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Two steps strategy for Adv-Virgo

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1. Abstract

This document reports a summary of results obtained in investigating the use of Non Degenerate Recycling Cavities versus Marginally Stable Cavities. The behaviour of the interferometer is analyzed with the help of Finesse and with a new simulation code named MIST. After investigation a scheme for a two step strategy for the realization of Adv-Virgo is proposed. The main trigger science goal triggering the proposal is the possibility that a “first detection” run will be carried out within few years in coincidence with LIGO. Morevoer, the two step strategy might allow devoting a significant part of the upcoming years to data taking runs with improving sensitivity.

2. Introduction

In the last few months a remarkable effort has been carried out within Adv-Virgo to explore the feasibility, the gain and the implications of using NDRCs or MSRCs. Many simulations have been carried out and noticeable simulations results have been reached by the collaboration. Among these works we report here the results of two main activities: the complete simulation of the behaviour of sidebands and carrier in the interferometer and some analysis performed on alignment issue.

Within the analysis of the interferometer, the main problem addressed has been the use of Non Degenerate Recycling Cavities versus Marginally Stable Recycling Cavities, considering performances and design implications. A first difficulty faced on this analysis has been the lack of a complete simulation of the ITF by the optical point view. In particular the unique tool capable of simulating the ITF was known to be Finesse. Unfortunately this software suffers from not being an open code, lowering the possibility to check the results (also does not take into account the radiation pressure).. Inspection on Ligo side, moreover, has shown that they also do not have a complete simulation of ITF with thermal effects and astigmatisms; both these aberrations are important for AdVirgo. The astigmatism, in particular, is even more important to be simulated in AdVirgo because in the Baseline design the recycling cavities are astigmatic.
For these reasons it has been developed a home-made code, named MIST, capable of describing the whole interferometer, taking into account thermal effects and astigmatism (no radiation pressure computation).. The code has been cross-checked with Finesse, exhibiting agreement in the results. It must be added that the two codes are both modal: other important checks are expected in the near future by FFT codes, like DarkF, SIS or others. The analysis with Finesse and MIST focused mainly on longitudinal degrees of freedom. Complementary analysis on alignment effects, with Ligo codes (Optickle) and home made tools, have also been carried out.

On the other side, it has been considered the possibility the Ligo take the decision to follow the “first detection strategy”, i.e. to run the ITF not at target design sensitivity, around middle 2014, but capable to reach a detection with not negligible probability.
The expected rates of detection at 60 – 70 Mpc for the 3 ITF spans around about 1-2 y^{-1}, so that a data taking could be justified with such sensitivities.

In this spirit a new planning has been considered, that suggests to reach the desired sensitivity in various steps, maintaining the control of the ITF and allowing the possibility to eventually participate to the first detection.

3. Simulation of the ITF

The goal of the optical simulation that have been performed is to characterize the behavior of MSRC and NDRC against thermal lensing in the input mirror substrate. The high-reflectivity surface deformations have not been considered since a perfect functioning of the the ring-heater compensation has been considered. This is not restrictive in this analysis, since if the ring heater does not meet the requirements Advanced Virgo will suffer of mismatch problems even in absence of thermal effects. The main results have been obtained using an analytical modal model, described in details in [VIR-0142A-10]. In brief the field amplitude at each point inside the interferometer is described as a vector of coefficient of high order modes in the arm cavity basis. Field propagation equations are analytically solved considering that mismatched mirrors or thermal lenses introduces off-diagonal couplings between modes. The main result of this simulation tool have also been cross-checked using Finesse. In all the simulations we described thermal effects using the approximation of thin lenses. We divided thermal effects in the common and differential parts.

The simulation of MSRC showed that they are mainly sensitive to common mode lensings. The main sideband recycling gain can decrease significantly with thermal effects. However, the detector sensitivity is much less spoiled by thermal effects. The main concern remains then on the control sidebands. However, loosing even a factor 3 in sideband recycling gain seems not a dramatic problem. Indeed Virgo+ has been operated stably with such level of sideband loss. This corresponds roughly to 70 km of residual focal length, which is comparable to the TCS performance obtained in simulations with the present design [Rocchi-Fafone presentazione, VIR-0148A-10]. With an improved TCS these cavities can provide controllable and sensitive interferometers even with high input power.

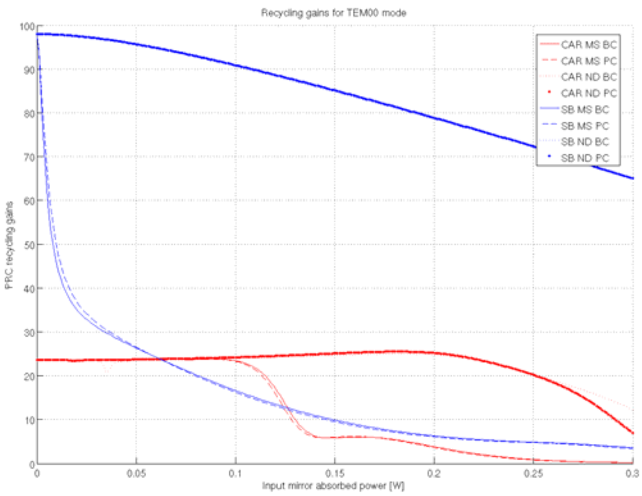

Figure 1: Comparison of carrier and sideband recycling gains as a function of common mode thermal effects.

In the case of NDRC the behavior in presence of common mode lensing is clearly better than MSRC, since sideband recycling gain remains high even in presence of badly compensated common thermal effects. However the present design of NDRC implies the use of fast off-axis telescopes which introduces astigmatism. The simulation shows than astigmatism can easily become a limiting factor in terms of detector sensitivity. As a rough indicator, if the incidence angle on SRC mirrors is larger than 1.5 degrees the sensitivity starts to be significantly spoiled. This poses stringent requirements on the design, forcing to put recycling mirrors on the injection and detection bench.

The main issue with NDRC concerns differential lensings. In presence of even small differential defects (lensing or mis-alignments) high order modes are generated inside the power recycling cavity. These are perfectly transmitted to the signal recycling cavity. If resonant therein they can extract a lot of power from the control sidebands, reducing almost to zero the recycling gain. This effect depends on the choice of SRC telescope design, macroscopic length and microscopic tuning.

Even if it might be possible to find a design such to have the desired steady state SRC tuning far away from critical points, differential defects might make the interferometer impossible to lock. Indeed during lock acquisition the signal recycling mirror will span random tunings. Every time it crosses the resonance of a high order mode (01, 10, 02, 20, etc...) the power recycling gain of one of the two main sidebands is lost. This can have dramatic effects on the error signals for angular and longitudinal control.

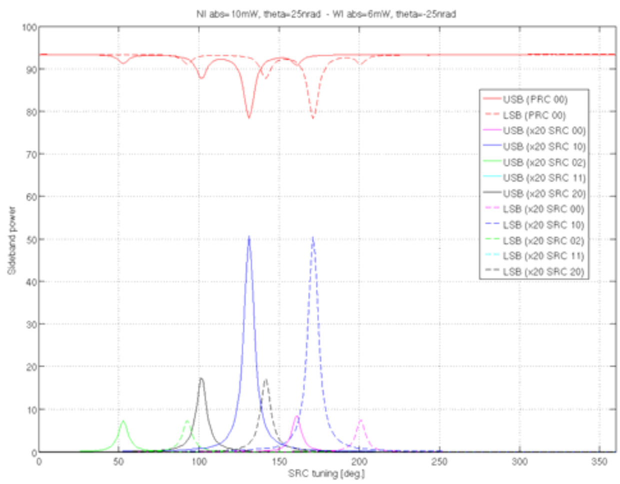

Figure 2 Effect of differential lensing and mis-alignment on the power recycling gain of 6MHz sidebands, as a function of SRC tuning.

4. Alignment

The main questions investigated by the alignment group have been the requirements for long arm mirrors and for recycling cavity mirrors and the Solimeno/Sigg instability in long arms and recycling cavities.
Both studies have been performed using the Ligo software (Optickle) and developing home made code to check the results or to cover some parts not addressed by other codes.

The Solimeno/Sigg instability is the instability in angular degrees of freedom due to radiation pressure. As sketched in figure 3.1, if a mirror rotates the cavity optical axis changes and hits the mirror out of center. The light pressure then exerts a momentum that, depending on the cavity geometry, can push the mirror away in the same angular direction, resulting in an anti-spring, or back toward the original equilibrium position, resulting in a positive spring.
The work of the alignment group focused on verifying the calculations and on applying them to Super Attenuator case. Interestingly, when considering the Super Attenuator mechanics, an instability is foreseen already in the present interferometer. Indeed the Super Attenuator is quite soft and calculations foresee an instability due to 30 mHz Ty resonance, which stiffness is too small to overcome the radiation pressure anti-spring. This effect is anyway not a problem for alignment or locking: indeed as shown in figure 3.2, as far as the frequency of real poles is sufficiently low the system remains controllable: the unity gain of the loop can be sufficiently low in frequency (1-2 Hz), so to allow suitable low pass filters preventing noise reintroduction at 10 Hz. This would be the case for bi-concave cavities (or also for plano-concave but only up to 3-4 cm waist on input beam, not higher: see ref 5).

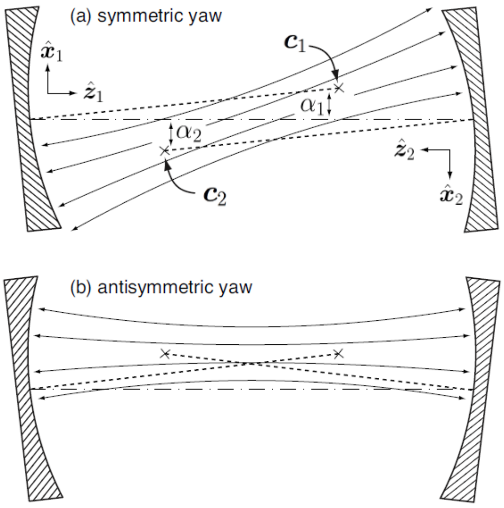

Fig 3.1: Position of the cavity axis due to rotations of the mirrors. In the picture it is seen that the symmetric yaw exibits a restoring momentum while the antisymmetric yaw corresponds to an unstable mode.

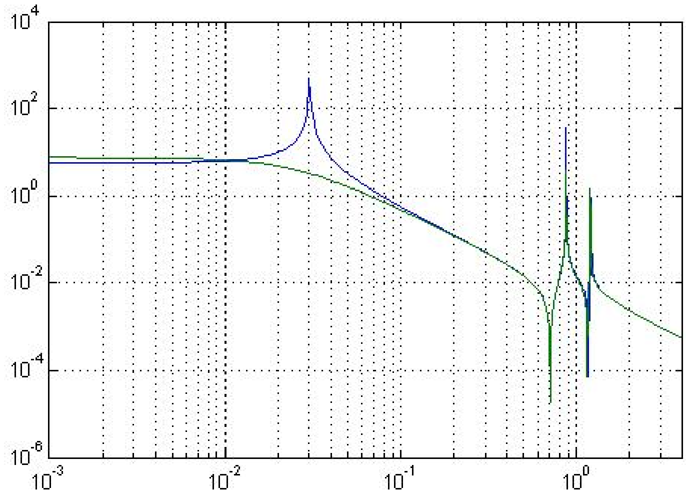

Fig 3.2: Mechanical transfer function of the Super Attenuator with a radiation anti-spring as present in Virgo+. The 30 mHz resonance frequency Ty mode is brought to instability but the corresponding poles have frequency sufficiently low and the overall system is not affected.

Another question about the differences between bi-concave and plano concave concerns the noise due residual gas in the arm pipe. Anyway the difference between the two cases (applying the Cella model as in gwinc) does not show remarkably differences in the two cases. Finally the alignments requirements, as reported in Ref. 5, are similar. Under these considerations the bi-concave case is preferable.

A further activity of the alignment group has regarded the behaviour of the Non Degenerate Cavities for recycling power and signal. In this case the aim is both to investigate eventual Solimeno/Sigg instabilities and to define the alignments requirements. It is very important to point out that due the fact that the proposed cavities use mirrors with short radius of curvature (few meters) the coupling between translations and rotations cannot be neglected.
The work is still in progress and we report the first results, which are under checking with Optickle. Further investigations would also be needed to estimate the jitter requirements: also this is in progress.
The method followed to evaluate the instabilities and the alignment requirements extends the geometrical analysis of Sigg to a 4 mirror cavity, whose last mirror is the input mirror of the arm cavity. The only prescription in this method is to consider that while in a cavity (made by whatever number of mirrors) the optical axis passes through the center of curvature of the input and end mirrors, in the recycling cavities, that are coupled to the arm the optical axis must pass through the waist of the arm cavity (see Ref 6).
With this prescription it is quite easy to calculate the position of the beam on each mirror as a function of mirrors tilts and translations, the momenta on each mirror and also to evaluate the cavity length dependence upon the same variables.
A sketch of the geometrical method is reported in figure 3.3

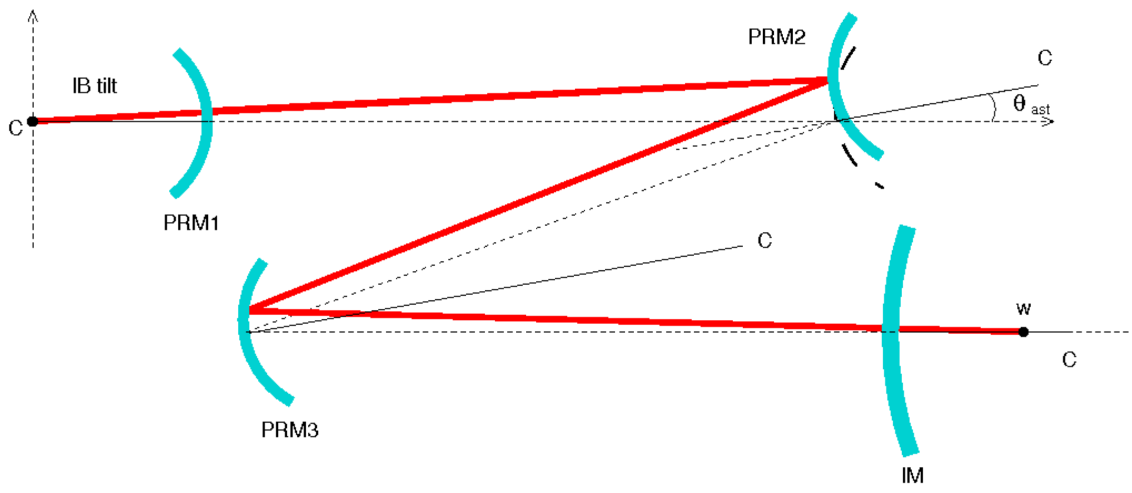

Fig 3.3: a sketch of the geometrical computation of the optical axis for the power recycling cavity

A remarkable result is that the coupling between the translations of the mirrors and the position and tilt of the beam can be a source of difficulties. It is found that the beam can undergo quite noticeable translations if the mirror transversal and angular displacements are of the order of the present one (in Virgo). As an example if the mirror PRM2 (whose radius of curvature is 2 meters) translates by 10 micron (an RMS value compatible with present vertical displacements), the beam undergoes a displacement of about 0.18 mm on the same mirror and about 2 mm on PRM3 and IM. Slightly higher displacement on PRM3 and IM are expected for the same 10 micron translation of PRM3. The same is valid for the signal recycling cavity.
If the beam abandon the center of the mirror it raises an immediate coupling between the tilt of the mirror and the length of the cavity. In case of the Signal recycling cavity the specifications are quite stringent. The allowed residual angular movement are of the order of $\tilde{\vartheta} \approx 10^{-15}$ rad/sqrt(Hz) at 10 Hz. This number is extremely stringent. Further work is necessary to verify it. In any case the coupling between translation and tilts makes it necessary to chose between two solutions: 1) to correct with larger control band-widths the translation by actuating on rotations at the price of more control noise 2) to correct directly translation by adding sensors and actuators also for these degrees of freedom. Both solution are difficult to implement meeting the noise requirements.

5. Conclusion and proposal

The main question addressed has been the use of the Non Degenerate Recycling Cavities and their installation versus Marginally Stable Recycling Cavities.
Another parallel important topic is to take into account is the change in the detection strategy of Ligo detectors.
In this case it has been considered if there is some possibility to match the same run with comparable sensitivity and being ready, after the run, to raise the sensitivity at the final Adv-Virgo design.

Various possibilities has been analyzed and discussed, especially taking into account the analysis of paragraph 2 and 3. Part of the discussions regards also the feasibility of a planning. Care has been devoted to suggest a solution that will not sound too optimistic in the times.
The main consideration is that the use of the Non Degenerate Recycling Cavities as drawn in the baseline or as already modified after recognizing the problem of astigmatism could be very problematic. The main first motivation is that, as clarified in paragraph 2, they are intrinsically weak with respect to differential aberration of the ITF. If differential (typically thermal) aberrations are present the RF sideband power is extracted from the power recycling cavity to the signal recycling cavity during the span of the signal recycling mirror. Thus it could be individuated a nominal position of correct working of the interferometer, but there is no (clear) way to reach it: during lock acquisition signals might be lost.
Another worry comes from the abandon of the use of big mirrors with long radii of curvature to use of small radius of curvature optics. The coupling between translations and rotations requires additional controls of degrees of freedom or higher bandwidth that are at risk of noise reintroduction.

For this reason we report here a sort of conclusive proposal on how to proceed in the next years, which is the result of our analysis up to now.
The starting point is July 2011, when the ITF will be de-commissioned to start the construction of Adv-Virgo. Our proposal is to use 2011-2012 until middle of 2013 to make the following Adv-Virgo installations:

1) NI displacement to reach Schupp aymmetry equal to 10 cm for DC readout
2) Installation of the new cryotraps
3)Installation of new payloads with compensation plate and new mirror – maintain the geometry of the cavity as it is now
4) Install the signal recycling tower
5) Study and prepare the installation of signal extraction from tilted compensation plates

Note: use the mirror coating layer-optimized

After the installation about 1 year of commissioning time is foreseen, devoted to:
1) Laser at 40 watt
2)Commissioning the use of compensation plates
3) Dc detection or other demodulation schemes
4) Sensitivities study toward high horizon
5) Run Preparation VSR4

Taking into account possible PR gain of 40, Finesse of 200 (layer optimized), Laser 40 Watts, DC detection, the nominal sensitivity is reported in figure 4.1. The horizon for NS-NS is 80 Mpc. The figure can have still some improvement for NSNS if higher power is used, or squeezed light. Notice that using higher power or squeezed would rise NSNS horizon but lower BHBH. It would be interesting to have turned-phase squeezing.

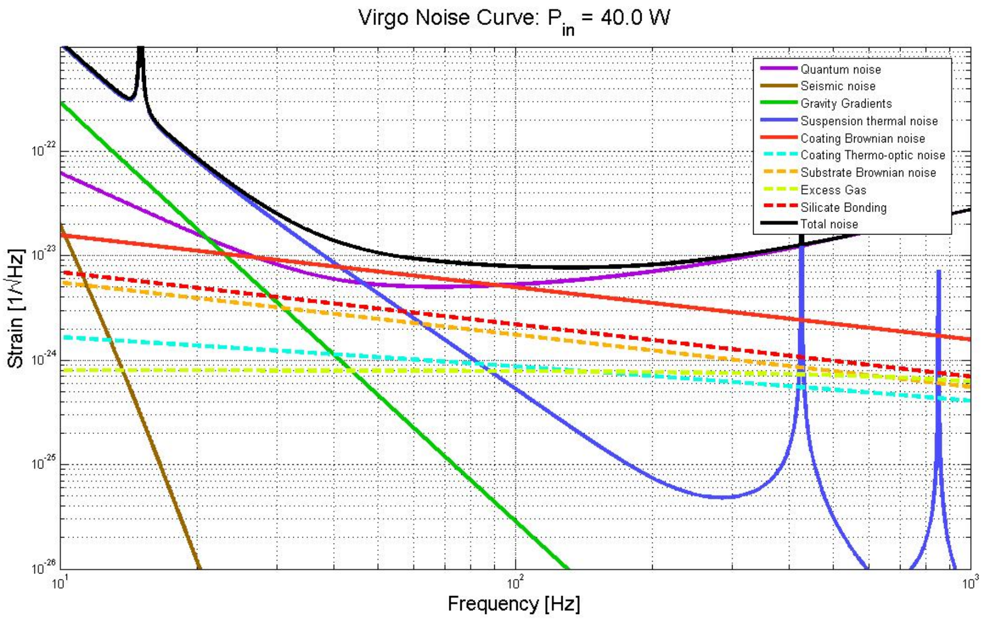

Fig 4.1: fundamental noises in an interferometer without signal recycling, with 40 Kg masses, cryotraps, higher power and recycling gain. Coating layer optimized, estimated 80% (in power spectral density) with respect to non-optimized. The NSNS horizon is 80 MPc.

The following step, after commissioning time and data taking, is the installation of the mirrors and beam splitter for the bi-concave cavities in order to have larger beams. The installation is simply a replacement of mirrors for what concerns the arm-cavity mirrors.

For the beam splitter the payload need to be changed in order to allocate the bigger beam splitter necessary for larger beams. For what concerns the power recycling and signal recycling mirrors the proposed solution is to remain in the configuration of marginally recycling cavities. Again we stress that the main reason is that the marginally stable cavities will work surely at low power (few watts) and will have on critical path only the TCS (thermal compensation system). This system will benefit from the commissioning phase during step 1.

On the other side, the Non Degenerate Cavities, as presently designed, are not sufficiently studied (both in the theoretical and with respect to actual design) to warrant the expected behaviour and moreover have many sub-systems on critical path: in particular INJ, SAT, PAY. Not negligible should also be considered the fact that all the new structures of these subsystems, together also TCS, should be commissioned almost all together during the after-installation commissioning phase.

The second step, having larger beams, initially without signal recycling but with same input power of step 1 will have the sensitivity reported in figure 4.2. With input power 40 Watt and 40 recycling gain, under the condition of optimized coating layer roughly estimated as above, the sensitivity without signal recycling reaches 108 Mpc for NSNS. Finally with the signal recycling and full input power it reaches the project sensitivity.

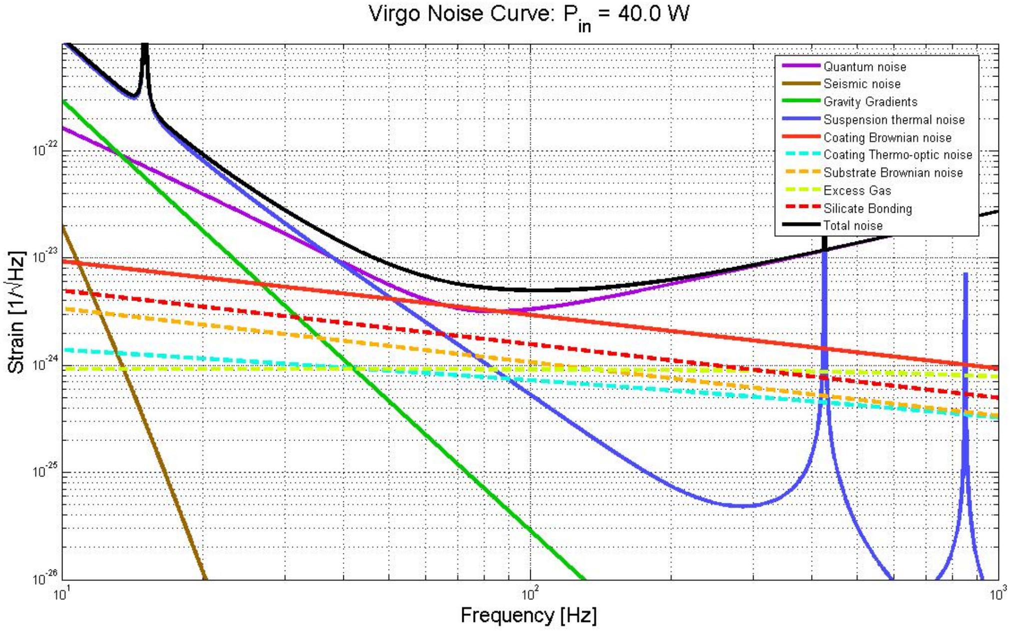

Fig. 4.2 Sensitivity of a bi-concave 40 Watt input power 40 recycling gain without signal recycling. The horizon is 108 Mpc.

As a resume we report a schematic of the evolution of sensitivity in the various steps, from present Virgo+, to Virgo+MS, to an intermediate step and to the final sensitivity.

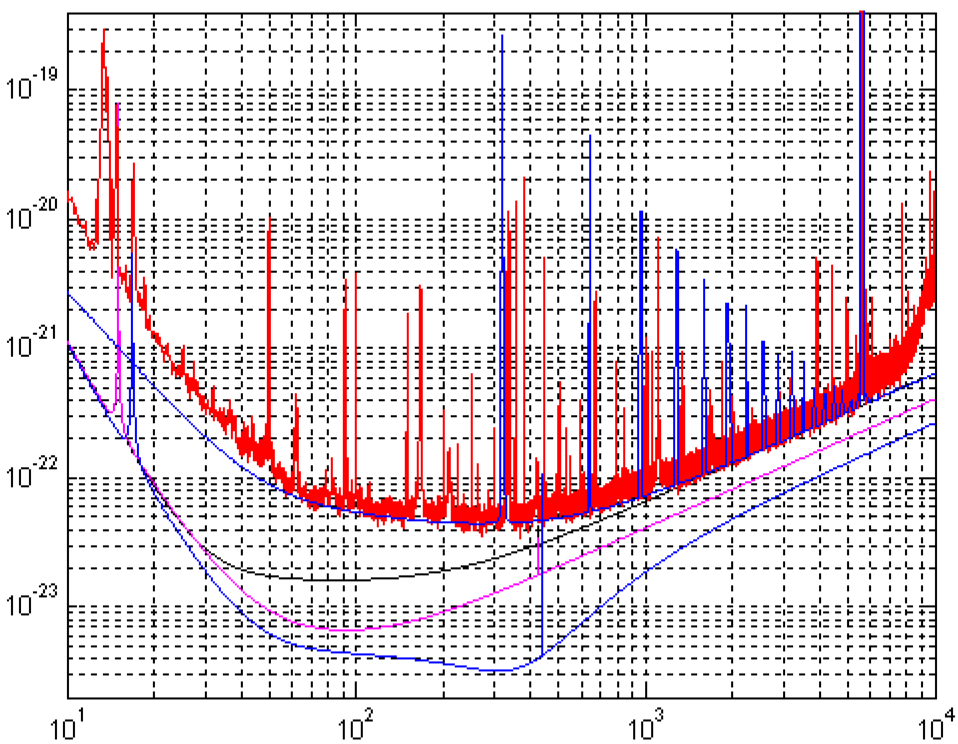

Fig 4.4: a possible evolution of the Virgo sensitivity

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