{pp,nom} = 0.2mW$ / $P_{pp,max} = 2.8mW$ Maximum at unlock: $P_{max} = 3.5mW$
		f_2	SM: $P_{pp,nom} = 10^{-4}mW$ / $P_{pp,max} = 0.12mW$ LA: $P_{pp,nom} = 0.1mW$ / $P_{pp,max} = 2.4mW$ Maximum at unlock: $P_{max} = 3mW$
			Continue on the next page . . .

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Port Name	#N	Signals	Nominal and Maximum Powers
XP/YP	4	DC	$P_{nom} = 50mW$ / $P_{max} = 100mW$
		f_1	SM: $P_{pp,nom} = 3 \times 10^{-6}mW$ / $P_{pp,max} = 6 \times 10^{-4}mW$ LA (PRCL locked): $P_{pp,nom} = 7 \times 10^{-4}mW$ / $P_{pp,max} = 0.01mW$ With PRCL unlocked: need amplification ×5
SP	2(+1)	DC	$P_{nom} = 50mW$ / $P_{max} = 100mW$
		$2f_1$	$P_{nom} = 1.1mW$ / $P_{max} = 2.2mW$
		$2f_2$	$P_{nom} = 0.8mW$ / $P_{max} = 1.6mW$
		$2f_3$	$P_{nom} = 1.1mW$ / $P_{max} = 2.2mW$
		f_1, f_2	SM: $P_{pp,nom} = 3 \times 10^{-4}mW$ / $P_{pp,max} = 2mW$ LA: $P_{pp,nom} = 0.25mW$ / $P_{pp,max} = 80mW$
		f_3	SM: $P_{pp,nom} = 2 \times 10^{-4}mW$ / $P_{pp,max} = 0.02mW$ LA: $P_{pp,nom} = 0.005mW$ / $P_{pp,max} = 8mW$

Table 12: Estimated power on longitudinal photodiodes for Advanced Virgo, $125W$, with Dual Recycling - Version 2.

4.1.3 Requirements on photodiode electronics

The powers expected in the photodiodes which are shown in Table 12 have been translated into specifications for the photodiodes electronics. The powers have been converted into corresponding currents at the output of the photodiodes by considering the following assumptions:

- For DC readout photodiodes (ASY) a quantum efficiency of 95% is assumed, leading to a conversion factor from power to current $K = 0.814A/W$.
- For all the other photodiodes (for which demodulated signals are requested), a quantum efficiency of 88% is assumed, leading to a conversion factor from power to current $K = 0.754A/W$. The quantum efficiency of 88% corresponds to the best performances of the photodiodes selected for high frequency operations in [5].

The expected nominal and maximum currents (I_{nom} and I_{max}) for DC and $2f$ channels at the output of each photodiode are given in Table 13. The signal dynamics required for AC channels ($I_{pp,max}$) is also given for each modulation frequency in Table 13. Requirements on electronic noise per photodiode have also been set, following the logic explained below.

Noise requirements on DC readout photodiodes

The DC readout photodiodes (ASY) will provide the gravitational wave channel and therefore need stringent requirements on electronic noise. As it was done in Virgo, we will request the electronic noise per photodiode (EN) to be at least a factor 5 lower than the shot noise. The photodiode shot noise SN is given by:

$$SN = \sqrt{2eI_{nom}} \quad (2)$$

where the nominal current I_{nom} is of the order of $33mA$.

The requirement on the photodiode DC readout electronic noise can thus be written as:

$$EN \leq \frac{\sqrt{2eI_{nom}}}{5} \approx 2 \times 10^{-8} mA/\sqrt{Hz} \tag{3}$$

Noise requirements on Control photodiodes

We will be referring as "Control Photodiodes" to all the photodiodes involved in the mirrors longitudinal control or laser frequency stabilization during science mode, namely the pick-off and the symmetric port photodiodes. We will request that their electronic noise remains at the level of the nominal shot noise given by:

$$SN = \sqrt{2}\sqrt{2eI_{nom}} \tag{4}$$

where $I_{nom} = 38mA$ refers again to the nominal DC current. The additional $\sqrt{2}$ is due to the demodulation.

Thus the requirement on electronic noise for those photodiodes is given by:

$$EN \leq \sqrt{2}\sqrt{2eI_{nom}} \approx 1.5 \times 10^{-7} mA/\sqrt{Hz} \tag{5}$$

We also request the demodulation noise (induced by phase noise (PN) between the photodiode RF signal and the LO signal) to be equal or lower than the shot noise. The coupling of phase noise in a demodulated signal is proportionnal to the RMS of the other quadrature. In order to set requirements on the phase noise PN we have considered that the RMS of the demodulated signals would be given by the maximum peak to peak amplitude $P_{pp,max}$ expected in science mode. We used the values $P_{pp,max}$ reported in Table 12 and divided by 2 (because the requirements are set for a nominal DC power). We then computed the requirements on phase noise by using the following equation:

$$PN \leq \sqrt{2}\sqrt{2h\nu\frac{P_{nom}}{\eta}}\frac{1}{P_{pp,max}} \tag{6}$$

Noise requirements on Lock Acquisition or Monitoring photodiodes

Noise requirements for photodiodes which are not used in science mode (i.e those who provide only signals for lock acquisition or for monitoring purposes) can be relaxed. We have requested that the electronic noise and demodulation noise of these photodiodes to be a factor 10 below the minimum peak to peak signals (cf. $P_{pp,nom}$ in Table 12) that need to be measured. If this constraint ends up to be too hard to achieve, then these requirements could probably be relaxed by a factor 2 or 3.

Port Name	#N	Signals	Dynamics	Noise requirements
ASY	2	DC	$I_{nom} = 33mA$ / $I_{max} = 82mA$	$EN < 2 \times 10^{-8} mA/\sqrt{Hz}$
	1	DC	$I_{nom} = 0.8mA$ / $I_{max} = 1.9mA$	
		$2f_1$, $2f_2$	$I_{nom} = 2.3 \times 10^{-3} mA$ / $I_{max} = 4.6 \times 10^{-3} mA$	$EN < 2 \times 10^{-4} mA/\sqrt{Hz}$ $PN < 2 \times 10^{-4} rad/\sqrt{Hz}$
		f_1	$I_{pp,max} = 0.8mA$	$EN < 3 \times 10^{-3} mA/\sqrt{Hz}$ $PN < 4 \times 10^{-3} rad/\sqrt{Hz}$
		f_2	$I_{pp,max} = 1.6mA$	$EN < 5 \times 10^{-3} mA/\sqrt{Hz}$ $PN < 6 \times 10^{-3} rad/\sqrt{Hz}$
AP	2	DC	$I_{nom} = 1.9mA$ / $I_{max} = 3.8mA$	
		$2f_1$ $2f_1$	$I_{nom} = 0.04\ mA$ / $I_{max} = 0.08\ mA$	$EN < 4 \times 10^{-3} mA/\sqrt{Hz}$
		$2f_2$ $2f_2$	$I_{nom} = 0.6\ mA$ $I_{max} = 1.2\ mA$	$EN < 6 \times 10^{-2} mA/\sqrt{Hz}$
		f_1	$I_{pp,max} = 1.6mA$	$EN < 6 \times 10^{-3} mA/\sqrt{Hz}$ $PN < 8 \times 10^{-3} rad/\sqrt{Hz}$
		f_2	$I_{pp,max} = 8mA$	$EN < 2 \times 10^{-2} mA/\sqrt{Hz}$ $PN < 5 \times 10^{-3} rad/\sqrt{Hz}$
B1s	2	DC	$I_{nom} = 38mA$ / $I_{max} = 76mA$	
		$2f_1$	$I_{nom} = 0.8mA$ / $I_{max} = 1.6mA$	
		$2f_2$	$I_{nom} = 13mA$ / $I_{max} = 26mA$	
		f_1	$I_{pp,max} = 24mA$	$EN < 10^{-2} mA/\sqrt{Hz}$ $PN < 8 \times 10^{-4} rad/\sqrt{Hz}$
		f_2	$I_{pp,max} = 90mA$	$EN < 4 \times 10^{-1} mA/\sqrt{Hz}$ $PN < 9 \times 10^{-3} rad/\sqrt{Hz}$
PO	2	DC	$I_{nom} = 38mA$ / $I_{max} = 76mA$	
		$2f_1$	$I_{nom} = 0.4mA$ / $I_{max} = 0.8mA$	
		$2f_2$	$I_{nom} = 0.3mA$ / $I_{max} = 0.6mA$	
		f_1	$I_{pp,max} = 2.2mA$	$EN < 1.5 \times 10^{-7} mA/\sqrt{Hz}$ $PN < 2 \times 10^{-6} rad/\sqrt{Hz}$
		f_2	$I_{pp,max} = 2mA$	$EN < 1.5 \times 10^{-7} mA/\sqrt{Hz}$ $PN < 2 \times 10^{-6} rad/\sqrt{Hz}$
XP/YP	4	DC	$I_{nom} = 38mA$ / $I_{max} = 76mA$	
		f_1	$I_{pp,max} = 8 \times 10^{-3} mA$	$EN < 2 \times 10^{-6} mA/\sqrt{Hz}$ $PN < 8 \times 10^{-6} rad/\sqrt{Hz}$
SP	2	DC	$I_{nom} = 38mA$ / $I_{max} = 76mA$	

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Port Name	#N	Signals	Dynamics	Noise requirements
		$2f_1$	$I_{nom} = 0.8mA$ / $I_{max} = 1.6mA$	
		$2f_2$	$I_{nom} = 0.6mA$ / $I_{max} = 1.2mA$	
		$2f_3$	$I_{nom} = 0.8mA$ / $I_{max} = 1.6mA$	
		f_1, f_2	$I_{pp,max} = 3mA$	$EN < 1.5 \times 10^{-7} mA/\sqrt{Hz}$ $PN < 2 \times 10^{-7} rad/\sqrt{Hz}$
		f_3	$I_{pp,max} = 3 \times 10^{-2} mA$	$EN < 1.5 \times 10^{-7} mA/\sqrt{Hz}$ $PN < 10^{-5} rad/\sqrt{Hz}$
	1	DC	$I_{nom} = 38mA$ / $I_{max} = 76mA$	
		f_1, f_2	$I_{pp,max} = 60mA$	$EN < 2 \times 10^{-2} mA/\sqrt{Hz}$ $PN < 6 \times 10^{-4} rad/\sqrt{Hz}$
		f_3	$I_{pp,max} = 6mA$	$EN < 4 \times 10^{-4} mA/\sqrt{Hz}$ $PN < 10^{-4} rad/\sqrt{Hz}$

Table 13: Electronic specifications for longitudinal photodiodes for Advanced Virgo, $125W$, with Dual Recycling.

A more synthetic summary of the electronic specifications for the longitudinal photodiodes of Advanced Virgo with $125W$ and dual recycling is presented in Table 14. Five different groups of photodiodes have been considered:

- The DC readout photodiodes with the most stringent requirements for the electronic noise of the DC channels.
- The control photodiodes used in science mode for the longitudinal mirror controls with quite stringent noise requirements and large dynamics.
- The end bench photodiodes that will contain very low powers in the side bands. They will only be used for lock acquisition and monitoring.
- The dark fringe photodiodes (AP and ASY) that will be used for lock acquisition and monitoring only. Although they receive very low DC power, they will contain rather high AC signals.
- The SP and B1s photodiodes used for lock acquisition or monitoring. They will contain large AC signals, but noise specifications are relaxed.

Sensor family	#N	Signals	Dynamics	Noise requirements
DC readout	2	DC	$I_{max} = 82mA$	$EN < 2 \times 10^{-8} mA/\sqrt{Hz}$
Control photodiodes	4	DC	$I_{max} = 76mA$	
		f_1, f_2, f_3, f_4 $2f_1$, $2f_2$, $2f_3$	$I_{pp,max} = 4.4mA$	$EN < 1.5 \times 10^{-7} mA/\sqrt{Hz}$ $PN < 2 \times 10^{-7} rad/\sqrt{Hz}$
LA/Monitoring (Low AC power)	4	DC	$I_{max} = 76mA$	
		f_1, f_2 $2f_1$, $2f_2$	$I_{pp,max} = 1.6 \times 10^{-2} mA$	$EN < 2 \times 10^{-6} mA/\sqrt{Hz}$ $PN < 8 \times 10^{-6} rad/\sqrt{Hz}$
LA/Monitoring (Intermediate AC power)	3	DC	$I_{max} = 3.8mA$	
		f_1, f_2, f_4 $2f_1$, $2f_2$	$I_{pp,max} = 10mA$	$EN < 2 \times 10^{-4} mA/\sqrt{Hz}$ $PN < 2 \times 10^{-4} rad/\sqrt{Hz}$
LA/Monitoring (High AC power)	3	DC	$I_{max} = 76mA$	
		f_1, f_2, f_3, f_4 $2f_1$, $2f_2$, $2f_3$	$I_{pp,max} = 126mA$	$EN < 4 \times 10^{-4} mA/\sqrt{Hz}$ $PN < 10^{-4} rad/\sqrt{Hz}$

Table 14: Summary of the electronic specifications for longitudinal photodiodes in Advanced Virgo, $125W$, with Dual Recycling. For DC readout photodiodes a quantum efficiency of 95% is assumed, leading to a conversion factor from power to current $K = 0.814A/W$. For control and lock acquisition photodiodes a quantum efficiency of 88% is assumed, leading to a conversion factor from power to current $K = 0.754A/W$. Specifications on electronic noise (EN) and phase noise (PN) are given for the nominal DC powers.

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