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(optional)

Contents

Chapter 1

The Input Optics subsystem or how to prepare the light for injection ...

Here are the 20 pages about the most complicated subsystems which should only be touched by the true professionals... .

Discussions we had prior to writing this outline:

- *With ISC (Hartmut Grote): IMC frequency servos will be discussed by ISC. Here we focus on frequency noise and passive stability and two sentences talking about further stabilization to the arm cavities is described in the ISC section.*
- *With ASC (Lisa Barsotti): See ISC, same approach. IMC as passive filter. Integrated into the overall ASC gobal control*
- *With TCS (Aidan Brooks): Mode matching into main interferometer is IO part. Maintaining the mode matching should the mode inside the main interferometer change is also within IO (Adaptive MM). But we should keep it short (or leave out). No discussion of OMC and MM into it yet. OMC will be discussed by ISC although not the mode matching part and only fairly superficial.*

1.1 Overview

The laser beams which are injected into the main interferometer in all ground-based laser-interferometric gravitational wave detectors are powerful ¿100 W near infrared laser beams. They are among the most ideal text book like laser beams ever prepared. In science mode, their frequency stability in the detection band with respect to their relevant references, the arm cavities, is unrivaled in the world. Similarly, the relative intensity noise (RIN) of the laser beams especially in lower parts of the detection band is defining the state of the art in laser power stabilization.

A laser beam is described by its propagation direction, its frequency or phase, its amplitude, its polarization, and its transversal spatial distribution. All these degrees of freedom are controlled within the PSL and the IO subsystems prior to injecting the beam into the interferometer. The IO subsystem receives the high power laser field from the PSL and prepares and injects it into the main inter-

ferometer. The IO provides the phase modulation which is required to sense and control the longitudinal and angular degrees of freedom of all mirrors inside the main interferometer. The input mode cleaner (IMC) provides a filter for the spatial mode of the laser field, acts as an intermediate frequency reference and reduces the amplitude fluctuations above its pole frequency. The triangular cavity is also one of the best polarizers available. The IO also isolates the laser from the main interferometer and directs the back-reflected light towards detectors which are used to sense some of the longitudinal and angular degrees of freedom of the interferometer mirrors. Last but not least, the IO matches the transversal field distribution to the spatial eigenmode of the main interferometer. The IO is a complex opto-mechanical system which prepares the laser field and provides the necessary signals to achieve this stability.
This chapter discusses the requirements imposed on the IO, looks at the main challenges the IO has to overcome to meet those, and then presents the specific aLIGO and advanced VIRGO layouts.

1.2 Typical requirement and challenges in the IO

Requirements we should list here. Ideally with an argument what is driving the requirement and the references to the available literature.

- *frequency noise*
- *RIN*
- *Power transmission*
- *mode quality*
- *beam pointing*
- *modulation stability*
- *...*

The frequency of the laser is initially stabilized with a tunable sideband locking technique to a fixed spacer cavity inside the PSL (see PSL chapter). The final frequency reference will be the common length or common mode of the two long arm cavities inside the interferometer. The IMC follows the laser frequency below the detection band, often called the control band, but is used as an intermediate frequency reference in the detection band. It is also the main in-band frequency reference during lock acquistion before the laser is resonant in the two arm cavities. The required longitudinal stability in the detection band depends on the gain distribution in the various nested frequency and length stabilization feedback loops. Typical requirements are in the $10\mathrm{mHz}/\sqrt{\mathrm{Hz}}$ ...

Asymmetries and imperfections in the main interferometer will cause differences in the power build-up in the two interferometer arm cavities. This differential power build-up causes differences in the radiation pressure imposed by the laser field on the test masses. These differences increase the susceptibility of the detector to laser power fluctuations often called relative intensity noise. It is expected that the power build-up in both arm cavities will be within 1% of each other and the resulting relative intensity noise has to be below $2 \times 10^{-9}/\sqrt{\mathrm{Hz}}$ at 10 Hz. This is equivalent to a shot noise limit of about 300 mW, a truly daunting requirement which so far has only been achieved by laser systems build for interferometric gravitational wave detectors. However, as the inertia of the mirrors prohibit the test masses from moving at higher frequencies, this requirement relaxes into the $10^{-8}/\sqrt{\mathrm{Hz}}$ range near 100 Hz **(Need to Check)** where laser power fluctuations couple directly to the main gravitational wave signal. The input optics has to ensure that the final photo detector signal which is used to stabilize the laser power is well correlated with the laser power inside the arm cavities. Note that the power inside the arm cavities is filtered in amplitude and beam pointing by the power recycling and the arm cavities and even more stable than the input beam.

The PSL is expected to generate about 165 W of single frequency light in a fundametal spatial mode which can be matched to the spatial eigenmode of the main interferometer. The IO has to deliver typically around 75% or 125 W of that light into the interferometer. An additional 5% is allowed in higher order modes although it is very advisable to reduce this number as much as possible. The interferometer will reject the higher order modes and they will co-propagate with the reflected field, contaminate the photo detector signals in the reflected port, and potentially prevent the common mode servos to stabilize the laser frequency sufficiently well. These signals will be discussed furthermore in the ASC and ISC sections. The higher order modes are also detected by the photo detector which is used to stabilize the laser power. Changes in the power distribution between the different spatial modes will only change the power inside the arm cavities and not on the power stabilization diode. This can ultimately limit the achievable relative intensity noise.

One of the crucial requirements is laser beam pointing or changes in the location and propagation direction of the laser beam going into the interferometer ...

Advanced laser interferometric gravitational wave detectors also place stringent requirements on the phase and amplitude fidelity of the phase modulators and require to keep the amplitude modulation at a minimum. As will be discussed in the ISC, the length sensing signals depend on the dispersion inside the interferometer which turns the injected phase modulation into amplitude modulation. Any change in the detected amplitude modulation indicates a length change in one of the degrees of freedom of the interferometer or is caused by changes in the amplitude modulation generated inside the phase modulators due to imperfections in the crystal or alignment ... .

1.3 Major parts of the Input Optics

- Modulator
- Mode Cleaner is the reference for input field
  - Cleaning the mode
  - intermediate frequency reference
- Faraday isolator
- Power stabilization in band
- Mode matching and alignment

Maybe 1 to 3 paragraphs about each part. Function/basic design, challenges associated with it if any. Lots of references but probably not yet specific to aLIGO or aVIRGO.

Interferometric gravitational wave detectors like aLIGO and Advanced VIRGO use electro-optical modulator crystals to modulate the phase of the injected laser field with frequencies between roughly 10 MHz and 100 MHz. These modulators are not very different from standard commercial EOMs except that the crystal material RTP (Rubidium Titanyl Phosphate or $RTiOPO_4$) is not as common as many other non-linear crystal materials. The advantage of RTP is that it has a very low optical absorptiuon coefficient, high damage threshold, and high electro-optic coefficient compared to many other materials. RTP is birefringent and can also be used as a polarizer to further improve the polarization of the injected laser beam ... (**Is your EOM crystal also wedged? References to early tests (eLIGO for example)**)

Faraday isolators are used in many optical experiments to isolate the back reflected from the incoming beam. They consist of two polarizers, a half-wave waveplate or quartz rotator and a Faraday crystal inside a strong magnetic field. The Faraday crystal rotates the polarization by 45deg. The rotation direction is independent of the propagation direction of the laser field and only depends on the direction of the magnetic field. The half wave plate or quartz rotator rotates the propagation by an addition 45deg although now the rotation direction depends on the propagation direction of the laser field. Faraday isolators are usually set up such that both rotations compensate each other in the forward direction and add to 90deg in the backward direction. The two polarizers are placed before and after the two rotating elements, respectively. None of the commercial Faraday isolators provided the required isolation ratio and beam quality for high power laser operations which would meet the stringent requirements imposed by advanced gravitational wave detectors. One of the challenges is caused by the fairly high optical absorption of all known Faraday crystals with a high Verdet constant such as Terbium Gallium Garnet (TGG). The absorption creates a thermal lens inside the TGG crystal, which would ruin the polarization and spatial mode of the laser beam. The ... **solutions (two TGG crystals, DKDP compensation)... References to**

early tests.

The most prominent component in the IO is the suspended IMC. The IMCs in all advanced detectors are formed by two closely spaced flat mirrors and a well separated curved mirror. These three mirrors form a medium finesse triangular cavity... **(I recommend to stay general here and move anything specific to the detailed layouts below. Finish with:)** The emitted laser field is then mode matched into the main interferometer. **(And discuss the differences in the next sections)**

1.4 Advanced VIRGO layout

Drawings and walk the reader through the layout. Also the place where the reader will see the differences. Performance and results here.

1.5 Advanced LIGO layout

Dito

1.6 Information, integrated later.

In AdV, the acute angle is much smaller (about 600urad). We will have for sure to underline the differences between ALigo and AdV for what concerns the IMC cavity (length, Finesse and consequently cavity pole frequency)
In AdV, the IMC cavity is a 145m-long triangular cavity with suspended optics and a finesse of 1200 (corresponding to an input/output coupler reflectivity of 2500 ppm, and total round trip losses lower than 100 ppm). The finesse and macroscopic length of the cavity are unchanged with respect to Virgo, as they are still thought to be a good compromise between high spatial filtering effect of the cavity and acceptable issues linked to the high finesse and length, namely radiation pressure, thermal effects and the backscattering at small angle from the cavity end mirror. The design is similar to what we had in Initial Virgo, except that the specifications for the polishing of the mirrors are more stringents. In this way, we expect to fulfill the following requirements:

- *less than 4% throughput loss on the TEM00 mode*
- *less than 4400 ppm of effective reflectivity of the IMC due to the mechanism of backscattering at small angle from the end mirror for a finesse of 1200.*

The waist of the cavity is located on the input/output mirrors which are flat. The half round trip length is 143.424 m. The waist size is 5.09 mm, corresponding to an end mirror radius of curvature of 185 m, in order to minimize losses due to High Order Mode (HOM) resonance. This choice is made to be at about mid-way between *the resonance of TEM10 (181 m) and TEM3 (191 m) which is the best choice in order to minimize the losses due to clipping of HOMs. Due to space constraints on the Suspended Injection Bench, and given the half round trip length of the IMC, the angle between both flat mirrors should be* $89°58'58''$.