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1997 Class. Quantum Grav. 14 1471

(http://iopscience.iop.org/0264-9381/14/6/012)

Class. Quantum Grav. **14** (1997) 1471–1476. Printed in the UK PII: S0264-9381(97)81864-3

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Received 15 August 1996, in final form 3 February 1997

Abstract. GEO600†, an interferometric gravitational-wave detector with an arm length of 600 m, is currently being built in northern Germany close to Hannover. GEO600 incorporates an externally modulated fourfold delay-line Michelson interferometer giving a round-trip optical length of 2400 m. A master–slave combination of a monolithic diode-pumped Nd:YAG ring laser and an injection-locked amplifier will give a light power of about 10 W at a wavelength of 1064 nm. Power recycling increases the light power inside the interferometer to a level of about 10 kW. The use of both power and signal recycling will yield a sensitivity of the same order of magnitude as the first stages of the other large-scale gravitational-wave detectors LIGO and VIRGO currently under construction. High signal recycling factors allow the sensitivity to be increased at a chosen frequency while reducing the bandwidth of the detector. This gives an advantage over broad-band detectors in detecting narrow-band periodic sources such as pulsars. The 25 cm diameter mirrors will be suspended as double pendulums from a platform supported by vibration-reduction systems. The passive filtering properties of this system sufficiently reduce the seismic noise in the frequency range of interest, i.e. 50–1000 Hz. The detector will start taking data in the year 2000.

PACS numbers: 0480N, 9555Y

1. Introduction

GEO600 is an interferometric gravitational-wave detector (IGWD) built by a German–British collaboration involving the University of Glasgow, the University of Wales (Cardiff), the Albert-Einstein-Institut in Potsdam, the University of Hannover and the Max-Planck-Institut für Quantenoptik in Garching with a team in Hannover. The detector is being built in northern Germany about 20 km south of the city of Hannover.

2. Experimental aspects

2.1. Noise sources

The overall sensitivity of an interferometer is usually limited by three different noise sources. In the low-frequency range, i.e. below 10–100 Hz, the sensitivity is limited by residual seismic ground motion coupling to the test masses. In the frequency range above several 100 Hz photon shot noise usually governs the noise spectrum. The most sensitive range of GEO600 (100 Hz to several 100 Hz) is limited by the thermal noise of the test masses.

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† GEO600 home page: http://www.geo600.uni-hannover.de

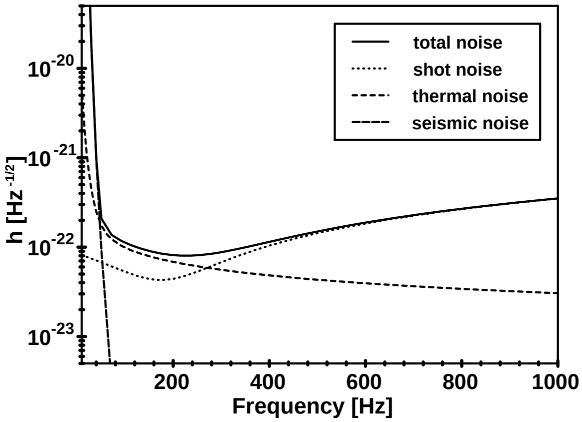

Figure 1. Contributions of the most important noise sources to the sensitivity limitations of GEO600. Shown is the linear spectral density of an apparent gravitational-wave signal.

2.1.1. Seismic noise. Seismic ground motion can change the distances of the test masses in an IGWD and must therefore be isolated. GEO600 uses different passive isolation systems to reduce the ground motion by about 10 orders of magnitude at 100 Hz (see figure 2). Two stacks of alternating stainless steel (SS) and rubber (graphite-loaded RTV) layers carrying a SS ring platform serve as a first attenuation stage. The stacks are encapsulated by SS bellows which are grease coated inside to dampen bellow resonances. A second platform, smaller in diameter, is held by cantilever springs attached to the outer ring. This second platform carries a movable upper stage which in turn holds a double pendulum with the test mass. The double pendulum is attached to the upper stage by double-leaf springs. The cantilever springs and the leaf springs improve vertical isolation. A rotational flexure holding the cantilever springs gives additional isolation for rotational seismic motion of the vacuum tank.

2.1.2. Thermal noise. Another important noise source directly affecting the position of the reflecting mirror surfaces is thermal noise. Mechanical losses that cause internal oscillations of the test masses to be dissipated into Brownian motion, i.e. heat, can also work the other way and excite macroscopic mechanical oscillations of the optical elements from Brownian motion. As the off-resonance amplitude of this thermal noise rises with increased mechanical losses, the mechanical Q-values of the optical elements as well as their suspensions have to be high to keep the noise low. For the thermal noise contribution shown in figure 1, fused silica test masses welded to fused silica fibres with Q-values of 5×10^6 and 10^7 for internal modes and for the suspensions, respectively, have been assumed.

2.1.3. Shot noise. The light power (P_{out}) at the output port of a Michelson interferometer varies with the cosine squared of the arm length difference δL. A natural choice for maximum sensitivity to changes of δL would therefore be the maximum of $\partial P_{\text{out}}/\partial\delta L$ which is at $P_{\text{out}} = P_{\text{in}}/2$ with P_{in} being the light power injected into the interferometer. Amplitude noise in the laser light, e.g. the photon shot noise due to the Poisson statistics of classical laser light, will give intensity noise in the output indistinguishable from a gravitational wave signal. With N being the number of photons returning from the interferometer arms per measurement interval, and thus being proportional to the signal strength, the noise is $\sqrt{N}$,

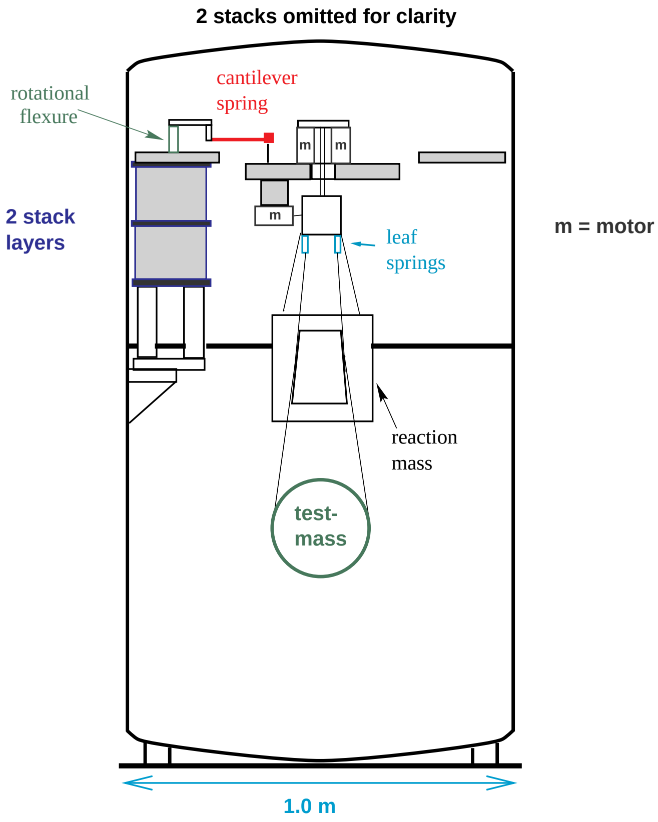

Figure 2. Side view of a vacuum tank with the seismic isolation system.

(This figure can be viewed in colour in the electronic version of the article; see `http://www.iop.org/EJ/welcome`)

giving an S/N ratio of $1/\sqrt{N}$. Technical problems associated with the high light power on the photodetector can be reduced by setting δL to get a dark output port, which in turn gives far less sensitivity as then $\partial P_{\text{out}}/\partial\delta L = 0$. Using heterodyne techniques, e.g. external modulation [6], solves the problem but it turns out that the shot noise problems remain the same and the S/N ratio is not improved [2]. Enhancing the light power inside the interferometer on the other hand improves the S/N ratio. If the output port is kept dark most of the light power (except the small amount lost due to mirror imperfections) returns to the input port and is wasted for the further detection process. Placing an additional mirror in the input port 'recycles' the light and thus forms a cavity consisting of the interferometer acting as one mirror and the additional, so-called 'power recycling' (PR), mirror [4]. With the proper position of the PR mirror the light power resonantly builds up in the PR cavity and reduces the shot noise limit. GEO600 will incorporate 2000-fold power recycling, giving a light power in the interferometer of approximately 10 kW. The signal sidebands exiting through the output port can be recycled in a similar way, called 'signal recycling' (SR), to enhance the signal strength [3]. The bandwidth of the SR is given by the linewidth of the SR cavity and can thus be chosen by the reflectivity of the SR mirror. The frequency of maximum sensitivity is determined by the position of the SR mirror. Figure 3 shows the shot noise levels for different optical layouts of the interferometer.

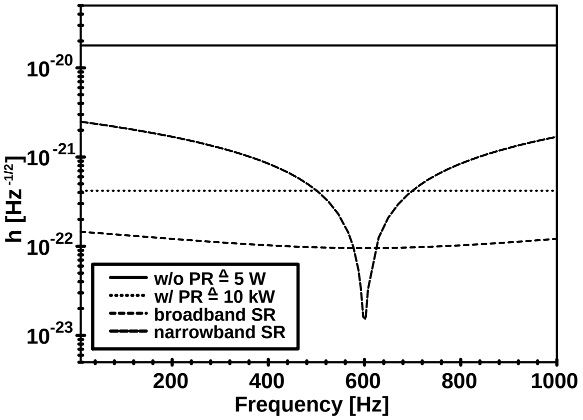

Figure 3. Shot noise levels for different optical configurations. The linear spectral density of an apparent gravitational-wave signal is shown.

2.2. *Optics*

After passing two successive triangular mode cleaners the beam of a stabilized Nd^{3+}:YAG laser is expanded to match the mode of the PR cavity. In addition to the PR and SR mentioned above the sensitivity is increased by folding the optical path in each interferometer arm to give a round-trip length of 2400 m. The main mirrors with a diameter of 25 cm and a thickness of 10 cm will be made of fused silica and the beamsplitter with a diameter of 30 cm and a thickness of 8 cm will be made of OH-free fused silica.

2.2.1. The laser. A Nd^{3+}:YAG laser in a master–slave configuration will give single-mode, single-frequency light at 1064 nm. A monolithic diode-pumped Nd^{3+}:YAG ring laser which is stabilized onto external cavities will serve as the master laser. Injection locking to an end-pumped Nd^{3+}:YAG laser delivers 10 W of light power with the noise characteristics of the master laser.

2.2.2. The mode cleaners. Two triangular mode cleaners (MC) with a finesse of about 1000 are used to filter the laser light with respect to spatial, amplitude and frequency fluctuations before injecting it into the PR cavity [5]. The frequency range most important for the laser stability is the modulation frequency of approximately 10 MHz. There the MCs with a round-trip length of approximately 8 m provide good enough filtering. The output mirror of the second MC serves as a lens for matching the laser beam to the fundamental mode of the PR cavity.

2.2.3. External modulation. GEO600 employs external modulation [6], i.e. the output of the interferometer is superimposed with a phase-modulated local oscillator in an additional Mach–Zehnder interferometer to give (after demodulation) a signal proportional to the amplitude of the gravitational wave. Since external modulation is independent of arm length differences the requirements of laser frequency stabilization can be relaxed in the case of equal arm lengths. It also gives the advantage to be free in choosing the modulation frequency independently of arm length differences or the free spectral range of the PR cavity.

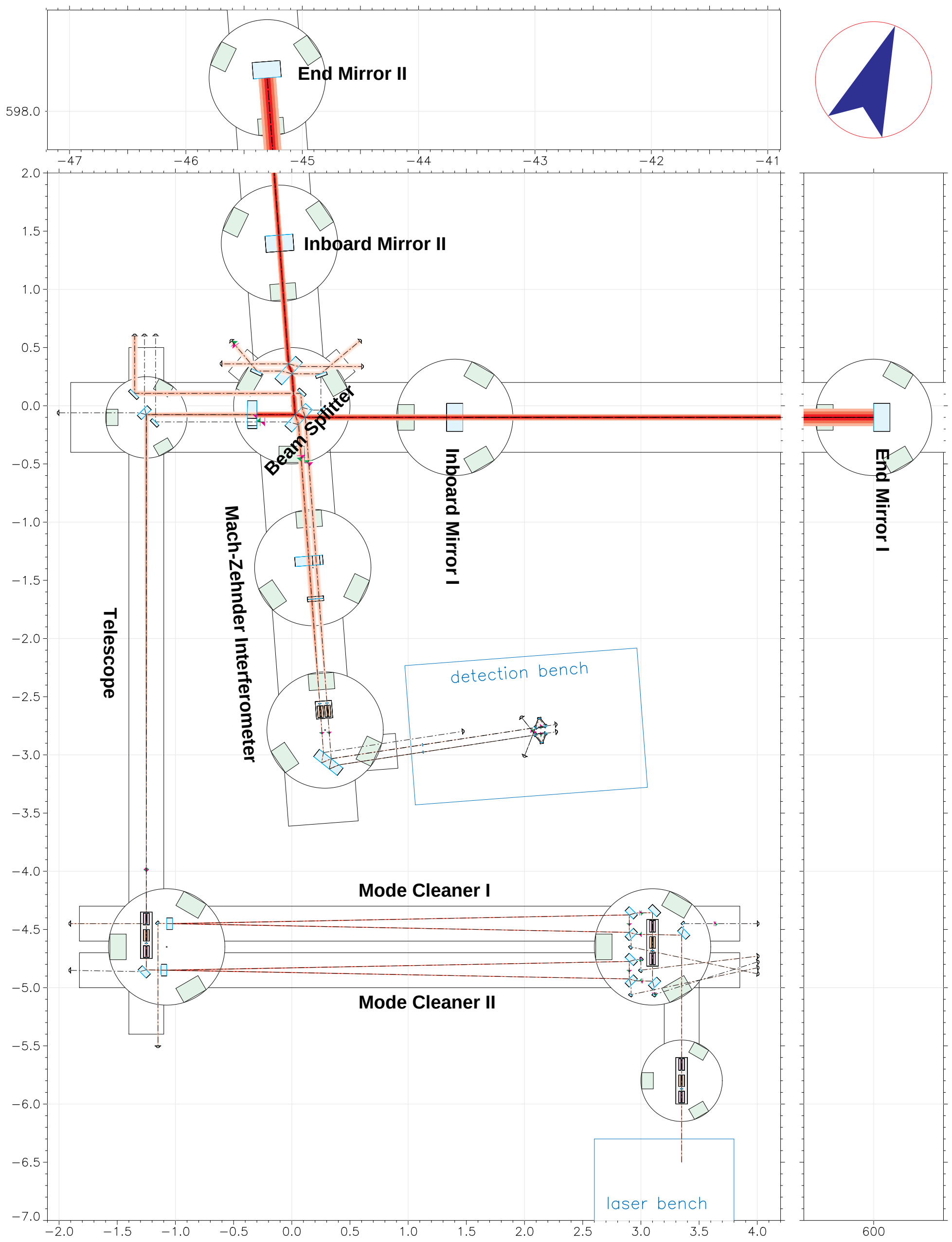

Figure 4. The optical layout for GEO600. The beam's path in the interferometer arms is folded in the vertical direction, hence the outgoing and the returning beams are vertically spaced by 25 cm at the location of the inboard mirrors. The three rectangles in each vacuum tank close to the walls are supports for the seismic isolation system. The beam intensity is coded in three different shades of grey (red in the electronic version) giving the diameter where the intensity has dropped to e^{-2}, e^{-4}, e^{-9}. The scale is in metres.

(This figure can be viewed in colour in the electronic version of the article; see `http://www.iop.org/EJ/welcome`)

2.3. The vacuum system

Fluctuations of the refractive index change the length of the optical path in the interferometer. Only at partial pressures below 10^{-8} mbar for H_2 and 10^{-9} mbar for other gases are these fluctuations small enough to become unimportant in the overall noise budget. The vacuum system consists of five sections separated by all-metal gate valves: three tank sections containing one tank at the end of each interferometer arm and a cluster of nine tanks at the vertex of the interferometer connected by 600 m long vacuum tubes. The whole vacuum system is made of SS. Most tanks have a diameter of 1 m and are 1.9 m high. The main vacuum tubes of 0.6 m in diameter are made of 0.8 mm thick SS (AISI 316L) and are corrugated for mechanical stability against the outside air pressure. Low out-gassing rates are achieved by air and vacuum baking the tubes at temperatures of 250 °C and 150 °C, respectively. Total pressure monitoring is done with Pirani and Penning gauges. Partial pressures are read with quadrupole mass spectrometers.

3. Current status

In August 1996 the buildings as well as the trenches were finished. Except for the 600 mm gate valves the vacuum system is purchased. Tube installation is about to commence. The seismic isolation system is currently being tested.

4. Time scales

The vacuum system will be finished by the end of 1996. The mode cleaners as well as the laser bench will be installed in the middle of 1997. By the end of 1998 one of the interferometer arms will serve as a 1200 m cavity with the laser locked to it. After the final optics are installed, data taking in the spring of 2000 will lead to the first signals to be analysed.

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