The GEO 600 Gravitational Wave Detector

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Abstract

The GEO 600 Gravitational Wave Detector is currently under construction near Hannover/Germany as a collaboration of scientists from Germany and Great Britain. Although only intermediate in size, the GEO 600 detector has a good chance to achieve a sensitivity comparable to the first version of the large baseline detectors. This is due to the fact that GEO 600 uses signal recycling, an advanced optical technique to shape the coupling of the optical read-out-noise into the detector strain-sensitivity, and a low-loss suspension system to reduce thermal noise. This talk will describe the different subsystems of the GEO 600 detector and the current status of the construction will be outlined.

1. Introduction

An international network of earth-bound laser-interferometric gravitational wave detectors is currently under construction [1]. A summary of the current understanding of astrophysical sources for gravitational waves and on predicted event rates is given in [9]. Although the expected sensitivities of the detectors under construction might be high enough to detect the first gravitational waves, only future detector generations with advanced technologies promise an event rate suitable for gravitational wave astronomy.

This contribution will focus on the GEO 600 interferometer, which will be one of the detectors in the international network and also serve as a testbed for advanced technologies. The GEO 600 detector was designed based on the experience with two prototypes, the 10 m interferometer in Glasgow and the 30 m interferometer in Garching, near Munich. The construction started in 1995 as a German/British collaboration on a site near Hannover in Germany. The optical layout incorporates power and signal recycling and an injection-locked laser system filtered by two suspended modecleaners will be used. The suspension systems of the main optics is base on a triple pendulum design to isolate the mirrors from seismic noise and a monolithic last pendulum stage will provide a low loss environment to minimize the thermal noise. Due to the limited funding of the project an armlength of only 600 m was chosen.

This contribution will describe the GEO 600 subsystems and give an overview on their current status. Some aspects which are the subject of later talks at this conference are covered only briefly.

2. The GEO 600 concept

The GEO 600 detector topology is a dual-recycled laser interferometer with four-fold delay lines in the 600 m long arms (see Figure 1).

An injection-locked laser system, the frequency of which is pre-stabilized to a fixed spacer reference resonator, is used as the light source of the interferometer. This laser has an output power of 12 W. Due to space limitations in the central building of GEO 600 two sequential suspended modecleaners with 8 m round-trip length will serve as spatial filters of the laser beam before it is injected into the power recycling cavity. A power recycling factor of 2000 is anticipated to increase the stored power to 10 kW. The Pound-Drever-Hall technique [3] is used to achieve an error signal for the length control system of the modecleaner cavities and the power recycling cavity, whereas a frontal modulation technique will be implemented to get informations on the differential interferometer armlength and
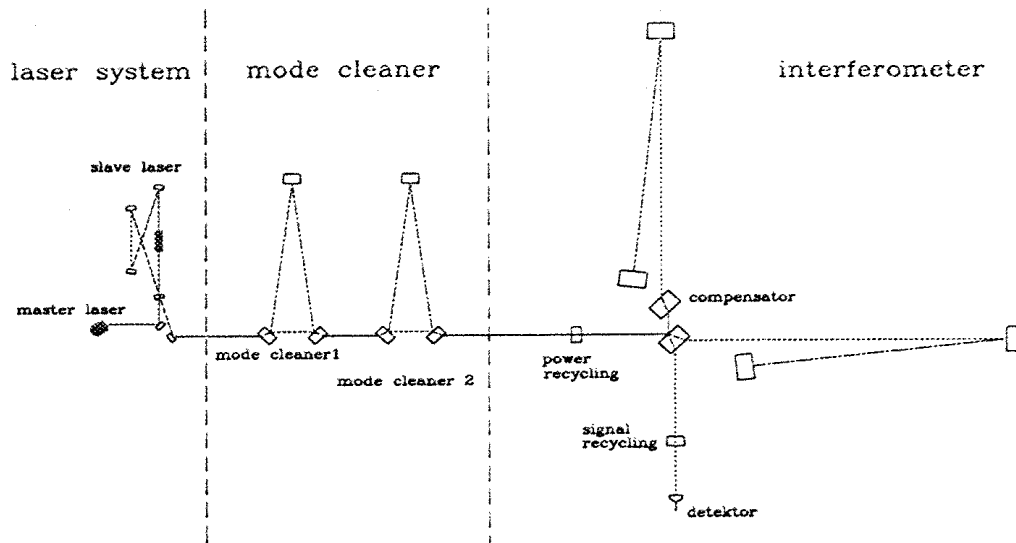
Fig. 1. The optical layout of GEO 600

for the length control system of the signal recycling cavity. The angular degrees of freedom of the cavities and the interferometer will be controlled by automatic beam alignment systems [5].

Three main noise sources will limit the expected sensitivity of the GEO 600 detector as shown in Figure 2. The low frequency range below 30 Hz will be limited by seismic noise. In the intermediate region thermal noise will be the main contribution and shot noise on the interferometer output photo-detector will dominate the noise spectral density in the high fourier frequency range. Other noise sources like radiation pressure noise, residual gas fluctuations, gravity gradient noise or laser noise are omitted in this figure as they are not expected to limit the performance of GEO600.

One feature of Figure 2 is special for GEO600, which is the shape of the shot noise curve. The use of signal recycling allows to shape the appearance of the shot-noise curve in the strain-sensitivity plot. Due to the buildup of the signal sidebands in the signal recycling cavity the absolute sideband field at the read-out photo-detector is increased. As the shot noise at the output photo-detector is dominated by the power of the modulation sidebands the signal-to-shotnoise ration is increased as well. In other words the buildup of the signal sideband in the signal recycling cavity reduces the apparrent shot noise at fourier frequencies where the signal recycling cavity is resonant. The bandwidth of the dip in the shot noise curve is defined by the reflectivity of the signal recycling mirror whereas the dip-position can be varied by changing the position of the signal recycling mirror.

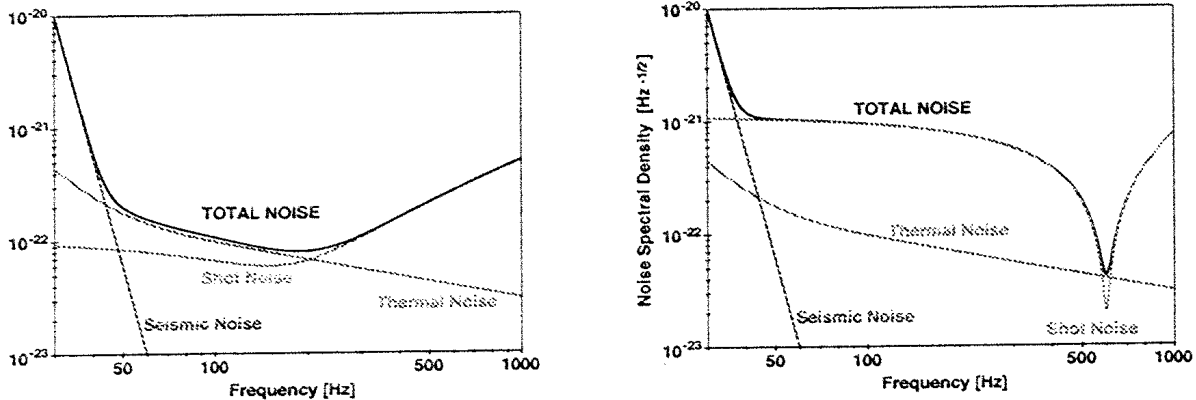The limit to which the total noise curve can be reduced by signal recycling

Fig. 2. Expected noise spectral density of the GEO600 detector shown in two different modes of operation: broad-band (left) and narrow-band (right).

is given by the thermal noise of the test-masses and their suspensions. According to the fluctuation-dissipation theorem low thermal noise corresponds to a high mechanical quality factor Q and a low loss design. Fused silica is known as a low loss material and hence GEO 600 uses fused silica test masses and fused silica fibers to suspend these test masses as pendulums.

Two more pendulum stages together with one active and one passive so-called stack-layer are used to isolate the test masses from seismic motion and from noise of control-loop actuators which are needed at different layers of this isolation system.

3. Buildings and Vacuum System

To avoid fluctuations of the optical path length caused by a fluctuating index of refraction, the whole interferometer has to be set up in a high vacuum system. For this purpose GEO 600 uses two 600 m long vacuum tubes of 60 cm diameter which are suspended in a trench under ground (see Figure 3, left picture). A novel convoluted tube design which allows a wall thickness of only 0.8 mm was used to reduce weight and cost of the stainless-steel vacuum-tube. Baffles are installed inside the tube to avoid stray-light reflections by the shiny tube wall. Each tube was baked for two days in air at 200°C and for a week under vacuum at 250°C. Currently the pressure in the beam tubes is in the upper 10^{-9} mbar region.

One central building (13 m x 8 m in size) and two end buildings (6 m x 3 m) accommodate the vacuum tanks (2 m tall) in which the optical components
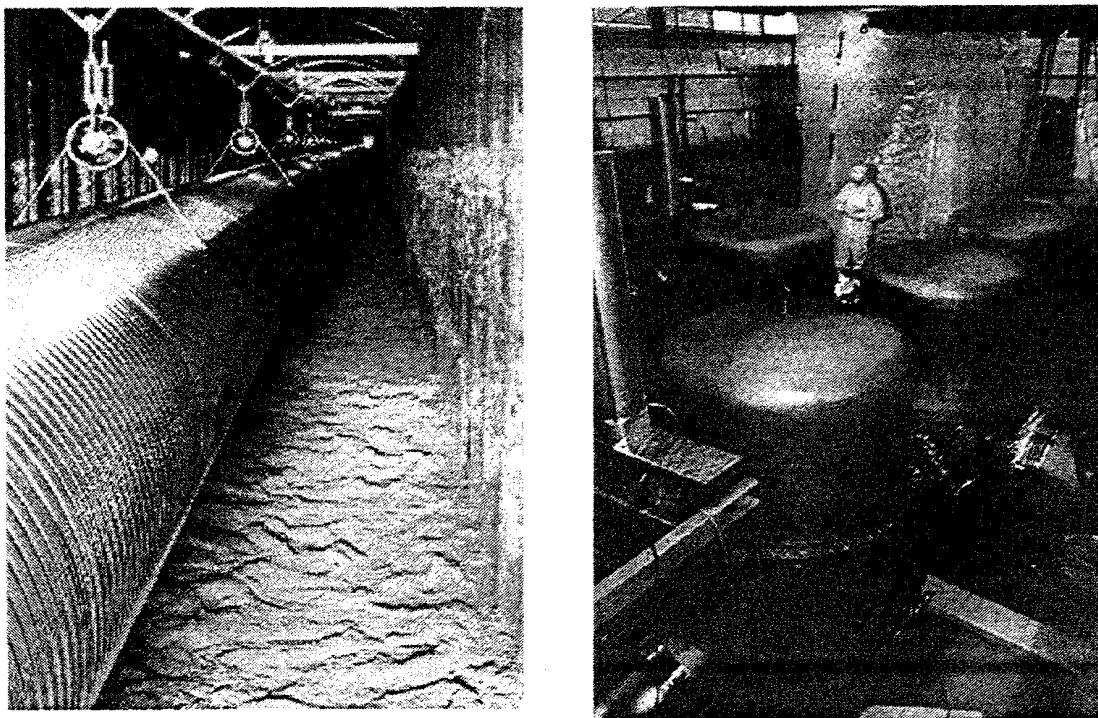
Fig. 3. The convolute beam tube and the central building of GEO 600. The tube has a diameter of 60 cm and a wall thickness of 0.8 mm. The tanks are 2 m tall and accommodate the triple-pendulum suspensions of the interferometer mirrors.

are suspended. Eight of these tanks form a cluster in the central building (see Figure 3, right picture) which can be divided into three sections to allow mirror installation without venting the whole cluster. Therefore only short down-times are expected for a change of the signal recycling mirror which is needed to change the detector bandwidth.

The whole vacuum system except of the modecleaner section is pumped by four magnetically levitated Turbo pumps with a pumping power of 1000 l/s (nitrogen) each backed by a Scroll pump (25 m^3/h). A dedicated turbo-pumping system is used for the modecleaner section.

Great care was taken to minimize contamination of the vacuum system by hydrocarbons. For this reason the seismic isolation stacks, which include rubber and other non hydrocarbon-free materials are sealed by bellows and pumped separately.

The buildings of GEO 600 are split into three regions with different cleanroom classes: The so-called gallery were people can work with normal clothes, the inner section which has a cleanroom class of 1000 and a movable cleanroom tent installed over open tanks with a class 100 cleanroom.

4. Laser System & Modecleaners

The GEO 600 laser system is based on an injection-locked laser-diode pumped Nd:YAG system (see Figure 4) with an output power of 12 W. A non-planar ring-oscillator (NPRO) with an output power of 0.8 W is frequency stabilized to a reference cavity with a servo bandwidth of 1 MHz and an error-point noise of less than 1 mHz / $\sqrt{Hz}$ for fourier frequencies below 1kHz was achieved. Two Nd:YAG crystals, each pumped by a fiber-coupled laser-diode with a power of 17 W, are used as the active medium in the four-mirror slave ring-cavity. Three of these mirrors and a piezo-electric transducer carrying the fourth mirror are mounted on a rigid copper spacer to increase the mechanical stability of the slave laser cavity. The PZT is used to control the length of the 45 cm long slave resonator to keep the slave laser frequency within the injection locking range of 1.6 MHz. Two Brewster plates are implemented in the slave cavity to define the polarization direction, reduce depolarization losses and compensate for the astigmatism introduced by the curved mirrors of the slave resonator. The good spatial beam quality ($M^2 \leq 1.05$) of the injection locked laser system allowed us to couple 95 % of the light into a Fabry-Perot resonator. The frequency noise of the injection-locked laser system was measured to be dominated by the master laser frequency fluctuations. The free-running intensity noise, which is in the $10^{-6}/\sqrt{Hz}$ region for fourier frequencies between 10 Hz and 1 kHz is dominated by fluctuations of the slave laser pump diodes. A detailed description of the GEO 600 laser system is given in [2].

Currently a prototype version of the frequency stabilized 12 W laser system is set up and works reliably. Although the error point frequency noise meets the requirement, a measurement with respect to an analyzer cavity shows a 2-3 order of magnitude higher noise level, which is probably caused by seismic-noise-coupling into the non-suspended cavities. We expect a reduction of this out-of-loop frequency noise as soon as the reference cavity is suspended and the suspended GEO 600 modecleaner is used as an analyzer cavity.

Two suspended modecleaners will be used in the GEO 600 detector as spatial filters of the laser beam. The modecleaner mirrors are suspended on damped double pendulums, the suspension point of which is at a top-plate supported by three two-layer seismic-isolation stack. Two vacuum tanks connected by two parallel vacuum tubes accommodate both modecleaner ring cavities which have a round-trip path-length of 8 m and a linewidth of 20 kHz. An additional double-pendulum, the so-called reaction pendulum, is suspended adjacent to one of the modecleaner mirrors. This reaction pendulum has three coils mounted to its lower mass which serves together with three magnets glued to the corresponding mod-
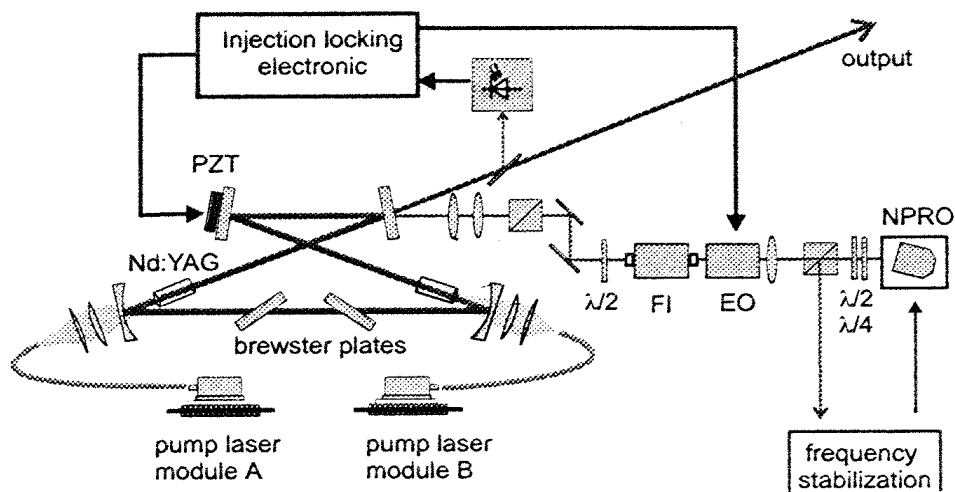
Fig. 4. Setup of the GEO600 high power laser system. A frequency-stabilized NPRO with 1 W output power is used as a master laser. The injection-locked slave laser with 12 W output power and a $M^2 \leq 1.05$ is pumped by two fiber-coupled diode-laser-modules each with 17 W optical power.

ecleaner mirror as fast actuator for the modecleaner length control system. The angular degrees of freedom of both modecleaners will be controlled by so-called auto-alignment systems, which feed back to the intermediate pendulum stage by biasing the coil-magnet units used for the local damping.

Both modecleaners are installed and lock reliably to a frequency stabilized 1 W NPRO currently used as the light source at the site. Work on the automatic lock-acquisition, the auto-alignment and the optimization of the modecleaner control systems is currently under way.

5. The GEO600 Main Suspension System

One of the most important sub-systems in a laser interferometric gravitational wave detector is the seismic isolation and suspension system. The design of this subsystem will determine the spectral density of two of the three limiting noise sources of GEO 600, namely the seismic noise and the thermal noise. GEO 600 will use an active/passive two layer seismic isolation stack, a rotational flexure stage, two vertical cantilever-spring stages and a triple horizontal pendulum system to reduce the influence of seismic noise on the testmasses (see Figure 5). The last pendulum stage will be made exclusively out of fused silica to reduce thermal noise. A detailed description of the suspension system can be found in [4,6].

Based on two models, one with a Lagrangian and one with a Newtonian approach, the suspension system was designed to meet the following design goals:
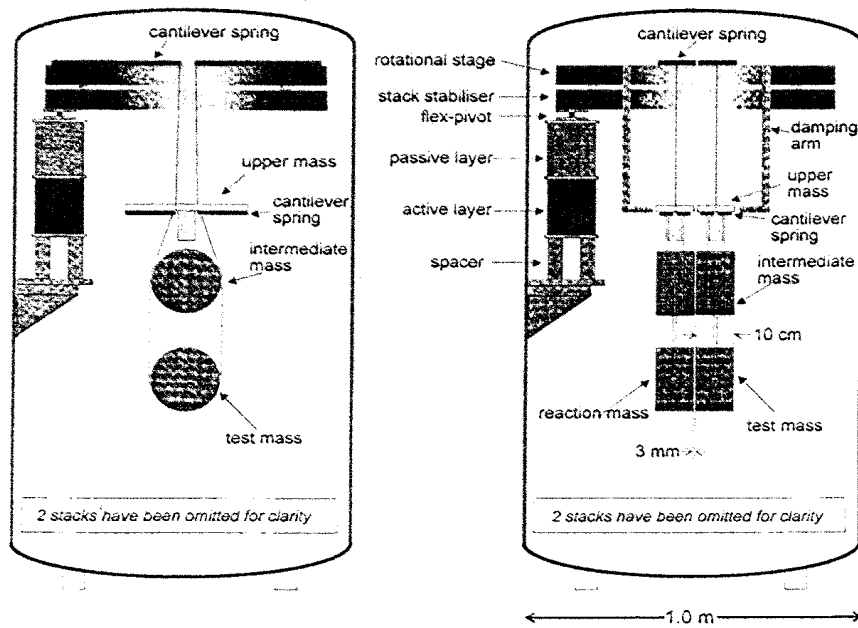
Fig. 5. The GEO 600 main suspension system. Two stack layers (one active, one passive), a rotational flexure, two vertical cantilever stages and a triple horizontal pendulum is used to isolate the test mass from seismic noise. The lower pendulum stage is a monolithic fused silica design to minimize thermal noise.

a seismic noise isolation factor of 6×10^9 in the horizontal direction and 6×10^6 in the vertical direction at 50 Hz, all mechanical resonance frequencies except the modes involving extension of the lower pendulum wires have to be between 0.5 Hz and 5 Hz and all modes couple well into a motion of the upper pendulum mass where co-located control systems will damp the pendulum modes. Similar to the modecleaner system a reaction mass pendulum will be installed adjacent to one of the test masses in each interferometer arm to allow fast feed-back of the length control system. In contrast to the magnetic actuator used in the modecleaners we will use electro-static actuators for the main optics.

To minimize the internal and the pendulum thermal noise the test masses and the suspension fibers of the lowest pendulum stage will be made out of high quality fused silica. Table 1 shows the used dimensions and the used materials for the main optics. The application of a new technique call hydroxide-catalysis bonding [7] promises to solve the low-loss attachment problem of the high Q fibers to the high Q substrates.

Design and engineering prototypes of the seismic isolation system were built and this fall the installation of the first main suspension system in the GEO 600 vacuum system will start. The test optics, which will be used during the

Table 1. Size and material of the GEO 600 main optic

optic	diameter	thickness	material [HERAEUS trade name]
main mirrors	18 cm	10 cm	Suprasil 1
beam splitter	26 cm	8 cm	Suprasil 311 SV
recycling mirrors	15 cm	7.5 cm	Suprasil 2

installation phase, are polished and will be coated within the next months. Only one of these test mirrors will be suspended monolithically to test the installation procedure.

6. Detector Control and Data Acquisition

GEO 600 has four suspended cavities and the suspended interferometer which need length and auto-alignment control systems. We use the Pound-Drever-Hall scheme to get an error signal for the length control systems of the modecleaner and the power recycling cavity. The phase modulation sidebands needed for the modecleaner lock are generated in electro-optical modulators before each mode-cleaner. The sidebands for the power recycling cavity lock are generated in the modulator before and transmitted through the second modecleaner. A third modulator is placed behind the second modecleaner to generate phase modulation at two additional frequencies. Demodulation of the light at the interferometer output at one of these frequencies gives the information needed for the Michelson lock. Phase-sensitive detection of light in one interferometer arm is used to achieve the error signal for the length control system of the signal recycling cavity.

In addition the laser frequency has to be pre-stabilized to enable lock acquisition of the suspended cavities. For low fourier frequencies the power recycling cavity will be locked to the laser. The laser fluctuations in the gravitational wave band will be reduced with respect to the power recycling cavity by adding a control signal into the feed-back loop that locks the pre-stabilized laser to the reference cavity. The power noise of the laser will be sensed before and after the modecleaners and fed back to the slave pump diodes.

Although all these degrees of freedom will be controlled by analog feed-back systems a LabView computer program will have authority to allow pre-alignment, guide lock acquisition, monitor the detector status and compensate for long term drifts. In addition this program will control the long term behavior of pendulum damping systems.

Two different sampling rates (8 kHz and 512 Hz) are used in the data ac-

quisition system (DAQ) of GEO 600, which is very similar to the one designed for the LIGO detector. In the central building 32 fast channels and 64 slow channels are available and in each end building we can use 16 fast channels and 64 slow channels. All these channels will be available to a program called TRIANA [8] to analyze the data at the site for detector characterization and debugging purposes. A selection of those channels together with information coming from the LabView control program will be combined to a data stream with a data rate of aproximately 0.5 Mbyte/s and sent via a radio link to Hannover where the data will be stored. From here the data will be distributed to the data analysis groups whereas the time critical data analysis will be performed in Hannover.

7. Outlook

Over the last years GEO600 finished the buildings and the vacuum system. The two modecleaners are installed and locked to a pre-stabilized laser. Over the next month we will install the main suspension system for the mirrors in one interferometer arm and for the power recycling mirror. Following this installation we will work on a 1200 m long cavity to get experience with optical systems of that dimension. After that an upgrade of the system to a michelson interferometer first with power recycling only and later with power and signal recycling is planned. During the learning phase we expect that we have to open the vacuum system for a number of times . To avoid contamination or damage of the high quality mirrors we will work with test mirrors suspended in steel wires until we have a good understanding of the systems behavior. The last step will be to change to the monolithic suspended high quality mirror pendulums. GEO600 expects to start with the first data run at the end of the year 2001.

8. References

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