The Modecleaner System And Suspension Aspects Of GEO 600

S Gossler †§, M Casey ¶, A Freise †, H Grote †, H Lück †‡, P McNamara ¶, M Plissi ¶, D I Robertson ¶, N A Robertson ¶, K Skeldon ¶, K Strain, C Torrie ¶, H Ward ¶, B Willke ‡, J Hough ¶and K Danzmann †‡

†Universität Hannover, Institut für Atom-und Molekülphysik, Abteilung Spektroskopie, Callinstrasse 38, D-30169 Hannover, Germany
‡Albert-Einstein-Institut für Gravitationsphysik, Aussenstelle Hannover, Callinstrasse 38, D-30169 Hannover, Germany
¶Department of Physics and Astronomy, Kelvin Building, University of Glasgow, G12 8QQ, Scotland, United Kingdom

Abstract.

GEO 600 uses two 8 m triangular ring cavities as a modecleaner system for the stabilisation of the laser. To isolate the cavities with respect to the seismic noise the optical components are suspended as double pendulums. The resonances of these pendulums are damped by a local-control loop via magnet-coil actuators acting on the intermediate masses. The suspension scheme and the measured key data (i.e. finesse, linewidth, visibility, throughput and in-lock durations of the cavitys, as well as the isolation performance and the resulting frequency stability) of the modecleaner system will be given in this article. Furthermore an overview of the GEO 600 interferometer suspension will be given.

Submitted to: *Class. Quantum Grav.*

PACS numbers: 04.80Nn, 95.55.Yn

1. Introduction

The assembling of the British-German interferometric gravitational wave detector GEO 600 in Ruthe close to Hannover, Germany is nearly completed. All the optical components except for the signal-recyling mirror are already installed and the modecleaner system is optimized to a sufficient state. [8]

It is necessary to isolate the gravitational wave detector and the injection optics against the seismic noise, which follows a $10^{-7}/\mathrm{f}^2\,\mathrm{m}/\sqrt{\mathrm{Hz}}$ slope above 10 Hz at the site to meet the sensitivity goals of GEO 600. Furthermore the Michelson interferometer as well as

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§ To whom correspondence should be addressed (`sfg@mpq.mpg.de`)

the modecleaner system needs to be operated in an ultra high vacuum.
The light source is a 1 W nonplanar ring oscillator (NPRO) of the company Innolight as a master laser and a 14 W Nd:YAG slave laser in bow tie configuration which is injection locked to the master [1]. As a modecleaner system we use two high finesse cavities in series to obtain the required noise level. For seismic isolation we use cascaded pendulums as mechanical low pass filters, giving a $1/f^2$ isolation performance per pendulum stage above its resonance frequency. All the optical components of the modecleaners are suspended as double pendulums damped at their resonance frequencies. The main interferometer optics are suspended as triple pendulums plus two vertical stages, as described below.

The suppression of higher order modes of a cavity scales with it's finesse $\mathcal{F}$ and depends largely on the cavity's geometry [2]. As the modecleaner system GEO 600 uses two high finesse triangular ring cavities each having two flat mirrors, defining the short side of the triangle and a curved mirror at the acute angle of the triangle (see Fig.1). With that geometry a simplified expression for the suppression factor $\mathrm{S_{mn}}$ belonging to the $\mathrm{TEM_{mn}}$ mode, is given by

$$S_{nm} \simeq 2\frac{\mathcal{F}}{\pi}\left|\sin\left[(n+m)\arccos\sqrt{1-\frac{L}{2R}}\right]\right| \qquad (1)$$

where L is the optical pathlength of the cavity. In the modecleaner's case the optical pathlength L is 8 m for the first cavity and 8.1 m for the second while the radius of curvature R of the nonplanar mirror is 6.72 m. That leads to a ratio of $\mathrm{L/2R} \simeq 0.6$. Since the finesse of the two cavities is 2700 and 1900 respectively, the modecleaner system provides a suppression of six orders of magnitude for the first few higher order modes.

2. Experimental setup of the modecleaner system

To suppress the coupling of seismic noise to the optics there are different stages of filtering mechanisms. The first stage is formed by passively isolating stacks containing three layers of steel plates separated by two layers of soft rubber cylinders giving a vertical resonance frequency of about 16 Hz when loaded. The stacks are encapsulated with internally damped convoluted stainless steel bellows to provide the ultra-high vacum compatibility [4]. On top of the stacks are flex pivots which are very soft in rotation and on top of the flex pivots lays the top plate. The top plate is a hollow stainless steel structure damped from the inside with graphite loaded silicone rubber. All the pendulums in one tank are attached to a common top plate via revolvable tables allowing rotational prealignment of the optical components. The final alignment is done by applying offset currents through the local control coils described below. Both cavities are fully autoaligned to the incoming laser beam with a bandwidth of 0.2 Hz, using the technique of differential wave-front sensing [7].

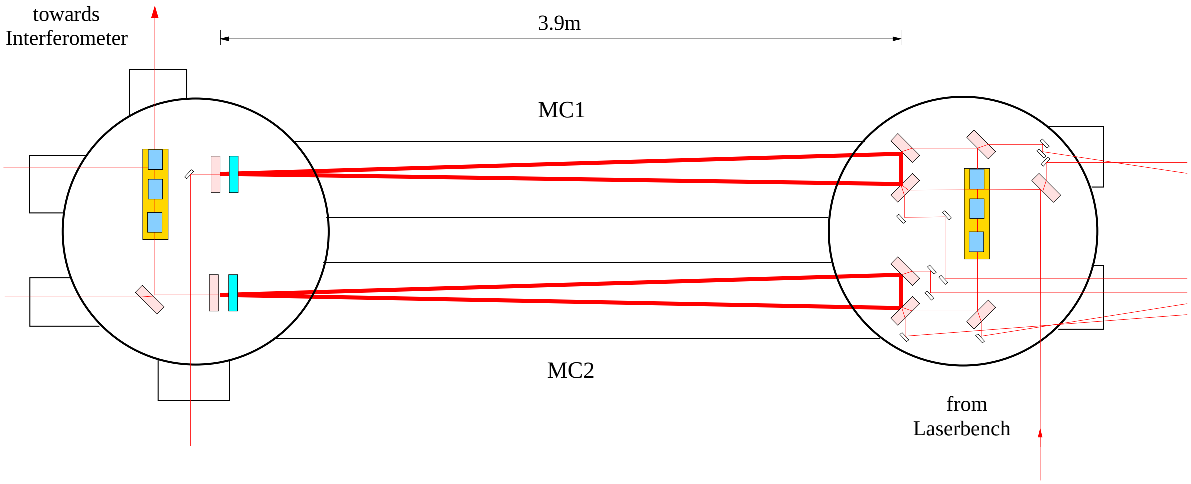

Figure 1. Optical layout of the modecleaner system: 12 similar double pendulums are suspended in two vacuum tanks. Also shown: Two as double pendulums suspended mounting units, supporting the modulators and farraday isolators.

2.1. The double pendulums

For further isolation against seismic noise all the optical components of the two modecleaners are suspended as double pendulums. In addition to the six cavity mirrors four beam steering mirrors are suspended as well as two phase modulators and optical isolators which are mounted on suspended platforms (mounting units).
The intermediate mass forming the first pendulum stage is made of aluminium, has a weight of 0.860 kg and is suspended from the top plate via two 290 mm long steel wires of 65 μm radius. Onto the intermediate mass two loops of steel wires with a radius of 51 μm are clamped, forming the second 460 mm long stage containing the mirror. The cylindrical mirrors weigh 0.864 kg, are 100 mm in diameter and 50 mm thick. Therfore the first resonance frequencies are calculated to be 0.6, 1.3, 1.6, 2.3 Hz for longitudinal motion and tilt, 0.6, 1.5, 15, 34.5 Hz for the sideways and roll mode, 0.7, 2 Hz for rotation and 11.8, 30.1 Hz for the vertical (or 'bounce') modes (see Fig.5). The resonance frequencies of the violin modes of the lower wires are predicted by our matlab model to be 195 Hz and are measured to be in between 190.6 Hz and 197.1 Hz. From the data shown in Fig.2 one can calculate the mechanical quality factor Q of the violin modes to be $5 \cdot 10^5 - 1 \cdot 10^6$ which is very close to the maximum value that can be obtained with steel wires.

2.2. The local control

To suppress the resonant enhancement of the pendulums motion we use local control damping with four magnet-coil actuators at the intermediate masses. The readout of the pendulum's position and movement is done via shadow sensors colocated with the actuator coils in a glass encapsulation. A rigid structure extending from the top plate

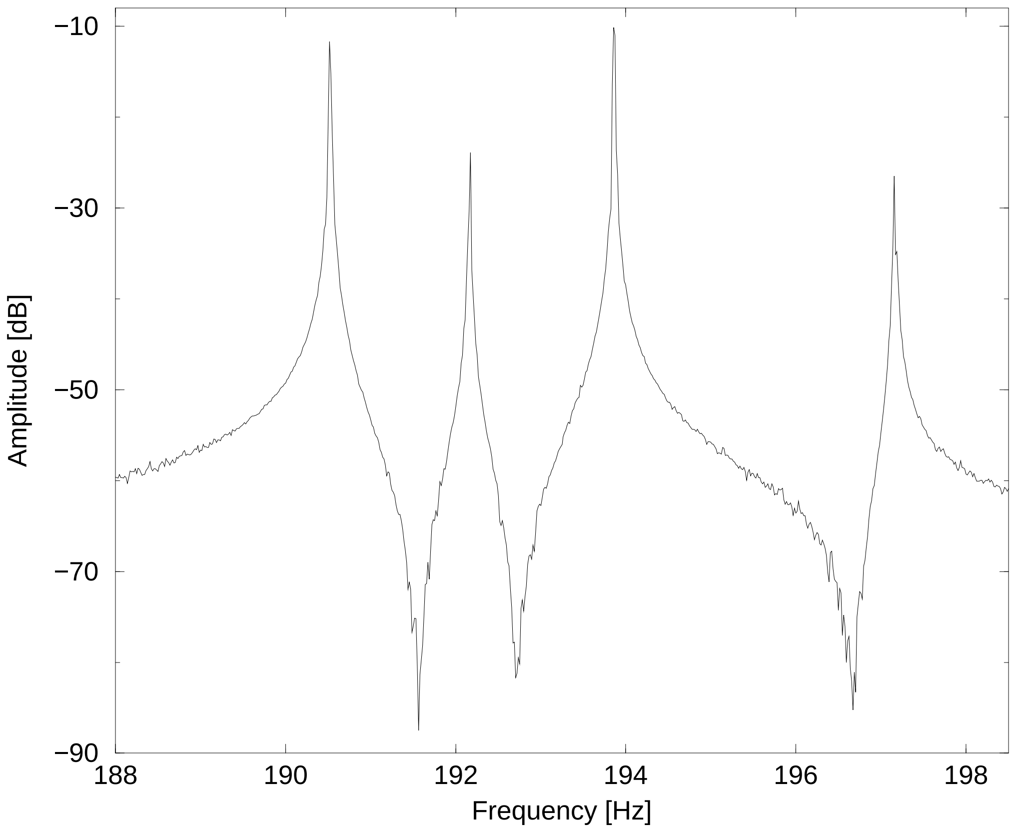

Figure 2. The violinmodes of the 4 steel wires of the lower pendulum stage of the curved mirror of the first modecleaner

supports the coils. The local control circuit has two unity gain frequencies at 0.3 Hz and at 3 Hz. The fact that there is no gain at very low frequencies allows to apply offset currents to the coils for alignment purposes. The analog local control servo is digitally supervised and can be controlled/adjusted from a PC using LabView.

2.3. The length control

To stabilize the laser frequency to the resonance frequency of the first cavity we use the well known Pound Drever Hall sideband technique. The first cavity's length is then locked to the length of the second which is finally locked to the length of the 2400 m long power-recycling cavity. This necessitates the possibility to apply feedback at one mirror of each cavity. For that reason we suspended a reaction pendulum separated by a 3 mm gap from the mirror pendulum to avoid the incoupling of seismic noise through the length control actuators. This reaction pendulum supports three coils matching magnets bonded onto the mirror's surface.

A long term measurement of the in-lock durations was taken in early 2001. Fig.3 shows a sketch of 90 h where the visibility of both modecleaners is monitored. During that period the modecleaners fell out of lock only twice, except when people were working on the servo systems. The relock of the cavities is fully automated and can be

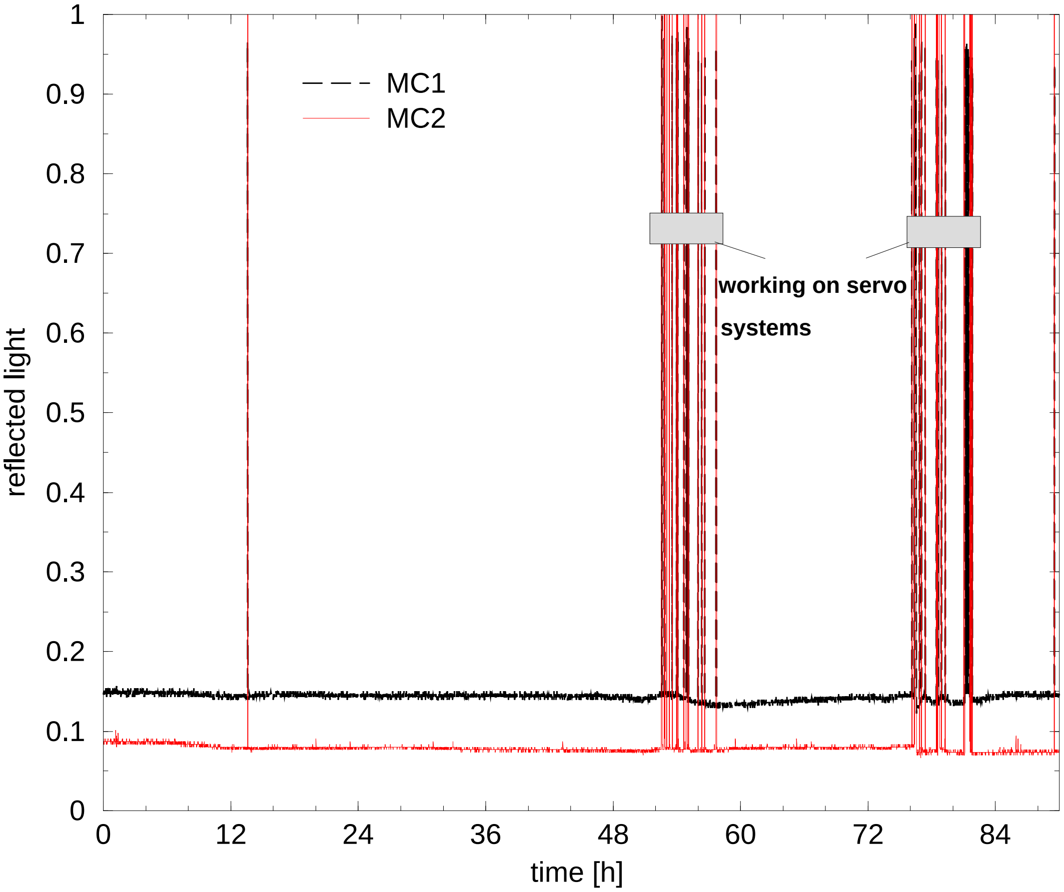

Figure 3. Longterm measurement of the modecleaner's visibilities

controlled/adjusted from a LabView PC. The average relock time for the whole system including the slave laser to the master, the master to the first modecleaner and the first modecleaner to the second one is less than 40 s. The locking bandwidth of the laser to the first modecleaner is about 100 kHz while it is about 25 kHz for the first modecleaner to the second [6]. In order to avoid the excitement of the internal modes of the mirror the modecleaner servos include scultety filters at 25.9, 35.5, 37.5, 50.5, 53.5, 69.4 and 70.9 kHz.

3. The main suspension

In contrast to the modcleaner suspensions the main optics of the interferometer are suspended as triple pendulums. The main optics are 180 mm in diameter, 90 mm thick and wheigh 5.8 kg (260 mm, 80 mm and 9.3 kg for the beamsplitter). The two upper stages are suspended with steel wires, whereas the third stage is only for the test phase made of steel wires. Finally this stage will be replaced by a monolithic one, providing a higher mechanical quality factor Q of about $5 \cdot 10^{-6}$ for the internal modes of the mirror and 10^{-7} for the pendulum modes. This leads due to the fluctuation-dissipation theoreme to lower thermally induced fluctuations of the suspension [3]. For internal

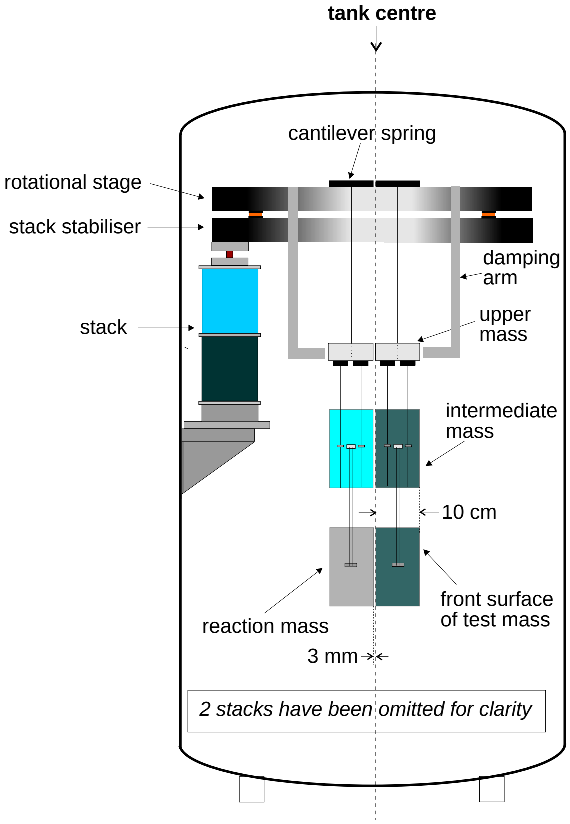

Figure 4. Schematic of a triple pendulum with reaction pendulum

damping the thermally induced displacement fluctuations are given by

$$x^2(\omega) = \frac{1}{Q} \cdot \frac{4k_BTg}{\omega ml\left[\left(\frac{g}{l} - \omega^2\right)^2 + \left(\frac{g}{l}\right)^2\left(\frac{1}{Q}\right)^2\right]} \tag{2}$$

The monolithic suspension consists of the mirror and the intermediate mass, both made of fused silica and of four fused silica fibres of a diameter of 300 μm [9]. With the technique of silicate bonding two ‘ears’ are attached to each mass [5]. Onto these ears the fibers are welded with a hydrogen/oxygen burner such that the two masses and the fibers form a monolithic structure.

It is necassery to damp the Q of the fibres’ violin modes to keep the michelson lock servo stable. For that reason we cover two small regions of the fibers belonging to the first two mechanical eigenmodes with amorphous teflon dissolved in fluorinert. Two of five optics are already suspended as monolithic pendulums.

In addition to the three longitudinal pendulum stages there are two cantilever spring stages improving the vertical isolation. The pendulum resonances are damped in all six degrees of freedom at the upper stage with magnet-coil actuators. The internal resonances of the upper cantilever springs are damped with magnets and copper tubes acting as eddy current dampers.

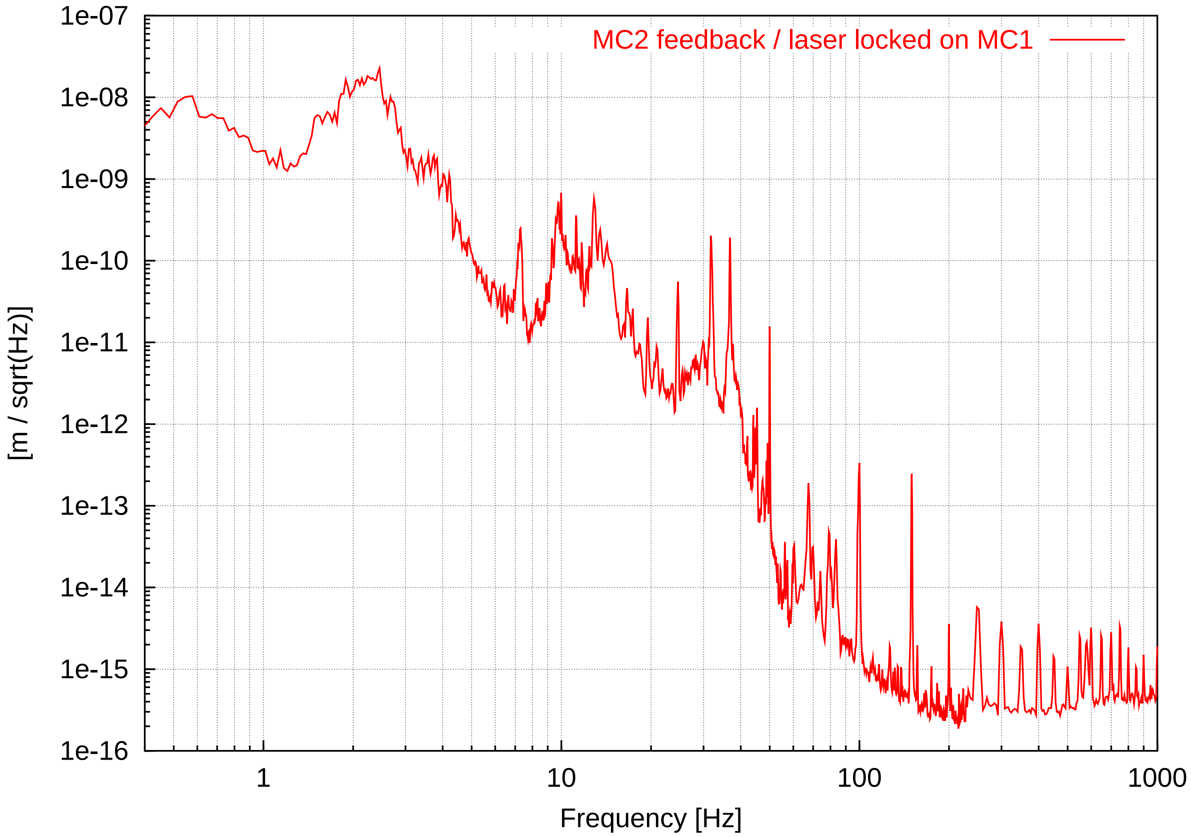

Figure 5. Differential motion of the two modecleaners

Like in the modecleaner case we apply the longitudinal feedback via a reaction pendulum suspended 3 mm behind the mirror pendulum. But at the interferometer suspensions we act on the intermediate pendulum stage with magnet-coil actuators and on the mirror with an electrostatic drive. For that purpose the lowest mass of the reaction pendulum is gold coated with two comb-like interleaved patterns forming a capacitor. The mirror behaves as a dielectric medium in the capacitor's field allowing fast feedback by changing the applied voltage.

4. Results

The finesse of the modecleaner cavities was measured both with a ringdown and with an amplitude transfer function method to give the values shown in Table 1. The measured visibilities and the throughput of each cavity lead to an overall throughput of the whole modecleaner system, including all beam steering mirrors, the phase modulators and optical isolators of about 50 %.

To measure the residual motion of the suspended mirrors we locked both the laser and the second modecleaner to the first modecleaner. From the feedback signal of the second modecleaner one gets the differential motion between the two cavities (see Fig.5).

	Modecleaner 1	Modecleaner 2
Finesse	2700	1900
Visibility	94 %	92 %
Throughput	80 %	72 %

Table 1. Measured modecleaner data

In the low frequency regime up to 1 Hz the spectrum is dominated by seismically induced motion. The bump at 2.3 Hz corresponds to the pendulum's longitudinal and tilt modes. The structure at 10-12 Hz is caused by mechanical resonances of the two tubes which are connecting the modecleaner vacuum chambers (11.4 and 13.2 Hz), of the tube that guides the beam from the modecleaners towards the interferometer (10 Hz) and by a vertical resonance of the double pendulms (common mode at 11.8 Hz). The very narrow peak at 23.5 Hz belongs to a vacuum pump which is now suspended by a coil spring. The two sharp peaks at 31 Hz and 36 Hz are corresponding to the differential vertical mode of the two pendulum stages and to a roll mode.
The residual differential motion of the two cavities at 100 Hz is about $10^{-15}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$. This corresponds to a frequency stability of

$$\frac{\delta \mathrm{L}}{\mathrm{L}} = \frac{\delta\nu}{\nu}, \qquad \nu \simeq 2.82 \cdot 10^{14}\,\mathrm{Hz} \quad \Rightarrow \quad \delta\nu \simeq 30\,\mathrm{mHz}/\sqrt{\mathrm{Hz}} \tag{3}$$

Finally we lock the second modecleaner to the 2400 m long power-recycling cavity which leads to an in-loop frequency noise of $100\,\mu\mathrm{m}/\sqrt{\mathrm{Hz}}$ [6].

Acknowledgments

This work was supported by PPARC in the UK, the BMBF in Germany and the state of lower saxony, Germany.

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