IL NUOVO CIMENTO **40 C** (2017) 119
DOI 10.1393/ncc/i2017-17119-1

COLLOQUIA: SciNeGHE 2016

Advanced LIGO: Status and prospects

D. HOAK on behalf of the LIGO SCIENTIFIC COLLABORATION

European Gravitational Observatory - Cascina (PI), Italy

received 14 June 2017

Summary. — In September 2015 the Advanced LIGO detectors inaugurated the era of gravitational-wave astrophysics with the observation of GW150914. In this proceeding, I will describe the upgrade that made the detection possible, review the binary black hole observations of the first aLIGO observing run, and discuss plans for the future.

1. – Introduction

On September 14, 2015, the Advanced LIGO detectors observed the coalescence of a pair of black holes [1]. This observation represents the first direct detection of gravitational waves and the first observation of a binary black hole merger, and demonstrates the existence of binary stellar-mass black hole systems. The event was detected following an ambitious upgrade of the initial LIGO detectors, which will ultimately provide ten times the sensitivity of the initial detectors and three times the sensitivity of the instruments at the time of the first detection.

2. – The instruments

The Advanced LIGO interferometers [2] are twin dual-recycled Fabry-Perot Michelson interferometers, designed to observe gravitational waves from astrophysical sources. These second-generation instruments are designed to realize a factor-of-ten improvement in sensitivity beyond the initial LIGO interferometers. Ultimately, the global network of terrestrial gravitational-wave detectors — comprising the two current LIGO sites, the Virgo detector in Italy, KAGRA in Japan, and possibly a third LIGO detector in India — is expected to revolutionize the fields of gravitation and high-energy astrophysics through the direct detection of gravitational waves.

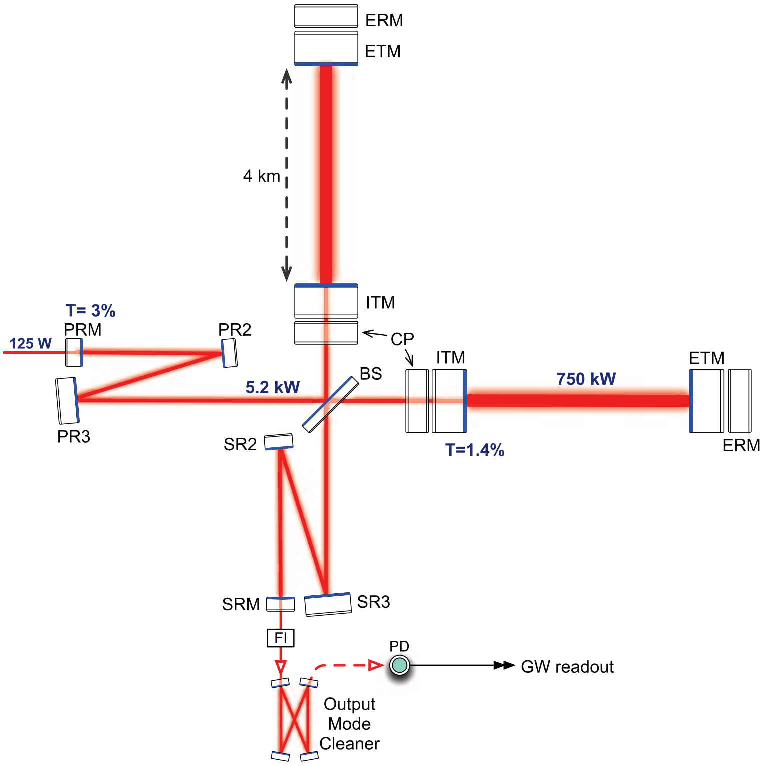

Fig. 1. – Optical configuration of the Advanced LIGO interferometers. Figure from [2].

In Advanced LIGO (fig. 1) the basic design from initial LIGO of a Michelson interferometer with Fabry-Perot arm cavities and power-recycling at the input port has been retained, with the following additions and upgrades:

- A signal recycling mirror has been added to improve the frequency response of the detector.
- Larger test masses (40 kg instead of 10 kg) are used to reduce the effect of suspension thermal noise.
- The isolation systems have undergone a complete redesign and provide a factor of 10^{10} suppression at 10 Hz.
- The reflectivity of the mirrors has been increased, which increases the number of round-trips made by the laser field in the Fabry-Perot arms and amplifies the effect of a gravitational wave signal.
- The laser has been upgraded to a 200 W design.
- The thermal compensation system, to counteract thermal lenses in the optics due to absorption of the main laser power, has been upgraded to include ring heaters and wave-front sensors to actively control the thermal effects.

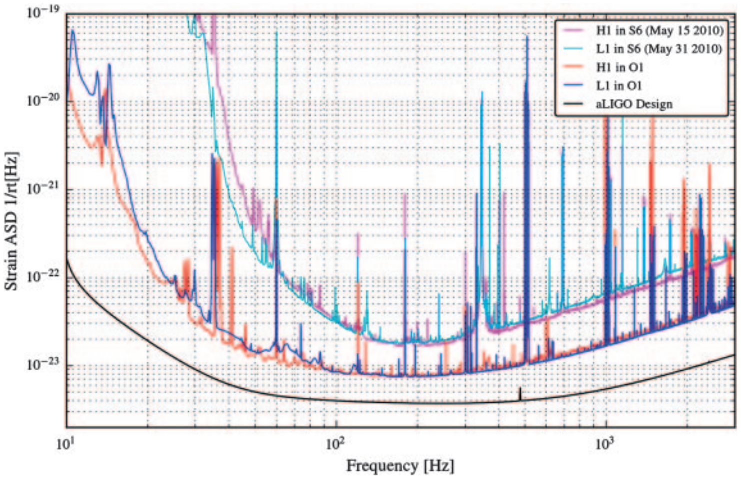

Fig. 2. – Sensitivity of the Advanced LIGO detectors during the first observing run. A comparison is made to the previous best sensitivity (from the last observing run of the first-generation detectors), and the ultimate sensitivity achievable by the advanced detectors.

- All sensing of length and alignment degrees of freedom is performed with in-vacuum photodiodes to reduce the coupling of acoustic noise into control signals.

The introduction of signal recycling has increased the complexity of the detector control topology, and required a redesign of the procedure to bring the instruments from an uncontrolled, nonresonant state, to a condition in which they are sensitive to gravitational signals. This lock-acquisition sequence is described in [3], and utilizes auxiliary lasers to maintain independent control of the different optical cavities before they have reached a fully resonant condition.

The benefit of signal recycling can be seen in fig. 2. Compared to the first-generation detectors, the Advanced LIGO detectors have a broader response to gravitational-wave perturbations. The improvement at high frequency is due to a combination of signal recycling and the increase of the finesse of the Fabry-Perot arm cavities. At low frequencies, the noise has been dramatically improved due to the upgraded seismic isolation systems; the improvement is about a factor of six at 60 Hz.

The sensitivity of the Advanced LIGO instruments is limited by a mixture of technical and fundamental noise sources [4]. At high frequency (above 200 Hz), the detectors are limited by quantum shot noise, due to the discrete nature of light. At low frequencies the sensitivity limit is defined by noise from auxiliary degrees-of-freedom that couple into the gravitational-wave channel.

3. – The first observing run

The two LIGO instruments performed round-the-clock observing operations between September 12, 2015 and January 19, 2016. This observing period is called "O1", for the first observing run of the advanced detector era. During this period the detectors collected about 50 days of coincident operation, with a sufficient sensitivity to detect the inspiral and merger of a binary neutron star (BNS) system out to 70 Mpc [5], a factor of three improvement over the best sensitivities achieved in initial LIGO.

During the observing run, the LIGO instruments made two confident detections of gravitational-wave signals, from the coalescence of binary black hole systems. These events, labeled GW150914 [1] and GW151226 [6], have already become the most stringent test of general relativity in the dynamical strong-field regime [7]. The observations are constraining the rate of BBH in the local universe and have raised questions about the progenitor mechanism for BBH systems [8].

To date, the LIGO-Virgo Collaboration has published several analysis results using the O1 dataset. In particular, the search for gravitational waves from two hundred known pulsars has placed limits on gravitational-wave emission that beats the spin-down limit on eight pulsars [9], and the search for a stochastic background of gravitational wave energy has improved the limit from the first-generation instruments by a factor of about thirty-three [10]. This search is particularly interesting, as rate of BBH coalescences implied by GW150914 and GW151226 indicates that a stochastic background of gravitational waves from unresolved BBH sources may be detectable by the Advanced LIGO instruments at their design sensitivity.

4. – Prospects for the future

In the near future, the LIGO observatories plan to carry out longer-duration observing runs at progressively greater sensitivity, joined by the Advanced Virgo and KAGRA instruments. An approximate timeline for these observing periods, the target sensitivity, and some estimates of the rate of detections is given in [11]. The addition of Virgo and KAGRA, and possibly a third LIGO detector in India, will improve position reconstruction and parameter estimation for gravitational wave events.

The LIGO Collaboration is exploring a variety of options for upgrading the detectors beyond the design sensitivity of Advanced LIGO [12]. In the near term, larger mirrors and improved dielectric coatings will reduce the fundamental noise limit at low frequency, and the use of squeezed light injection will improve the sensitivity at high frequencies. More ambitious upgrades in the next decade could utilize cryogenic environments to reduce the thermal noise from the mirror coatings and suspensions. Completely new facilities, either underground or above ground with significantly longer interferometric arms, could achieve ten times the design sensitivity of Advanced LIGO, and allow us to observe binary black hole coalescences out to redshifts of $z = 3$.

REFERENCES

[1] Abbott B. P. *et al.*, *Phys. Rev. Lett.*, **116** (2016) 6.
[2] Aasi J. *et al.*, *Class. Quantum Grav.*, **32** (2015) 074001.
[3] Staley A. *et al.*, *Class. Quantum Grav.*, **31** (2014) 245010.
[4] Martynov D. V., Hall E. D. *et al.*, *Phys. Rev. D*, **93** (2016) 112004.
[5] Abbott B. P. *et al.*, *Astrophys. J. Lett.*, **832** (2016) L21.
[6] Abbott B. P. *et al.*, *Phys. Rev. Lett.*, **116** (2016) 241103.
[7] Abbott B. P. *et al.*, *Phys. Rev. X*, **6** (2016) 041015.
[8] Abbott B. P. *et al.*, *Astrophys. J. Lett.*, **818** (2016) L22.
[9] Abbott B. P. *et al.*, arXiv:1701.07709 (2017).
[10] Abbott B. P. *et al.*, *Phys. Rev. Lett.*, **118** (2017) 121101.
[11] Abbott B. P. *et al.*, *Living Rev. Relat.*, **19** (2016) 1.
[12] Abbott B. P. *et al.*, *Phys. Rev. Lett.*, **116** (2016) 131103.