Chapter 1
Towards Gravitational Wave Astronomy

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Abstract This chapter is meant to introduce the reader to the forthcoming network of second-generation interferometric detectors of gravitational waves, at a time when their construction is close to completion and there is the ambition to detect gravitational waves for the first time in the next few years and open the way to gravitational wave astronomy. The legacy of first-generation detectors is discussed before giving an overview of the technology challenges that have been faced to make advanced detectors possible. The various aspects outlined here are then discussed in more detail in the subsequent chapters of the book.

1.1 Introduction

This book sees light at a time when a new generation of interferometric detectors, capable in principle to expand the explorable volume of the universe by three orders of magnitude, and thus to start the era of GW astronomy, is being realized. Virgo and LIGO have stopped taking data in 2011, and started the decommissioning and then the construction of Advanced Virgo and Advanced LIGO. Thus, no new science data will be available until 2015. In the GW community, this period with no data is usually known as *the crossing of the desert*: a tough time when scientists get ready to discover a new *promised land*, working on the prototyping and construction of the new detectors, preparing their commissioning and the data analysis for the upcoming years. A good time to focus on the technology challenges that we are facing in the realization of such new detectors (and even beyond), which are discussed in this book. This first chapter aims to provide a reference frame for the following chapters: it starts with a brief summary on what has been achieved by the first-generation

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detectors and then discusses the main technology novelties, pointing to the rest of the book for a more exhaustive description.

1.2 The Legacy of the First-Generation Interferometric Detectors

The existence of gravitational waves (GW) was predicted by Albert Einstein almost one century ago [1]. The effort to detect GW was initiated by Joe Weber, half a century ago, using resonant bars at room temperature. For several decades the resonant bars have been used, improving the technology and the sensitivity and establishing, for the first time, an observing worldwide network. In the first decade of the twenty-first century, the interferometric detectors of GW have overcome the resonant detectors demonstrating a big improvement in sensitivity and bandwidth. The operation of the kilometer-scale ground-based interferometers LIGO [2] and Virgo [3] has proven that such a technology is now suitable and reliable to realize a worldwide network of wideband detectors with duty cycle and sensitivity sufficient to aim and open the way to the GW astronomy (for a more complete description and bibliography of the history of GW research see [4] and references therein).

No discovery has been reported after some years of operation. However, interesting science results have been collected and a significant legacy has been left by the so-called *first-generation detectors* to the science community:

- *Infrastructure*: The relevant investments undertaken to create the infrastructure hosting the first-generation interferometers will continue to pay off, since the same facilities will host the advanced interferometers: the LIGO facilities (Hanford, WA and Livingston, LA), the Virgo site (Cascina, Italy), and GEO600 (Hannover, Germany) [5]. However, the expansion of the network requires the creation of new observatories. The construction of the underground 3 km detector KAGRA has been funded in Japan [6] and the possibility to move one of the three Advanced LIGOs to India is being explored.
- *Sensitivity and robustness*: LIGO and Virgo have reached or approached the design sensitivity over the whole frequency range. Some important upgrades have allowed us to enhance the detectors and go beyond the initial design sensitivity. Most of the noise contributions were understood and modeled. The reliability and robustness achieved has been quite impressive (given the complexity of these machines): all detectors could finally run with duty cycles of $\sim 80\,\%$ or larger. These achievements have eventually demonstrated the technology of the interferometric detectors of GW.
- *Commissioning experience*: Reaching the design sensitivity required about 5 years of commissioning work (alternated to data taking periods). The sensitivity (see Fig. 1.1) was improved progressively: the interferometric detectors were new instruments, never before tested in such extreme configurations. Commissioning teams had to learn how to operate and control the interferometers, cope with optical configurations of increasing complexity, cope with thermal effects and scattered
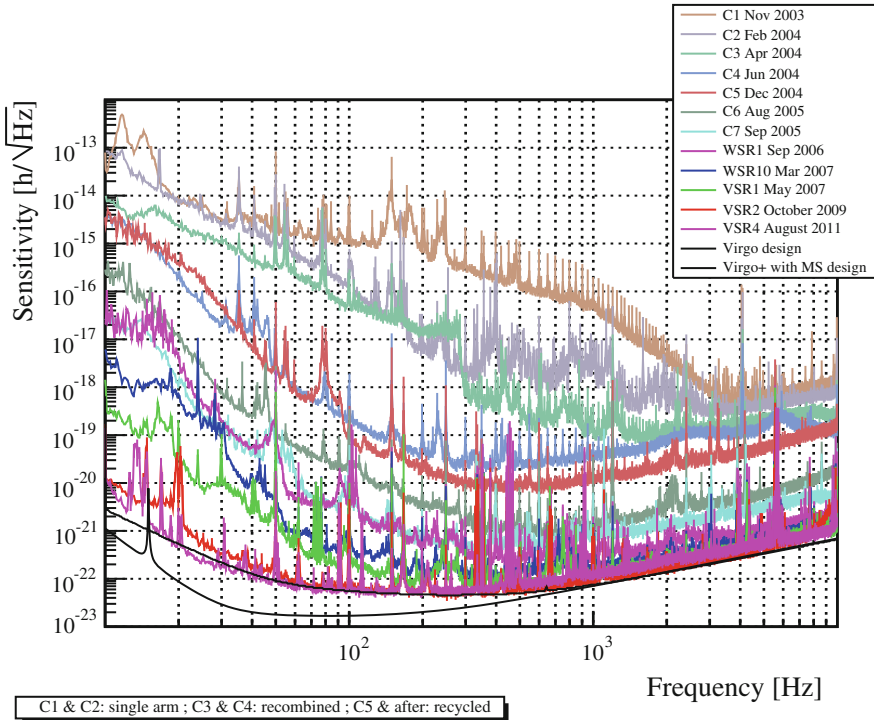
Fig. 1.1 The evolution of the Virgo sensitivity. The *black solid lines* are the design sensitivities of the initial Virgo and the enhanced Virgo+ configuration (*Credit* The Virgo Collaboration)

light, identify unknown sources of noise, and fix the detectors when unexpected problems emerged.

- *Technologies for advanced detectors*: Some technologies relevant for the second generation have been tested in most recent years on Virgo, LIGO, and GEO600, allowing debugging and further developments which will pay off in the commissioning and operation of the advanced detectors.
- *Data analysis*: An intense effort has been pursued to analyze the data of the first-generation detectors, leaving a big heritage in terms of methods, software, and expertise which will be very useful to analyze the data of the advanced detectors.
- *Network*: During the years the GW community became more and more aware that joint observation is necessary to increase the confidence in the events and the amount of science that could be extracted from them. The creation of a worldwide network of GW observatories is the cornerstone for the start of the GW astronomy.
- *Multi-messenger observations*: In addition to establishing a network, the GW community has advanced further by initiating a multi-messenger approach, signing memoranda of understanding for joint observation with optical and radio telescopes, gamma and X-ray satellites, and neutrino detectors.

- *Science*: Extensive science runs have been performed and, despite the fact that no detection has been claimed, relevant upper limits have been set.

1.3 Creating a Worldwide Network

The LIGO Scientific Collaboration (including the LIGO and GEO600 detectors) and Virgo have signed a Memorandum of Understanding for joint data taking, and publications policy joint analysis after May 2007. They have been operating as a "single machine," thus enhancing the chances of detection. Several joint science runs have been held so far:

- LIGO S5 (Nov. 2005–Sept. 2007) and Virgo VSR1 (May 2007–Oct. 2007): the overlap between the long S5 run and the VSR1 lasted 4 months.
- LIGO S6 (July 2009–Oct. 2010) and Virgo VSR2 (July 2009–Jan. 2010) / VSR3 (July 2010–Oct. 2010): LIGO and Virgo run together for 6 months at the end of 2009. Then Virgo was shut down to install monolithic suspensions. Once Virgo was back in operation (with monolithic suspensions) LIGO and Virgo run jointly for 2 more months. Then LIGO was shut down to start the upgrade to Advanced LIGO.
- Virgo VSR4 and GEO S6e (June–Aug. 2011): Virgo and GEO run together for 3 months. Then Virgo was shut down to start the upgrade to Advanced Virgo.

The network of interferometers has pushed the upper limits on gravitational wave amplitude emitted by several astrophysical sources to the lowest level ever reached (see for instance [7–11]). The most relevant results achieved so far are discussed in Chap. 2. The analysis of the data of the last runs is still ongoing and more papers are expected in the following months. Hopefully, this network approach will be undertaken also for the second generation, with a much better sensitivity. The science case for the advanced detectors and the expectations for the event rates are discussed in Chap. 2 of this book.

1.4 Advanced Detectors: The Scenario

The first decade of the century has been characterized by the operation of the first generation of the interferometric detectors and the demonstration of their technology. In the second decade a network of advanced interferometers, exploiting the results of many years of R&D, will be taking data. The construction of the Advanced LIGO detectors and of Advanced Virgo is in progress and a first science run could be possible in 2015. GEO600 is undergoing a phase of incremental upgrades (GEO-HF) aimed at reaching a competitive sensitivity in the high frequency range. Besides the upgrades of existing detectors, a 3 km underground detector (KAGRA) has also been funded in Japan and currently the tunnels are being excavated. The schedule is

Table 1.1 This table has been extracted from Aasi et al. [12]

Epoch	Estimated run duration	BNS range (Mpc)		Number of BNS detections	% BNS localized within	
		LIGO	Virgo		5 deg^2	20 deg^2
2015	3 months	40–80	–	0.0004–3	–	–
2016–2017	6 months	80–120	20–60	0.006–20	2	5–12
2017–2018	9 months	120–170	60–85	0.04–100	1–2	10–12
2019+	(per year)	200	65–130	0.2–200	3–8	8–28
2022+ (India)	(per year)	200	130	0.4–400	17	48

It contains a summary of a plausible observing schedule, expected sensitivities, and source localization with the advanced LIGO and Virgo detectors. In the first two columns, the possible dates and durations of the science runs are listed. For each run, in the third column, the expected inspiral range (a figure of merit indicating the distance at which a coalescing binaries can be detected, averaged over the GW polarization states and the source direction in the sky) for coalescing binary neutron stars (BNS), computed on the basis of the likely sensitivity evolution of the detectors, is indicated for LIGO and Virgo. In the next columns, the corresponding number of events and network capability to localize the source in the sky are indicated. See [12] for the full explanation of the underlying assumptions

quite ambitious: the goal is to be a part of the second-generation network as soon as 2017. A further novelty might be the installation of a new detector in a location far enough from LIGO and Virgo to considerably enlarge the network baseline, and thus to improve the accuracy in the reconstruction of the source angular position: LIGO and the Indigo consortium have proposed to install a third Advanced LIGO in India.

The goal of Advanced LIGO/Virgo is to extend the distance at which a target source can be detected by a factor ∼10, which corresponds to increasing the event rate by ∼1,000 with respect to the detectors of first generation. The final sensitivity goal, as the experience with the first-generation teaches, will be reached gradually. As the sensitivity improves, the detection rate, as well as the source localization capability, will improve. The likely evolution of the network capabilities (based on the experiment construction schedules and on the former experience on the commissioning evolution) has been outlined in a recent paper by the LIGO Scientific Collaboration and the Virgo Collaboration [12] and it is summarized in Table 1.1.

The improved sensitivity of the GW detectors and the largely increased expected event rate widens the possibilities with multi-messenger science. The joint operation of GW detectors and high energy neutrinos (HEN) telescopes is particularly appealing. Both GW and HEN travel undisturbed over cosmological distance and escape dense media. Both carriers are likely to provide an image of the universe complementary to that given by electromagnetic information. Thus, coincident observation of GW and HEN from the same event could allow a deep investigation of the source. Moreover, current plans of advanced GW detectors and neutrino telescopes (IceCube [13] and KM3NET [14]) promise observation on the same timescale. Among the astrophysical targets for a simultaneous detection of GW and HEN there are several sources that could be also observed through electromagnetic waves: gamma ray burts, supernovae, and soft gamma repeaters.
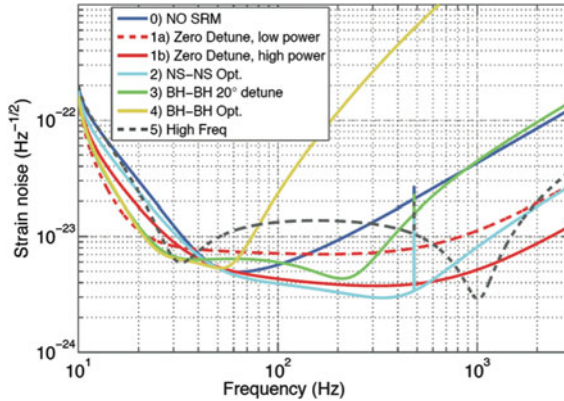
Fig. 1.2 The Advanced LIGO principal anticipated noise sources limiting the sensitivity in different configurations. The *solid red curve* (the one with the best sensitivity at 2 kHz) is the reference configuration, using tuned signal recycling, which provides a good sensitivity over a wide range. The *yellow* and *light blue curves* (respectively, the one with worst and best sensitivity at 400 Hz) correspond to a tuning which optimize the SNR for binary *black holes* and binary neutron stars respectively. The *black dashed curve* corresponds to a narrow band tuning, useful to enhance the sensitivity at the frequency of a monochromatic source. Figure from Harry [15]

In Sect. 1.5 an overview of the technologies needed to achieve such an ambitious goal is given and the following chapters in this book provide a deeper insight into each of those aspects. The crucial features allowing to increase the sensitivity are recalled here:

- the mirror technology has been improved in all the aspects: better substrates, better polishing, coatings with reduced absorption and mechanical dissipation;
- the mirrors are suspended through silica fibers, thus reducing the suspension thermal noise;
- the input laser power is increased by one order of magnitude to improve the shot noise limited high frequency sensitivity. This requires improved thermal compensation systems (to cope with thermal lensing) and heavier mirror (to reduce the effect of radiation pressure noise);
- the Advanced LIGO bandwidth is extended at lower frequencies by implementing a new vibration isolation system. This is not needed in the Virgo case thanks to the existing Superattenuator;
- signal recycling allows to tune the detector bandwidth and enhance the sensitivity in a chosen frequency range (see Fig. 1.2).

The path toward the best sensitivity will obviously take time. Both the operation of signal recycling and the increase in the input power by almost one order of magnitude with respect to the first generation will put forward relevant commissioning challenges. Therefore, Advanced LIGO/Virgo will start their operation with low input power and increase the complexity and performance in steps.
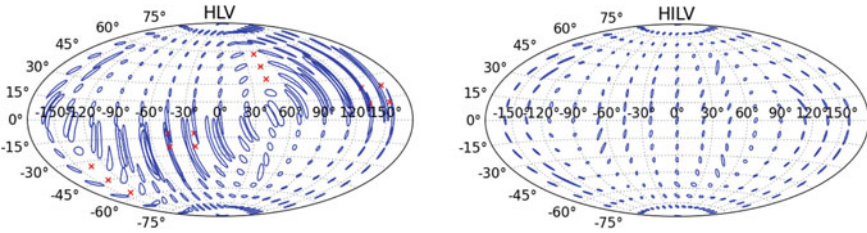
Fig. 1.3 The angular resolution of the LIGO-Virgo network without and with LIGO-India. Figure from Fairhurst [17]

1.4.1 Advanced LIGO

The Advanced LIGO project has been approved by the National Science Foundation in April 2008. It foresees the upgrade of the three LIGO interferometers to second generation. At the time of this writing, the construction works are close to completion while the commissioning of components of the detector has already started in 2012. At the design sensitivity (in the configuration optimized for BNS detection) the BNS inspiral range will be of 200 Mpc, which corresponds to detecting a BNS up to a distance of 450 Mpc if optimally oriented. With such a sight of distance, tens of BNS events per years are expected [16].

The LIGO laboratory and the Indigo Consortium are studying the possibility to move the third interferometer (Hanford-2) to India. This would require the indian funding agencies to provide the vacuum system and the infrastructure, while all the rest of the equipment will be shipped by LIGO. Such a choice would allow to considerably increase the angular resolution of the worldwide network [17] (see Fig. 1.3).

1.4.2 Advanced Virgo

Advanced Virgo [18] has been approved by INFN and CNRS at the end of 2009 (beside the Virgo funding agencies, Advanced Virgo will be contributed by the dutch laboratory NIKHEF). The Advanced Virgo design is described in the Technical Design Report [19].

In Fig. 1.4 the noise budget is shown. The sensitivity below 50 Hz is limited by a combination of suspension thermal noise and radiation pressure noise. The first is minimized by suspending the large mirrors (42 kg mass) with fused silica fibers similarly to what has been done for Virgo+. Around 100 Hz the main limitation to the sensitivity is due to the thermal noise in the mirror coatings. The sensitivity shown in the figure assumes current coating technology. So, any further improvements from this ongoing R&D will have a direct positive impact on the detector sensitivity. The

Fig. 1.4 The Advanced Virgo
target sensitivity with the main
noise contributions in the
BNS-optimized configuration
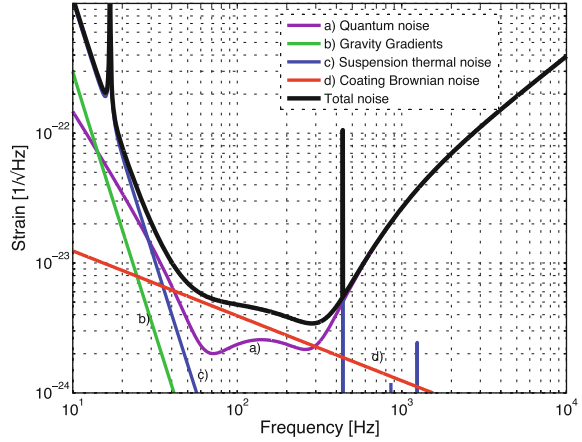
effect of coating thermal noise is minimized running the Fabry–Perot cavities near
the co-focal configuration, thus maximizing the beam size on the mirrors.

In order to reduce the laser shot noise and thus increase the interferometer
sensitivity at higher frequencies the available laser input power will be around
200 W. A different choice with respect to LIGO has been made for the Advanced
Virgo laser: a fiber amplifier will be used instead of a solid-state one. To cope with the
larger radiation pressure effects due to the larger power injected heavier test masses
(42 kg) will be used and will be suspended, as it was in Virgo+, through fused silica
fibers. To this extent, the experience done with the new Virgo+ payloads will be pre-
cious to understand all the features of this technology, improve it further, and reduce
the risk for the advanced detectors.

The optical scheme is modified by the introduction of a signal recycling cavity.
The sensitivity shown in the figure assumes that the signal recycling is detuned in
such a way as to have the best sensitivity to binary neutron stars coalescences. In this
case, the coalescences of binary neutron stars will be visible up to distances of about
135 Mpc. Other tunings are possible and can be used to target other sources. Also,
the finesse of the 3 km Fabry–Perot cavities will be larger ($\sim$450). A DC detection
scheme will be adopted to reduce some technical noises.

The vacuum system and the infrastructures will also be upgraded to improve the
sensitivity in the low and mid-frequency ranges. Large cryotraps will be installed at
the extremes of the 3 km vacuum pipes to isolate them from the rest of the vacuum
system. This, combined with the baking of the tubes, will allow reducing the residual
gas pressure to the target of 10^{-9} mbar. The air-conditioning machines as well as
several other sources of acoustic and seismic noise will be moved out of the central
experimental hall to reduce the sources of vibrations of vacuum pipes, optical mounts,
or any other parts that could scatter photons and generate stray light noise.

All the photodiodes to be used in science mode will be in vacuum and seismically
isolated by compact vibration isolators.

Virgo+ has been shut down in November 2011 and the installation of Advanced Virgo has started. The installation of the upgrades is expected to be completed in 2015.

1.4.3 KAGRA

KAGRA (KAmioka GRAvity and gravitational waves) is a 3 km underground detector to be realized in Japan, in the mine of Kamioka. KAGRA will start its operation at room temperature and will then be upgraded to the cryogenic (baseline) configuration. In its final configuration, the KAGRA test masses will be cooled down to 20 K. Therefore, KAGRA will anticipate some of the features envisaged for the third generation: being underground and cryogenic.

The reduction of the sapphire mirror thermal noise by cooling has been recently demonstrated on CLIO, a 100 m interferometer in the Kamioka mine used as a test facility for KAGRA technologies [20].

The construction of the KAGRA detector has officially started on January 2012. KAGRA aims to joining Advanced LIGO, Advanced Virgo and GEO-HF in the world network of second generation from 2017.

1.5 Advanced Detectors: The Technologies

In this section, we discuss the relevant technologies that allowed to approach the design sensitivity of the first-generation interferometric detectors and how these technologies have been further developed to realize the advanced interferometers.

1.5.1 Optical Configurations

The optical configurations of the advanced detectors will maintain the general scheme of the Michelson interferometer with Fabry–Perot cavities but will be updated in several features:

- *Fabry–Perot cavities in the arms*: the finesse of the Fabry–Perot cavities will be increased to ∼450 (for Advanced LIGO/Virgo).
- *Signal recycling*: a *signal recycling mirror* suspended between the beam splitter and the output port of the interferometer can *recycle* the audio sidebands containing the signal created by the impinging GW and increase the signal-to-noise ratio in a limited bandwidth [21]. The position of the signal recycling mirror and its reflectivity determine the central frequency and the bandwidth, respectively. Signal recycling has already been used by GEO600 in the first generation, and will be adopted by Advanced LIGO/Virgo.
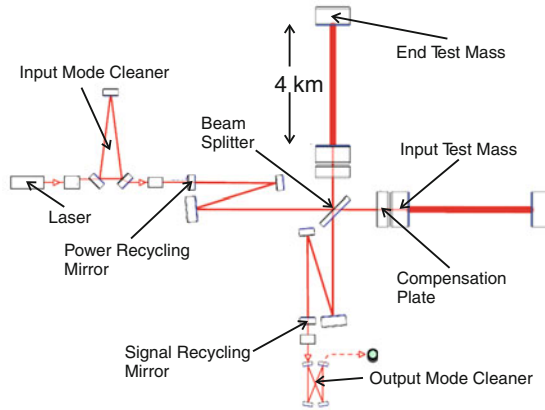
Fig. 1.5 Optical layout of Advanced LIGO

- *Stable recycling cavities*: the power recycling cavity of the initial Virgo and LIGO
  is *marginally stable*: the Gouy phase of the cavity is close to zero and high-order
  modes can resonate into it. This makes the cavity more sensitive to aberrations,
  induced by thermal effects, optical defects, or misalignments. To increase the
  robustness with respect to such effects Advanced LIGO will be provided with
  stable recycling cavities (see Fig. 1.5). The non-degeneracy is achieved by folding
  the beam path and having the mode matching telescope inside the cavity.

   The optical schemes for Advanced LIGO/Virgo are shown in Figs. 1.5 and 1.6.
Chapter 3 explores in detail the optical configuration aspects mentioned here.

1.5.2 Mirrors

The quality of the mirrors is a crucial element for the correct operation of the detectors.
It may affect the final performance in several different ways since it plays a role in
the thermal noise budget, scattered light, optical aberrations, and radiation pressure
noise:

- the *diameter* of the mirrors must be large to allow for large beam spot size (which
  helps reducing the impact of thermal noise). The Advanced Virgo test masses are
  350 mm in diameter as the Virgo mirrors, but twice as thick (20 cm). The beam
  splitter will be exceptionally large (55 cm in diameter) to reduce the risk of spurious
  scattering (see Fig. 1.7);
- the weight of the mirrors should be sufficient to reduce the effect of radiation pres-
  sure fluctuations below the other noise contributions. The mass of the Advanced
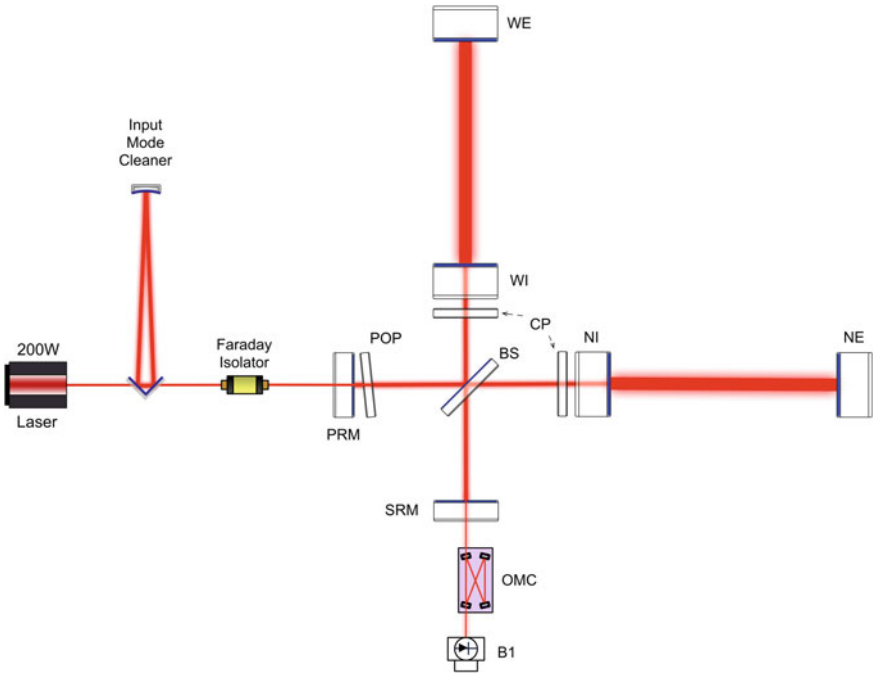 Virgo test masses will be 42 kg (twice as heavy as the Virgo mirrors);

Fig. 1.6 Optical layout of Advanced Virgo

Fig. 1.7 The Advanced Virgo beam splitter

- the material used to make the mirror must be chosen in such a way as to minimize the absorption at the laser wavelength (better than 1 ppm/cm) while keeping the mechanical internal dissipation responsible for thermal noise at a minimum. Different kinds of fused silica are available today on the market that meet the stringent requirements for GW interferometers;
- the polishing of the surface must be excellent, since the deviations from perfect flatness and the residual microroughness are responsible for scattering losses (see Chap. 10). The flatness required for the Virgo test masses was 8 nm rms, while for the advanced detectors it should be better than 0.5 nm rms. Superb polishing figures (∼0.2 nm rms) have been already achieved on the Advanced LIGO test masses by ion beam milling;
- the coating should guarantee low absorption and low thermal noise. In the advanced detectors, the thermal noise generated in the high reflectivity coating layers limits the sensitivity in the mid-frequency range, while its absorption is mainly responsible for the thermal lensing aberrations. Progress has been made in reducing the coating losses by doping the high index layer of Ta_2O_5 with Titanium [22, 23]. A very good uniformity in the thickness of the coating layer (at the level of 0.5 nm rms) must also be achieved in order to avoid excess optical losses (see Chap. 8 for more details).

1.5.3 Vibration Isolation

The test masses and the other sensitive optical components of interferometric detectors must be suspended and isolated from ground vibrations. The isolator must also allow to apply suitable control forces to the mirrors to bring the interferometer into operating conditions and maintain it as such. The approach to the problem of the vibration isolation has been different for the various projects. Virgo was the only one to pursue, since its beginning, the development of a vibration isolation system able to extend the detector bandwidth down to ∼10 Hz: the superattenuator [24]. It was conceived to suppress seismic vibrations by about 300 dB at 10 Hz. This is achieved by an 8 m long vertical chain of mechanical filters, able to low-pass vibrations in 6 degrees of freedom above their resonance frequencies. Passive filtering is not the end of the story: the chain of filters is suspended from an inverted pendulum platform [25] actively controlled to compensate for the earth tidal strain over the interferometer arm length and to damp the superattenuator normal modes [26]. Moreover, the mirror position and alignment can be controlled at the level required by the interferometer control system. Three main actuation points are envisaged and the mirror control is achieved by splitting the actuation over them with a hierarchical approach [27]. The superattenuator was already conceived as a *second-generation device*: it has been thoroughly and successfully tested in the operation of Virgo and its isolation performance has been demonstrated to be compliant with the requirements of Advanced Virgo [30]. More details are provided in Chap. 7.

Fig. 1.8 The monolithic payload installed in Virgo in 2010

Unlike Virgo, initial LIGO was provided with less performing vibration isolation: the mirrors were suspended from a bench laying on a stack of metal and rubber layers [31]. One of the most important upgrades to Advanced LIGO is the implementation of new isolators capable of pushing the seismic wall down to 10 Hz [32]. It is made of three different parts:

- a hydraulic external pre-isolator (HEPI) for low frequency control;
- a two-stage actively controlled platform, designed to suppress the seismic noise by $\sim 10^{-3}$ at 10 Hz;
- a quadruple pendulum passive isolation system providing passive isolation above a few Hz.

1.5.4 Monolithic Suspensions

The Virgo low frequency sensitivity was limited by the thermal noise of the steel wires suspending the mirrors. To beat that limit both Advanced Virgo and Advanced LIGO will use *monolithic suspensions*, that is, to suspend the test masses by means of fused silica fibers. The intrinsic dissipation of fused silica is a factor $\sim 1,000$ better than steel, so there is a large potential improvement of the corresponding thermal noise. The pioneering work on this technology was pursued at GEO600 (see [5] and references therein), which has been using *monolithic suspensions* for years. Their design was not pushed to the level required by advanced detectors (for what concerns thickness of the fibers and weight of the mirrors). However, this has triggered a long R&D work that finally allowed to engineer monolithic payloads suitable for advanced detectors.

A further step forward has been achieved when Virgo built monolithic payloads with 21 kg standard mirrors and operated them successfully on the interferometer [33] (see Fig. 1.8). For the first time the *first generation* suspension thermal noise limit was beaten. The realization of monolithic payloads has required several important technological achievements:

Fig. 1.9 The Advanced LIGO
quadruple pendulum
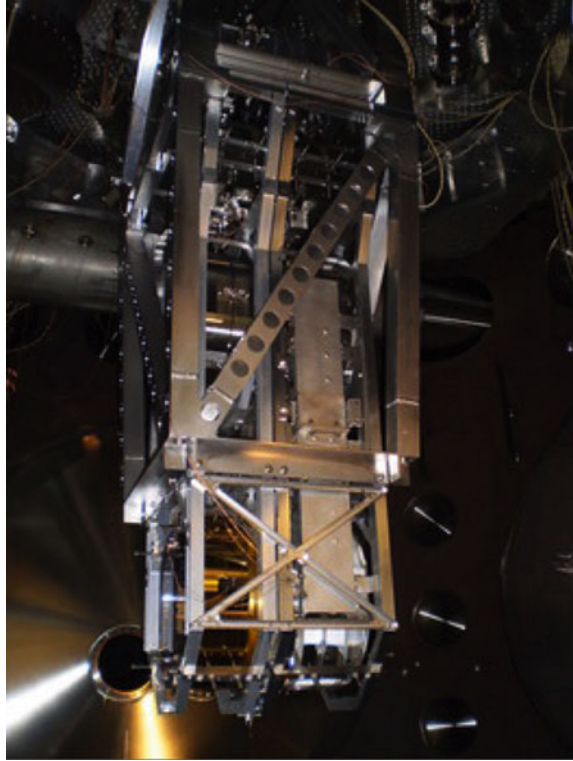
- the production of the fibers: the fibers are produced starting from a fused silica
  rod. The rod is heated in the central part by a CO_2 laser and its two ends are then
  pulled away in a controlled way (the speed profile determines the shape of the
  fiber) [34].
- the handling of the fibers: monolithic payloads have proven to be very robust in
  the usual operation on the interferometers. However, the handling of the fibers
  must be very careful: any contact of the fiber with an external body, no matter how
  gentle and soft, will cause microcracks on the fiber surface that will lead to its
  breaking.
- the attachment of the fiber to the mirror: this is achieved in two steps. First
  an intermediate fused silica block must be attached to the mirror side. This
  is done using a hydroxy-catalyst bond (better know as *silicate bonding*), a
  chemical procedure able to joint the parts in a low loss way (unlike using
  ordinary glues) [28, 29]. The second step is the welding of the silica fiber to
  the intermediate block, which is done again using a CO_2 laser.

The technology has been further refined for the advanced detectors. Advanced
LIGO will use a quadruple pendulum where the last stage (test mass) and the penul-
timate stage are made in silica and connected through silica fibers (Fig. 1.9).

1.5.5 Laser

New lasers are needed for the advanced detectors which plan to improve the high frequency sensitivity by reducing the laser shot noise. The nominal power of such laser is 200 W. The lasers for GW detectors must satisfy stringent requirements:

- continuous, single frequency, single mode;
- high power (10–20 W for the first generation, 200 W for the advanced detectors);
- low noise (frequency, power, geometry);
- long lifetime;
- good efficiency.

In the early phases of interferometer design Argon-ion lasers emitting at 514 nm had been considered and used on prototypes (see for example [35]). Their performance was not satisfactory, mostly for efficiency and reliability. They were phased out as the Nd:YAG amplifiers were developed. Virgo chose the 1,064 nm wavelength first and in 1989 the first 18 W injection locked Nd:YAG amplifier was developed [36–39].

Eventually, all the first-generation detectors were equipped with infrared sources at 1,064 nm (Nd:YAG or Nd:YVO) providing power of 10–20 W. The advanced detectors have been designed assuming an available power of $\sim$200 W. A solid-state laser using a three-stage injection locked oscillator scheme has been developed at the Albert Einstein Institute and Laser Zentrum Hannover and will be used in Advanced LIGO [40, 41].

A different technology has been chosen for Advanced Virgo: a fiber amplifier. Fiber lasers are more efficient (and so it is easier to manage thermal effects), more compact, tunable in power, and have very good performance in terms of noise and stability. They are cheaper than solid-state laser and show great potential for extrapolation to higher power. The development of such amplifier is still in progress. In fact, Advanced Virgo will start its operation with the old solid-state laser of Virgo+, which can provide up to 60 W, more than enough for the first phase of the operation. Implementation of the 200 W fiber laser is foreseen in 2017 or 2018 (see Chap. 4).

1.5.6 Thermal Compensation

Heat absorption in the mirror bulk and in the coatings can induce both geometrical distortions (depending on the thermal expansion coefficient) and purely optical ones (through the temperature dependence of the refraction index). Such *thermal lensing* causes aberrations of the beams and proper thermal compensation systems are needed to cope with it. When the first generation of interferometers was being designed nobody foresaw to introduce actuators to cope with thermal effects. While it was well known that the heat absorption in the mirrors could be a source of thermally induced aberrations [42], their effect was expected to be negligible. During the commissioning

it was found that the impact of thermal effects on the mirrors could be large enough to degrade the performance of the interferometers already at low power. Therefore, techniques to manage such effects had to be implemented. On the other hand, it was also understood that *thermal actuators* could be also used to correct for optics imperfections or to fine-tune the detector. GEO600 installed ring heaters around the tests masses to tune the radius of curvatures and reduce the aberrations observed [43]. LIGO used a flexible thermal compensation system using a CO_2 laser beam to deposit heat on the test mass [44]. A similar system was used in Virgo and was successfully used to increase the power in the interferometer.

In the second-generation detectors, the impact of such effects will be much larger due to the higher power envisaged and the design of the thermal compensation system is rather sophisticated. First of all, it is necessary to act independently to correct the thermal effects both in the Fabry–Perot cavities and in the power/signal recycling cavities.

- The main effect in the Fabry–Perot cavities is associated to the heat absorption in the high reflective coatings which causes a change in the radius of curvature of the test masses via thermoelastic deformation. This will be corrected by using ring heaters around each test mass.
- The input test masses heat up in the center due to absorption of laser power. Since the refraction index is temperature-dependent this effect causes the optical path to be not uniform, which is equivalent to having a spurious lens in the interferometer. This can be corrected by heating up the borders of the mirror in such a way as to null the thermal lensing. In LIGO and Virgo, this has been done by projecting on the mirror a CO_2 laser beam in annulus shape, obtained by an axicon. In Advanced LIGO/Virgo a similar approach will be followed. However, given the increase of power to be managed and the better sensitivity, it will not be possible to shine the CO_2 laser directly on the test masses: the amplitude noise of the CO_2 laser would spoil the detector sensitivity. To solve this problem a further optics, named "compensation plate" will be suspended and the CO_2 laser will be shone on it. Such plate will stay in the recycling cavity, thus its movement is not directly coupled to the dark fringe.

The thermal compensation system described so far can only cope with deformations with cylindrical symmetry. In some cases, non- axisymmetric deformations can play a relevant role.[1] Thus, a thermal compensation system for the non-axisymmetric part should as well be designed. The technology chosen for Advanced Virgo is a scanning laser, first developed by Ryan Lawrence in his PhD thesis [45].

The thermal compensation system needs suitable sensing: Hartmann sensors [46] and phase cameras will be used. The Hartmann sensors are able to measure the thermal deformations, while the phase cameras are suitable to measure the intrinsic optical defects (such as the inhomogeneity of the substrates crossed by the laser

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[1] This is expected in Advanced Virgo, which is designed with so-called *marginally stable recycling cavities*. With such a design the detector is more sensitive to aberrations induced by thermal effects and optical defects. For instance, an inhomogeneous pattern of the refraction index of the mirrors, which can be non-axisymmetric, can cause important aberrations and must be compensated for.

beam). The combination of the information by the sensors and a proper combination of the different actuator should be sufficient to approach an *aberration free interferometer* (in practice, to reduce the aberrations to a tolerable level). This topic is widely discussed in Chap. 9.

1.5.7 Squeezing

Shot noise limits the sensitivity at high frequency. In principle, the possibility to improve it is associated to the progress of the laser technology and the available laser power. In fact, already in the first generation, thermally induced aberrations have been limiting the possibility to increase the power inside the interferometer and thermal compensation systems capable of correcting such aberrations have been implemented. The advanced detectors are designed for an available laser power ten times larger and more sophisticated thermal compensation.

However, another possibility to improve high frequency sensitivity without increasing the thermal load has been put forward by recent experiments: the injection of squeezed light [47] in the interferometer (better known as *squeezing*). Sources of squeezed light have been realized and progressively improved and a gain of 13 dB below the shot noise level has recently been achieved [48].

An experiment of squeezing on a real interferometric detector has been done first by GEO600, achieving promising results. A broadband noise reduction of up to 3.5 dB has been achieved in the shot noise-limited frequency range (Fig. 1.10). This results opens the way to implementing squeezing in the advanced detectors. Chapter 11 is dedicated to this topic.

1.6 Third Generation: The Einstein Telescope

Advanced detectors at their best sensitivity promise to detect tens of events per year. However, the expected signal-to-noise ratios might be insufficient for accurate astronomical and astrophysical studies. Therefore, a natural question arised in the GW community: could we conceive a third-generation detector, able to enhance the sensitivity of the advanced detectors by an order of magnitude and further extend the low frequency bandwidth toward 1 Hz? A large part of the European GW community participated in a design study, funded by the EU within the Framework Program 7, and came up with the proposal of the Einstein Telescope, a large underground and cryogenic interferometer aiming to reach that sensitivity goal.

The sensitivity goals of ET cannot be met within the current infrastructure. On ground, the gravity gradient noise, generated by the fluctuations of the local gravity fields due to seismic oscillations of the ground, couples directly to the test masses and short-circuits the vibration isolators. The only way to suppress such noise is to
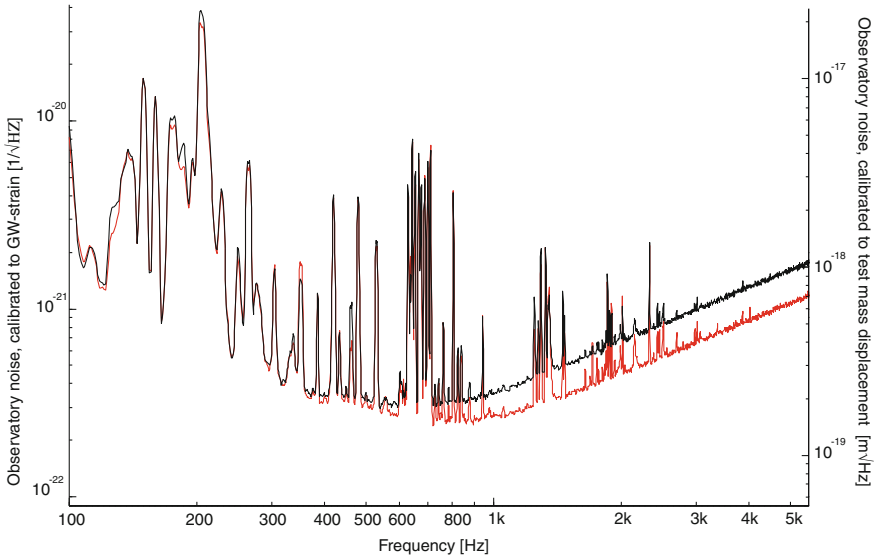
Fig. 1.10 Nonclassical reduction of the GEO600 instrumental noise using squeezed vacuum states of light. Figure from LIGO Scientific Collaboration [49]

go underground, where seismic activity is orders of magnitude lower than on the surface. The following features are envisaged [50]:

- 10 km armlength, underground detector;
- very long vibration isolators, able to push the *seismic wall*[2] down to 1 Hz;
- cryogenic test masses for thermal noise suppression;
- non-gaussian beam profiles, for thermal noise and thermal lensing suppression;
- high power: ∼1 kW laser, high finesse Fabry–Perot arm cavities, high power recycling factor;
- signal recycling and squeezed states injection;
- heavy test masses for suppression of radiation pressure noise.

The observatory will have the shape of an equilateral triangle with 10 km long side (thus, 30 km of tunnel should be excavated). Such infrastructure would host three co-located interferometers.

The science reach of such an instrument would be formidable [51]:

- the high SNR would allow to investigate with great details the physics of compact stars (e.g., constraining the equation of state of neutron stars);
- the details of the waveforms would allow to constrain alternative metric theories of gravity;

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[2] Vibration isolators act as very steep low-pass filters. Therefore, the residual seismic noise transmitted to the mirrors has a spectrum that behaves as ∼$1/f^N$ with $N \gg 1$, looking like a "wall" limiting the sensitivity at very low frequencies.

- cosmological parameters could be measured using standard sirens[3];
- detection of GW and neutrino from a supernova event would allow to constrain the graviton and neutrino masses.

Chapter 13 is dedicated to the ET project while Chap. 14 describes the cryogenics aspects.

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