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Virgo gravitational wave detector: Results and perspectives

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J.-F. Hayau(27), A. Heidmann(22), H. Heitmann(26)(27), P. Hello(19),
P. Jaranowski(35), I. Kowalska(33), A. Królak(32)(36), N. Leroy(19),
N. Letendre(21), T. G. F. Li(24), N. Liguori(28)(29), M. Lorenzini(3),
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L. Milano(6)(7), Y. Minenkov(16), M. Mohan(2), N. Morgado(23),
A. Morgia(16)(17), B. Mours(21), L. Naticchioni(14)(15), F. Nocera(2),
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P. Rapagnani(14)(15), V. Re(16)(17), T. Regimbau(26), F. Ricci(14)(15),
F. Robinet(19), A. Rocchi(16), L. Rolland(21), R. Romano(6)(8),
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Summary. — The Virgo detector reached during the past science run a sensitivity very close to the design one. During the last year the detector has been improved by suspending the main interferometer mirrors with monolithic fibers, with the goal of reducing the thermal noise contribution and testing the new technology. At the same time the design of the next detector improvements are on-going and they will be implemented during the construction of Advanced Virgo.

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1. – Introduction

The Virgo gravitational wave (GW) detector [1] is a power-recycled Michelson interferometer with arms consisting in 3 km long Fabry-Perot resonant cavities. It is located at the European Gravitational Observatory (EGO) site near Pisa in Italy. Gravitational signals would cause a differential change in the two arm lengths which will be detected by monitoring interferometrically the distance between test masses, which consist of high-reflectivity mirrors. They are suspended to high-performance multistage passive isolation systems (the *super-attenuators* [2]) designed to reduce the transmission of ground seismic motion to the test masses of a factor already 10^{-14} starting from 10 Hz up, which is the opening frequency of the observational band-width. The input laser beam is provided by a 60 W Nd:YAG laser with a wavelength of 1064 nm.

Since 2007 Virgo has completed three scientific data-taking periods (Virgo Science Run 1 to 3) and started recently (on June 3rd 2011) its fourth run. The first three periods were carried out in partial or complete coincidence with similar runs of the LIGO [3] detectors located in USA. The use of three detectors at the same time allows a reduction of background events by selecting only those events with triple coincidence. Furthermore it allows to reconstruct an estimate of the sky location of the source by triangulation.

Between VSR2 and VSR3 the Virgo detector has been upgraded by replacing the bottom part of each suspension chain (the *payload*). The mirrors were previously suspended using steel wires. The new suspension system is made with fused silica fibers monolithically bonded to the mirror itself. Such *monolithic suspensions* were installed with the goal of reducing the thermal noise contribution to the detector sensitivity and to test this new technology in view of the Advanced Virgo upgrade [4].

The fourth science run is planned to continue until October 2011. After this date a long shutdown is planned to install all the upgrades needed to implement Advanced Virgo. The goal is to improve the design sensitivity of the detector of a factor 10 with respect to the first generations. Early runs are expected, in coincidence with Advanced LIGO [5], at the end of 2015.

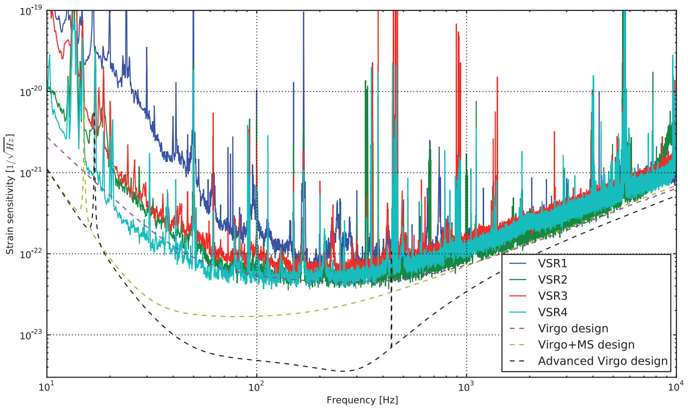

Fig. 1. – Virgo detector measured sensitivities during the past and present science runs. Design sensitivities are also included for Virgo with steel wire suspensions, with monolithic suspension and for Advanced Virgo.

2. – Selected astrophysical results from past runs

The typical detector sensitivities during the four science runs are shown in fig. 1. The Virgo detector operated with typical duty cycle of about 80%. Data collected during all these data-taking periods have not been completely analyzed yet. However some results of astrophysical interest have already been published. Only a selection of them are discussed here.

One of the most promising candidates for detection are signals coming from coalescing binary systems, typically neutron stars or black holes. Updated estimates of the expected rates have been recently published [6] showing that first-generation detectors, like Virgo and LIGO, have little chances of detecting such a signal: the expected rate of a binary neutron star coalescence is of the order of $6 \times 10^{-5}\, L_{10}\,\mathrm{y}^{-1}$ (where L_{10} is equal to 10^{10} the sun luminosity in the blue wavelength, or $2.16 \times 10^{33}\,\mathrm{erg/s}$) or 0.02 event per year considering a maximum observable distance of the order of 15 Mpc. Rates are even lower for higher mass systems. The joint Virgo and LIGO analysis of data collected during VSR1 allowed setting an upper limit of the order of $8.7 \times 10^{-3}\, L_{10}\,\mathrm{y}^{-1}$. The analysis of VSR2 and VSR3 data is still on-going.

In the framework of short transient signals there were both all-sky searches [7] and gamma-ray burst targeted ones [8]. These results are not discussed here.

Other sources of particular interest are continuous ones, in particular those emitted by known pulsars. An intrinsic limit on the amplitude of GW emitted by such systems is given by the spin-down limit, *i.e.* considering that all the rotational energy lost by the pulsar is converted in GWs. Observations of the Crab and Vela pulsars allowed setting tighter limits than that from the spin-down: the energy emitted by the Crab pulsar in GW is less than 2% of the spin down [9], while for the Vela pulsar the limit is set at 35% [10].

3. – Status of the Virgo detector

During VSR2 the Virgo detector reached a sensitivity very close to the design one, see again fig. 1. To reduce the contribution of thermal noise the last stage of suspension has been re-designed, replacing the steel wire used for the suspension with fused silica fibers monolithically bonded to the mirror body [11]. In this way dissipative processes are expected to be largely reduced resulting in lower thermal noise and better sensitivity at low frequency (see the Virgo+MS design curve in fig. 1).

These new monolithic suspensions have been installed for all four-arm test masses between January and April 2010. In May commissioning activities were restarted and between July and October the third science run took place. The detector sensitivity was not as good as expected and even slightly worse than the one obtained during VSR2. The main reason was that the four-arm mirrors needed to be replaced and the new ones showed radius of curvature and losses asymmetries much larger than before, resulting in a worse contrast of the interferometer. This in turn increased significantly the amount of spurious light reaching the output port, causing scattered light which was the main limiting noise source during VSR3. After the end of the run these problems have been tackled in two ways. A better dumping of the spurious light at dark port was implemented. Moreover a system to actively change the end mirror radius of curvature has been designed and installed. This system uses an infrared in-vacuum heat source which is projected in the center of the mirror. Thermal dilatation can be tuned by changing the source temperature, thus actively modifying the mirrors radii of curvature. Two such systems have been installed since March 2011 in both end mirror vacuum vessels. Their dynamic range proved to be more than adequate: the radius of curvature of the mirrors could be changed from a cold value of about 3400 m up to 4000 m. Properly tuning the working point of these two systems it was possible to reduce by about a factor 3 the amount of power reaching the dark port and also to improve the interferometer contrast by a large amount. In this condition the fourth Virgo Science Run started, with improved sensitivity with respect to VSR2, see fig. 1. The most important result so far is the sensitivity improvement below 50 Hz. In this region the noise level was significantly reduced with respect to before the monolithic suspension installation and reached a level below the Virgo design sensitivity. More commissioning work will be needed to further push the sensitivity significantly below the steel-wire thermal noise limit and fully demonstrate the improvement coming from the installation of monolithic suspensions.

4. – Conclusions and perspectives

The fourth science run is expected to continue till September 2011. During the scientific data-taking short periods of commissioning are planned with the goal of possibly understanding the noise sources and improving the sensitivity. At the end of the year a long shutdown period is planned to install all the system and optical upgrades for the Advanced Virgo project. To improve the sensitivity the optical design of the interferometer will change (see [4] for more details). All the present optics will be also replaced. The construction of Advanced Virgo is expected to continue until 2015 and first engineering and scientific runs are expected for the end of the same year, in coincidence with the Advanced LIGO detectors [5].

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