Progress report #1

I. BACKGROUND

Sensitivity of the the second generation laser interferometric gravitational-wave (GW) detectors: Advanced LIGO [1, 2], Advanced VIRGO [3, 4], and KAGRA [5, 6], which are under construction now, in major extent will be limited by the quantum noise. Namely, at higher frequencies the shot noise will dominate, originating from the quantum fluctuation of the phase of the optical field inside the interferometer. At lower frequencies, the radiation pressure noise created by the amplitude fluctuations will constitute the significant part of the noise budget, so it becomes crucial to find ways to minimize total quantum noise of light, circulating within interferometer.

In our project we assume two main methods to improve sensitivity: first one - noise cancellation scheme, based on use of pairs of antisymmetric optical carriers [7].

For double pump configuration with parameters: $J_1 = J_2$, $r_1 = r_2$, $\Gamma_1 = \Gamma_2$ - even, and $\beta_1 = -\beta_2$, $\zeta_1 = -\zeta_2$, $\theta_1 = -\theta_2$ - odd, effective shot noise spectral density has minimum at Ω_0 frequency, increases as $1/\Omega^2$ and as Ω^2 at lower and higher frequencies respectively. The corresponding effective radiation pressure noise spectral density has maximum at Ω_0, and mirrors the shot noise dependence. Thus, it is meaningful to use two pairs of antisymmetric carriers, tuned on different Ω_0 to form a configuration with each pair responsible for its own frequency band [7].

Another approach is to change the dynamics of the test mass itself, by means of double

Quantity	Description
$m = 40$ kg	Test mass (aLIGO)
$L = 4000$ m	Arm length (aLIGO)
ω_p	Pump laser frequency
Ω	GW frequency
γ	Bandwidth
$\delta = \omega_p - \omega_0$	Detuning
$\beta = \arctan\dfrac{\delta}{\gamma}$	Effective detuning
$\Gamma = \sqrt{\gamma^2 + \delta^2}$	Effective bandwidth
I_c	Optical power, kW
$J = \dfrac{4\omega_p I_c}{MLc}$	Normalized optical power
η	Quantum efficiency
r	Squeezing factor
θ	Squeezing angle
ζ	Homodyne angle

Table I: Main notations

optical spring effect. When the power, detuning and bandwidth of the two carriers are chosen appropriately, the effect of the double optical spring can be described as a negative optical inertia, which cancels the positive inertia of the test mass and thus increases its response to the signal force [8]:

$$J_1 = \frac{\Gamma_1^4 \Gamma_2^2}{\delta_1(\Gamma_2^2 - \Gamma_1^2)} \qquad \text{and} \qquad J_2 = \frac{\Gamma_1^2 \Gamma_2^4}{\delta_2(\Gamma_1^2 - \Gamma_2^2)}. \tag{1}$$

The main goal is to combine above mentioned effects and to carry out a numerical optimization for parameters of six pumps (negative optical inertia for the first pair of carriers, and antisymmetric carrier regime for other pairs). As a necessary simplification we proposed to exclude squeezing on the first stages of optimization.

II. INITIAL RESULTS

Parameter	1	2	3	4	5	6
I_c, kW	26.28	70.48	784.14	784.14	7.48	7.48
γ, Hz	3.34	2.03	297.27	297.27	1.76	1.76
δ, Hz	149.4	-401.0	-300.0	300.0	200.3	-200.3
ζ	-1.568	0.998	-0.804	0.804	-0.001	0.001

Table II: Quantum efficiency $\eta = 1$

Parameter	1	2	3	4	5	6
I_c, kW	25.94	77.82	782.81	782.81	5.31	5.31
γ, Hz	4.71	10.47	311.81	311.81	0.74	0.74
δ, Hz	150.3	-451.1	-300.8	300.8	198.0	-198.0
ζ	1.473	-0.185	-0.891	0.891	-0.210	0.210

Table III: Quantum efficiency $\eta = 0.95$

III. FURTHER STEPS

There is a slight improvement in sensitivity in low-frequency region in comparison with baseline configuration (Fig. 1). The next goal is to carry out the same procedure for longer time in order to find the global minimum. As the following step we propose to introduce squeezing, which should give better overall sensitivity.

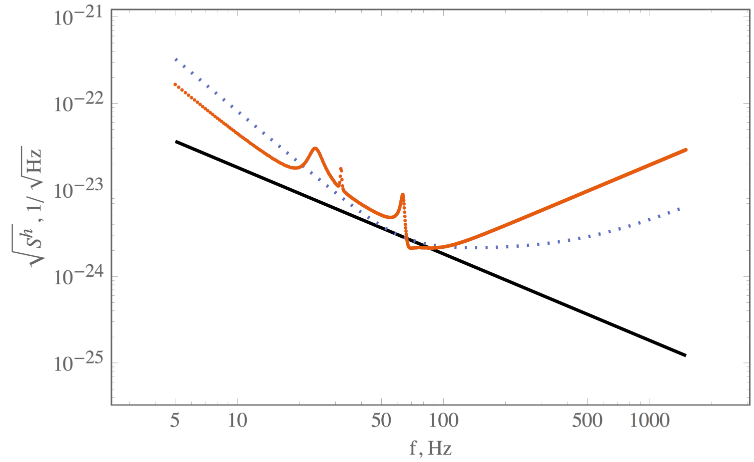

Figure 1: Plot for Table II

Black solid line: SQL. Blue dotted line: baseline configuration (1 pump, $I_c = 1680$ kW, $\gamma = 2\pi \times 500$, no detuning, no squeezing), orange thick line: data plot after optimization.

[1] `http://www.advancedligo.mit.edu/`.

[2] G.M.Harry (for the LIGO Scientific Collaboration), Classical and Quantum Gravity **27**, 084006 (2010).

[3] `http://wwwcascina.virgo.infn.it/advirgo/`.

[4] F.Acernese et al, J. Phys.: Conf. Ser. **32**, s223 (2006).

[5] `http://gwcenter.icrr.u-tokyo.ac.jp/en/`.

[6] Y. Aso et al., Phys. Rev. D **88**, 043007 (2013).

[7] M. Korobko, N. Voronchev, H. Miao, and F. Y. Khalili, Phys. Rev. D **91**, 042004 (2015).

[8] F. Khalili et al., Phys. Rev. D **83**, 062003 (2011).

[9] GNU scientific library, `http://www.gnu.org/s/gsl/`.

[10] GNU scientific library interface, `http://cafim.sssup.it/~giulio/software/multimin/multimin.html`.