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The VIRGO injection system

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Abstract
The VIRGO injection system, designed to provide a stable single-frequency 20 W laser to the VIRGO interferometer, is under commissioning. All functions have been demonstrated to work close to requirements, and the integration of all of them is in progress.

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(Some figures in this article are in colour only in the electronic version)

1. Introduction

The VIRGO injection system is designed to provide a continuous, single-frequency and stable TEM00 20 W laser to the VIRGO interferometer. This system is rather complex as it comprises all the functions of stabilization of the laser beam at the input of the interferometer: frequency stabilization, power stabilization, beam position stabilization, spatial filtering and beam matching as well as frequency lock to the interferometer.

2. Setup

To get an efficient single-frequency high-power laser, an injection-locking technique has been chosen, using a 700 mW Nd:YAG master laser (provided by the Laser Zentrum at Hannover), to phase lock a 10 W Nd:YAG slave laser (built in collaboration with the BMI Co.). This slave laser is pumped by ten fibre-coupled diodes. The injection process allows the slave laser to run in single-frequency operation; it has a 1 MHz bandwidth, and the injection process is maintained by a correction to the slave laser cavity length with an analogue servo loop which has a unity-gain bandwidth of 100 kHz. The parameters of the laser (diode temperature, output power, etc) are monitored remotely. The details of the laser configuration are given in [1].

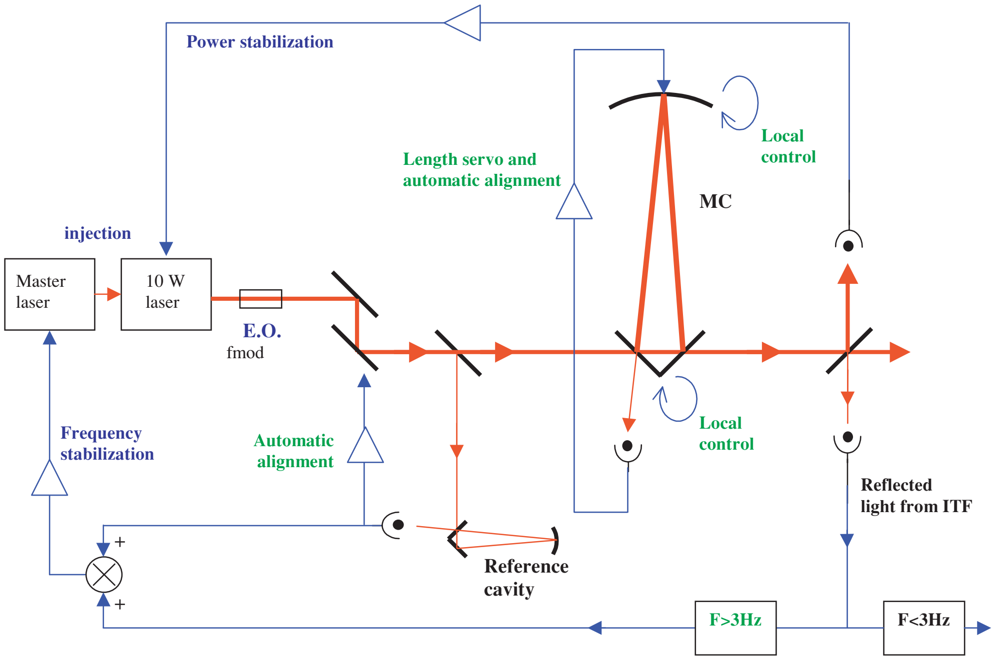

Figure 1. VIRGO injection system setup and servo loops. Automatic alignment, local controls, stabilization of frequency to the interferometer and lock of Mode Cleaner length are realized with digital loops monitored with software.

To achieve the beam filtering and elimination of beam jitter, a 143 m long triangular suspended Fabry–Perot cavity (the 'Mode Cleaner') has been designed and realized, resulting in a good compromise between filtering efficiency and power density on the optics inside the cavity. To avoid seismic and acoustic noise on the laser beam, the three mirrors of the Mode Cleaner are suspended in vacuum as a four-stage pendulum. The two flat mirrors are placed on the injection bench that also carries the matching optics that enlarge the beam before sending it into the Michelson interferometer.

The stability requirements of the laser source come from the residual asymmetries of the VIRGO interferometer. The expected main asymmetry is the finesse asymmetry, and is estimated to be around a few per cent. The requirements of laser stability have been established with a safety factor of 10 in order to take into account all defects simultaneously [6]. Figure 1 shows a schematic of the injection system and the different servo loops that allow the stability requirements to be attained.

For the frequency stabilization, the best reference, in the gravitational wave detection band, is the VIRGO interferometer itself. Using only this reference, however, would require too many orders of magnitude of frequency correction in a single-loop configuration, so that a first stage of frequency pre-stabilization is necessary. When the laser beam hits the injection bench, which is the first suspended optical bench in vacuum, a fraction of the beam is sent to a very stable ultra low thermal expansion ceramics reference cavity, which gives the error signal of the frequency pre-stabilization loop; this cavity has shown a length noise of 3×10^{-18} m Hz^{-1} at 1 kHz, in a comparative measurement with a second identical cavity [2]. The frequency correction is applied to the master laser. The injection process and the slave laser cavity length correction cause the oscillation of the slave laser to be driven by the master laser oscillation, so that the master laser frequency stability is transferred to the slave laser cavity [1].

The power stability is measured in the vacuum chamber with a small sample of the light being sent to the interferometer. The fluctuations are corrected by a change in the current of the pumping diodes of the slave laser. This servo loop has a 100 kHz unity-gain bandwidth.

The Mode Cleaner cavity consists of two 80 mm diameter flat mirrors optically connected to a Zerodur dihedron at one end, and an 80 mm diameter curved mirror with a radius of curvature of 186.5 m at the other end. The dihedron is placed on the injection bench, while the curved mirror is placed on the Mode Cleaner bench, suspended inside another vacuum chamber located 143 m away, connected to the first one by a 300 mm diameter tube, operating at a vacuum level of 10^{-6} mbar. The cavity finesse is 1150, so it acts as a low-pass filter with a pole at about 500 Hz for power and frequency fluctuations.

Each of the optical benches used for the Mode Cleaner cavity is hung to a 'short suspension', consisting of a 2 m high inverted pendulum, one intermediate filter [7] and the optical bench itself suspended via a steering mass called a marionetta. In the suspension, there are two stages with vertical attenuation. Accelerometers at the top of the seismic isolation systems allow sensing and damping of the low frequency motion of the inverted pendulum. The positions of the benches are sensed with an out-of-vacuum CCD camera. Software computes the deviation with respect to a reference position and the correction signal to stabilize the position of the bench. The correction signal applied to coils pushes magnets linked to the benches. The bench position is corrected up to about 1 Hz in all six degrees of freedom ('local control'); along the translational degrees of freedom, only the oscillations are damped, whereas the rotational degrees of freedom have also a DC correction, maintaining the alignment constant. The resulting in-loop error signals are about 1 μm rms for position and 1 μrad rms for the angles [3, 4].

The relative motion between the benches of the Mode Cleaner defines the jitter of the beam entering the interferometer. This jitter, in the detection band, is reduced because of the fact that the benches are suspended.

In order to maintain the long-term (days) alignment, automatic alignment systems are used. They superpose a laser beam with a resonator axis: the error signals are measured using the wavefront-sensing technique of [5]. One automatic alignment system aligns the laser beam with respect to the reference cavity using piezo-equipped mirror mounts before the beam enters into vacuum. The other automatic alignment system aligns the Mode Cleaner resonant mode to the incident laser beam by acting on the orientation of the curved mirror.

The frequency of the laser is planned to be locked on the reference cavity, and then the Mode Cleaner cavity length locked with the laser wavelength as a length reference.

The shape of the beam coming out of the Mode Cleaner cavity is defined by the cavity resonator parameters. The size and waist position of the beam coming out of the Mode Cleaner cavity are adapted to the interferometer with an off-axis telescope with 3×10^{-3} aberration losses.

3. Status

The laser system in operation since July 1999 (master laser and injected slave laser) has proved to be very reliable: it delivers 11 W, and has worked for more than 6000 h. The local control of suspended benches has been in operation since the beginning of 2000, working with expected performances for months without interruption. The parameters of the Mode Cleaner cavity are displayed in table 1. While the finesse is as expected, the transmission is not good enough. The reason could be the curved mirror deformation or cleanliness of mirrors.

For the commissioning phase, the laser frequency is locked to the Mode Cleaner cavity length, and then the Mode Cleaner cavity length to the reference cavity length in the

Table 1. Mode Cleaner parameters.

Parameter	Value	Measurement technique
Finesse	1150 ± 10	Cavity decay time
Contrast in reflection	79%	
Transmission	26%	$P_{\text{transmitted}}/P_{\text{incident}}$
Coupling on 02 and 20 modes	7%	Measurement of transmitted power
Round trip length	$285.46 \pm 0{,}3$ m	Notch in frequency transfer function at $f = \text{FSR}$
Curvature radius	$186.5 \pm 0{,}4$ m	Notch in frequency transfer function at 356 kHz

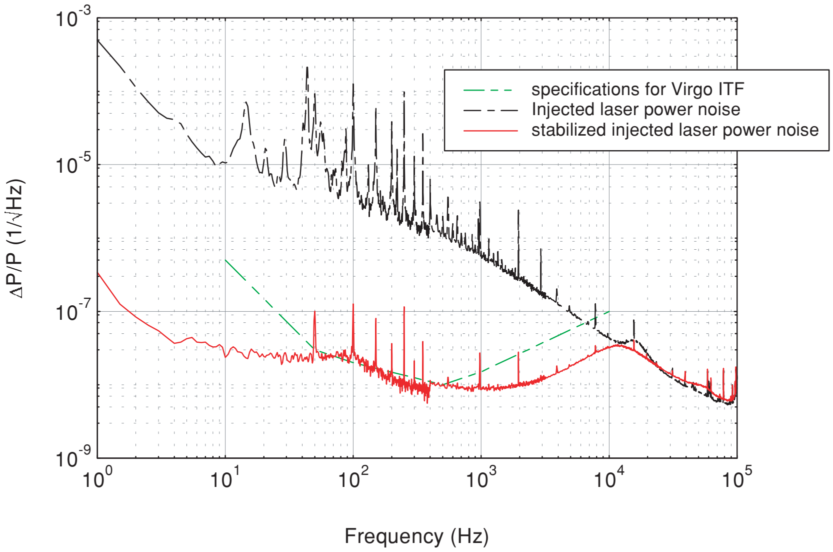

Figure 2. Laser power stabilization. The top curve is the spectrum of power fluctuations of the 10 W laser. The bottom curve is the in-loop error signal of the stabilized laser; the mode cleaner pole is simulated electronically. The straight lines show the requirements for power stability.

low-frequency range. The power variations at the output of the Mode Cleaner, with no automatic alignment and power stabilization, are less than 1% on a second timescale. The power stabilization has been demonstrated using the light from the laser system, before it enters the vacuum chambers, and simulating the Mode Cleaner cavity pole electronically. The resulting in-loop power noise meets the requirements (see figure 2). The power stabilization using light picked up from the Mode Cleaner cavity is yet to be done together with a check of the out-of-loop power fluctuations.

The length noise of the Mode Cleaner is an important issue, since it adds frequency noise to the frequency of the laser. The actual length noise has been measured using the reference cavity as a discriminator. The result, while not far from requirements, is not yet good enough in the high-frequency range, above 300 Hz (see figure 3). Understanding of the extra noise is underway.

The automatic alignment of the Mode Cleaner cavity with respect to the beam has been achieved; it shows some improvements of the Mode Cleaner noise in the 50 Hz range.

The next step will be the integration of all the servo loops of the system (four analogue and five digital loops) and their sequence management with the local supervisor.

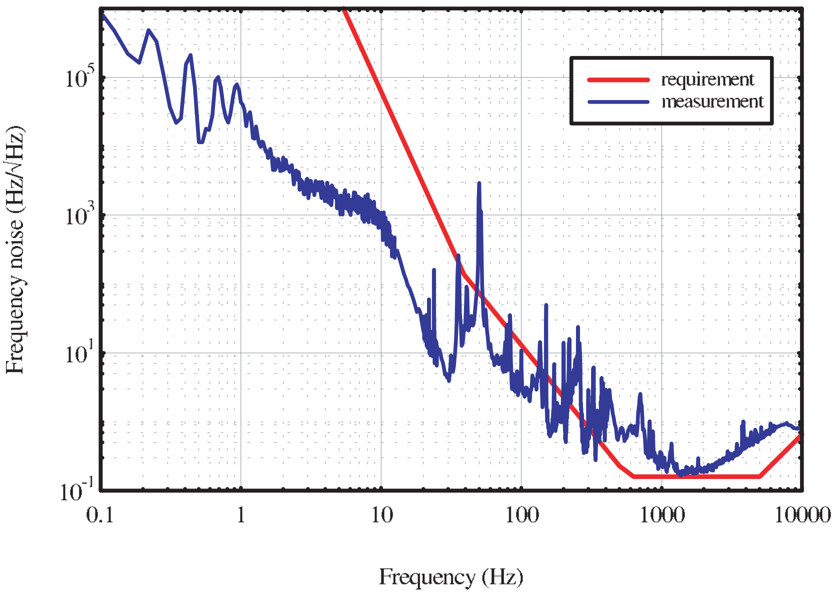

Figure 3. Noise spectrum of the Mode Cleaner length, converted into frequency noise. The noise is much higher than expected for frequencies above 10 Hz.

4. Conclusions

We have shown that all the functions can work close to the requirements, except for the optical throughput of the Mode Cleaner. The integration of all the final functions is in progress: power stabilization, lock and automatic alignment of the reference cavity simultaneously with the Mode Cleaner cavity. The extremely good reliability that is required for the continuous operation of the interferometer is also being researched: we demonstrated a 20 h continuous lock of the automatic alignment, and improving the performance requires the implementation of all the automatic alignment loops and better software reliability. A 20 W laser is being prepared in the laboratory of the VIRGO group at Nice, and will replace the current 10 W laser in 2002.

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