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Status of ACIGA High Power Test Facility for Advanced Interferometry

Pablo Barriga[*a], Mark Barton[f], David G. Blair[a], Aidan Brooks[b], Ron Burman[a], Raymond Burston[c], Eu-Jeen Chin[a], Jong Chow[d], David Coward[a], Benedict Cusack[d], Glen de Vine[d], Jerome Degallaix[a], Jean Charles Dumas[a], Mikael Feat[a], Slawomir Gras[a], Malcom Gray[d], Murray Hamilton[b], David Hosken[b], Eric Howell[a], John S. Jacob[a], Li Ju[a], Thu-Lan Kelly[b], Ben H. Lee[a], Chuen Y. Lee[e], Kah T. Lee[a], Antony Lun[c], David E. McClelland[d], Kirk McKenzie[d], Conor Mow-Lowry[d], Andrew Moylan[d], Damien Mudge[b], Jesper Munch[b], David Rabeling[d], David Reitze[g], Albert Romann[d], Sascha Schediwy[a], Susan M. Scott[d], Anthony Searle[d], Benjamin S. Sheard[d], Bram J. J. Slagmolen[a], Peter Veitch[b], John Winterflood[a], Andrew Woolley[a], Zewu Yan[a], Chunnong Zhao[e]

[a] School of Physics, University of Western Australia, Perth, WA 6009, Australia
[b] Department of Physics, University of Adelaide, Adelaide, SA 5005, Australia
[c] Department of Mathematical Science, Monash University, Melbourne, VIC 3800, Australia
[d] Department of Physics, Faculty of Science, Australian National University, Canberra, ACT 0200, Australia
[e] Computer and Information Science, Edith Cowan University, Perth, WA6050, Australia
[f] California Institute of Technology, LIGO Project, Pasadena, CA 91125, USA
[g] Department of Physics, University of Florida, Gainesville, FL 32611, USA

ABSTRACT

The Australian Consortium for Gravitational Astronomy has built a High Optical Power Test Facility north of Perth, Western Australia. Current experiments in collaboration with LIGO are testing thermal lensing compensation, and suspension control on an 80m baseline suspended optical cavity. Future experiments will test radiation pressure instabilities and optical spring in a high power optical cavity with ~200kW circulating power. Once issues of operation and control have been resolved, the facility will go on to assess the noise performance of the high optical power technology through operation of an advanced interferometer with sapphire tests masses, and high performance suspension and isolation systems. The facility combines research and development undertaken by all consortium members, which latest results are presented.

Keywords: Gravitational Waves, Lasers, Radiation Pressure, Vibration Isolation, Thermal Lensing

1. INTRODUCTION

To detect known sources of gravitational waves it is necessary to achieve mirror displacement measurement sensitivity of ~10^{-21} m/√Hz. A critical source of noise which has to be overcome is photon shot noise which is related to the statistical arrival time of the photons. In order to minimise the shot noise very high laser power is necessary. The use of a high power laser presents new challenges that will require new approaches to the interferometer design.

In collaboration with the world gravitational wave community, the objectives of the Australian Consortium for Gravitational Astronomy (ACIGA) are to undertake research and development aimed at improving the performance of present laser interferometer gravitational wave (GW) detectors through advanced designs to ultimate limits set by mechanics, quantum mechanics, lasers and optics.

As part of the research ACIGA has built a High Optical Power Test Facility (HOPTF) on the site of the future Australian International Gravitational Observatory (AIGO) in Gingin, 90km north of Perth in Western Australia. Three

[*] E-mail: pbarriga@cyllene.uwa.edu.au; phone: +61 8 6488 1844; fax: +61 8 6488 1170

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tests were designed in collaboration with the Laser Interferometer Gravitational-Wave Observatory (LIGO). The objective is to determine and measure the effects of high laser power in the test masses including thermal lensing due to losses in both the substrate and the coating, and optical spring effects due to radiation pressure.

These experiments are designed to provide experience in the operation of advanced laser interferometers which will require the conditions created in the Gingin test facility. In order to perform these tests it was necessary to put a lot of effort into the technology development that will allow us to successfully achieve our goals. This includes new approaches to vibration isolation, and facilities for high power laser operation, the study of parametric instability and radiation pressure, test mass developments, thermal lens compensation, and cavity auto-alignment and control.

2. VIBRATION ISOLATION

By reducing the vibration even at frequencies below the gravity detection band (10Hz – 1 KHz) we seek to facilitate the locking of high finesse cavities. This not only applies to the main Fabry-Perot long arms of the interferometer, but it also includes other optical components like the input optics and the beam-splitter. The reduction of vibration will reduce the residual motion of the mirrors. As a consequence we will need less force on the actuators to control them. These lower forces imply a reduction on the servo forces that will maintain the locking reducing the noise injection by them. All of it simplifies the control system design and the locking of the cavities.

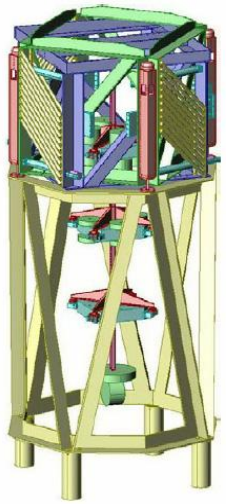

Figure 1a: Test mass mounting system with 3-D pre-isolation on top

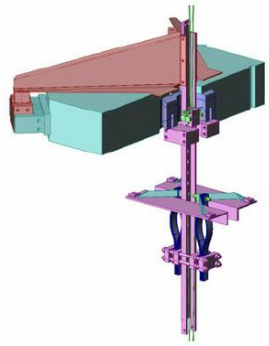

Figure 1b: Euler spring isolation system

In order to achieve the isolation requirements at low frequencies different components and techniques have been developed by the University of Western Australia (UWA) as part of this isolation system. A compact isolator structure includes two stages of horizontal pre-isolation, and one stage of vertical pre-isolation, all with resonant frequencies ~30mHz, so as to achieve residual motion at the nanometre levels. In addition passive self damping of subsequent stages prevents the need for active mode cooling. The isolator illustrated in Figure 1.a, consists of an inverted pendulum horizontal stage cascaded with a LaCoste vertical stage[1]. The tilt rigidity of this structure allows us to cascade a Roberts Linkage[2] horizontal stage of pre-isolation, before the mounting of a four stage multi-pendulum system, where Euler springs (Figure 1.b) for vertical suspension are included[3]. Each of the three intermediate masses is pivoted for self damping. The self damping is achieved by mounting the pendulum masses from gimbals which allowed them to freely rock with respect to a short rigid section of the main pendulum chain, and then viscously coupling these two together with magnetic eddy current coupling. Then the test masses are attached to the pendulum chain through a Niobium flexure final pendulum suspension that minimise internal modes and provides a high Q-factor[4].

An important part of our research has been the characterisation of the seismic environment at the site. This has revealed excellent attenuation of seismic noise[5].

3. LASER

Advanced GW interferometers will require high power, continuous-wave, low-frequency noise lasers. Adelaide University is developing such lasers for future interferometers. As part of this development it will also deliver the lasers for the Gingin tests which include a 10W and a 50W laser. Research has been centred in injection locking (Figure 2) of high power slave lasers using stabilised low power master laser. A 5W injection-locked slave laser has been demonstrated with noise performance suitable for use in gravitational wave interferometers.

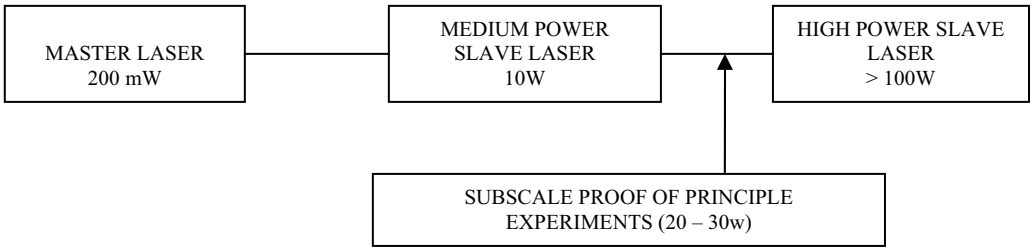

Figure 2: Chain of injection locked laser

The design strategy for high power lasers is based on a power scalable, diode laser pumped continuous-wave Nd:YAG laser using a stable-unstable resonator. The use of an unstable resonator allows the mode volume in the gain medium to be increased, which reduces wavefront distortion and losses due to birefringence. They also offer efficient energy extraction, good mode discrimination and good beam quality at high powers. It has also being shown that the quality of the laser beam produced by an unstable resonator is less sensitive to changes in the refractive power of a thermal lens than a stable resonator[6].

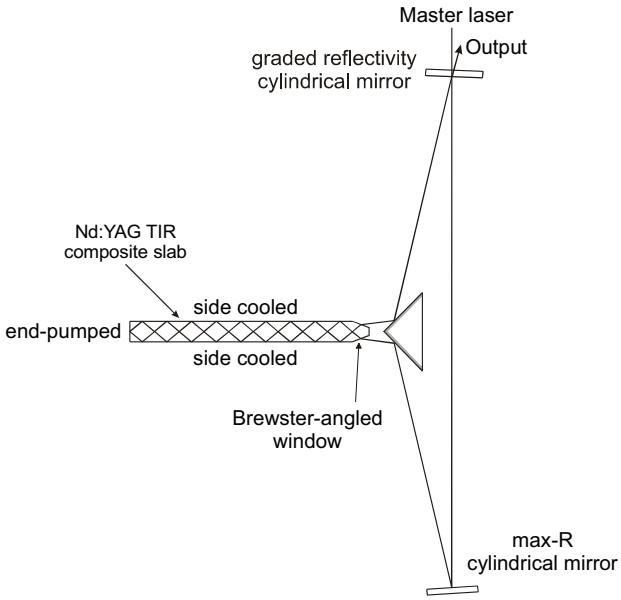

Figure 3: Schematic of the high power slave laser. The resonator is unstable in the direction perpendicular to the page and stable in the orthogonal direction.

Previously, we have demonstrated 80W output and that a stable/unstable resonator laser can be injection-locked. However, the output power was limited by the non-uniform pumping of the gain medium[7]. In the current design, shown in Figure 3, the gain medium is a composite slab, composed of diffusion-bonded layers of Nd-doped and un-doped YAG, and the side-faces are coated with a layer of SiO_2. The pump light is gradually absorbed as it propagates along the

longitudinal axis of the slab, and the heat is removed from the slab by conduction cooling through the side faces. The top and bottom edges of the slab are insulated or heated slightly using a Peltier cell to further reduce the strength of the thermal lens in the unstable direction, thereby enabling collimation of the unstable mode and thus good overlap of the mode with the pumped volume. The effect of the thermal lens in the stable direction is reduced by the zigzag of the mode[8].

4. AUTO ALIGNMENT

Control of the alignment of the laser beam into the optical system is crucial to ensure stable circulating power and ultra stable fringe visibility. At the HOPTF we will employ the widely used differential wavefront sensing technique[9]. This method use the interference between the fundamental and first order Hermite-Gauss spatial modes, reflected from a resonant cavity to generate error signals arising from misalignment. A novel feature of our implementation is the use of a Guoy Phase telescope[10]; see Figure 4, to ensure maximum decoupling between the error signal for tilt misalignment and error signal for offset misalignment in a real optical system.

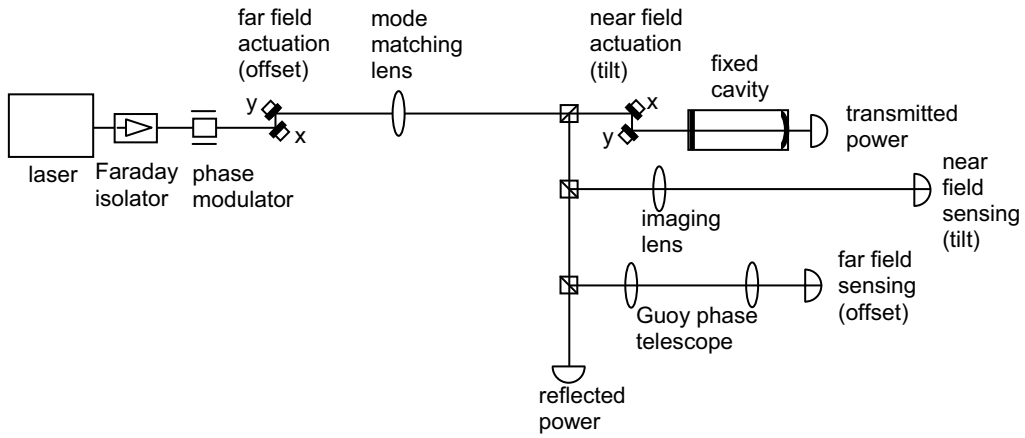

Figure 4: Simplified schematic of the experimental layout used to verify decoupling of alignment error signals.

The auto alignment system has been demonstrated on a fixed spacer cavity in the Gravitational Wave Research Facility at the ANU[11] and will be implemented at the HOPTF in the near future.

5. RADIATION PRESSURE AND OPTICAL SPRING

Radiation pressure can be interpreted as the transfer of momentum from photons as they interact with a surface. For instance during the third test at the HOPTF the power that will build up inside the cavity will exerts significant forces on the mirrors due to the momentum of the photons. This creates an optical spring effect, which can be difficult to control. The radiation pressure force for 200kW will be of the order of 1.3mN when using a 50W laser[12]. This is enough to cause the suspension pendulum to be deflected by 20μm, which is about 40 times the free spectral range of the cavity[13]. This displacement has to be controlled by a force exerted through the suspension system.

This mirror displacement will modulate the light intensity inside the cavity changing the radiation pressure force. This change will act on the mirror resulting in a spring effect. The spring constant for this system will depend on the frequency offset between the laser and the cavity resonance.

At the quantum level the noise correlations between radiation pressure and intensity fluctuations can be used to suppress the total noise below the SQL[14]. At the classical level, the cross-coupling between intensity and radiation pressure can lead to a various effects which include amplification or attenuation of perturbations, instabilities, bi-stability, and mechanical frequency tuning effects. Their effects depend on the parameters of the opto-mechanical system.

The optical spring effect was recently experimentally observed in a bench top experiment at the ANU using a detuned Fabry-Perot resonator in which one mirror was mounted on a Niobium flexure so that it could respond to radiation pressure[15]. The observed shift in the mechanical resonance due to the presence of the optical spring agreed will with a simple model.

At UWA two separate bench-top experiments are being conducted in order to measure and better understand the effects of high power lasers inside optical cavities[16]. These experiments are designed to study the effects of radiation pressure in suspended optics, and optical spring effects and parametric instabilities in a high finesse optical cavity in a mechanical Niobium resonator[17].

6. THERMAL LENSING

Thermal lensing appears in any optical component as a direct consequence of the optical power absorbed inside the substrate and coating in presence of a laser beam. The temperature gradient that will appear in the test mass substrates depends on the absorption level, the laser power density and is inversely proportional to the substrate thermal conductivity. These thermal effects will seriously degrade the performance of the advanced GW interferometers where very high power builds up inside the main cavities[18].

The refractive index is both temperature and stress dependant. Therefore the presence of a temperature gradient in the substrate will make the optic to behave like a lens. Inside the optics, the temperature gradient induces a refractive index gradient. Moreover the substrate temperature gradient inside the material due to absorption will produce a non-uniform expansion. As a consequence of this expansion the optical path length of the transmissive optics is increased. For reflective optics the thermal expansion will increase the radius of curvature.

A very strong thermal lens effect will be induced in the test mass. This can be explained by the fact that we will be using sapphire test masses with rather high absorption coefficient and a laser beam of rather small radius, almost eight times smaller than LIGO I.

In order to correct this effect we proposed the use of a fused silica lens mounted in a ring with controlled heating[19]. The temperature of the heating ring is adjusted to make the spatial variation in optical path length of the compensating plate exactly opposite to that of the input test mass.

7. HARTMANN SENSOR

To investigate the effect of temperature gradient in the test mass we will use an off-axis Hartmann sensor to measure the wavefront distortion in the Input Test Mass (ITM). This type of sensor was selected due to its robustness and easy operation.

In the Hartmann sensor, a Hartmann plate, an opaque plate sustaining an array of holes, is used to generate an array of light rays as in Figure 5. The rays propagate through the ITM and their positions are recorded using a CCD camera, thereby defining the reference positions. Absorption in the ITM creates a refractive index gradient within the ITM, which refracts the Hartmann rays. The transverse aberration of the rays is then used to calculate the wavefront distortion introduced by the ITM[20].

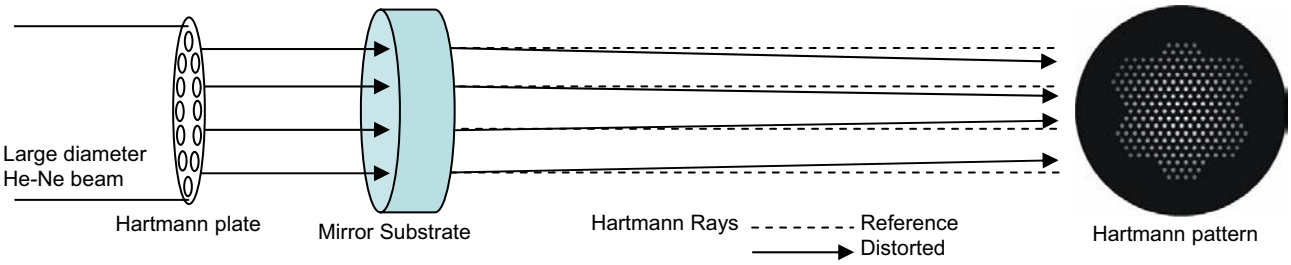

Figure 5: Schematic of an archetypical Hartmann sensor.

For reasons of geometry we shall use an off-axis Hartmann sensor, in which the Hartmann rays pass through the ITM at an angle to longitudinal axis of the optical cavity, so the sensor optics do not interfere with the optical mode of the cavity. A schematic of the input test bench for the Gingin test 1 can be seen in Figure 7, where it is possible to see the location of the Hartmann plate. A wavefront sensor will also be used to examine the eigen-modes of the optical cavities to reveal changes in mirror curvatures. These sensors are being tested in bench-top experiments at Adelaide University.

8. TEST MASSES

The present GW interferometers use fused silica as substrate for their test masses. The fact that high laser power will be used for the next generation of advanced GW detectors makes the thermal effects in the optical components more important. From this point of view synthetic sapphire present several advantages compared to fused silica. Sapphire has higher thermal expansion coefficient α, and also higher thermal conductivity k. All of this implies that the thermal gradient effects will be lower in sapphire producing less thermal effects in the test mass, which makes it more suitable for advanced GW detectors. The high thermal conductivity of sapphire is also an advantage for future cryogenic detectors[21]. Sapphire also presents some problems when used as test mass substrate due to scattering and relatively high optical absorption (higher than fused silica). In order to characterise and improve the material Rayleigh scattering measurements have been conducted at UWA with results showing inhomogeneous structures and point defects[22].

The higher Q-factor of sapphire indicates lower thermal noise in the test mass. The problem is that by changing the test mass it is difficult to use fused silica fibres as suspension material due to the differential thermal expansion of the materials. In order to solve this problem UWA is investigating different alternatives. The use of a Niobium flexure has been proposed[23]. This design requires cutting a small groove in to the sapphire test mass. We were concerned that this might degrade the Q factor of the test mass. However measurements of Q-factor on sapphire test masses performed at UWA[24] showed that even with roughly cut grooves, the Q-factor is not dramatically affected, reaching values of 2.3×10^8.

9. ACIGA HIGH OPTICAL POWER TESTS

At the HOPTF an 80m Fabry-Perot cavity will be used to demonstrate and measure the effects of high laser power in the test masses to be used for Advanced GW interferometry.

The first test consists of an 80m long cavity in a half-symmetric configuration with the particularity that the substrate of the ITM will be inside the cavity. This configuration was chosen in order to induce strong thermal effects in the test mass.

The first test involves the following sub-systems. The pre-stabilised laser (PSL) is locked to a 10W laser that for future tests will be upgraded to 50W. The input test bench includes the mode matching telescope and a He-Ne laser that will be used to measure the thermal lens and deformation of the ITM. The ITM is made from a-axis sapphire, is flat and has an anti-reflective coating (AR) with R < 100 ppm on the front surface and a T = 1800 ppm out-coupling coating on the back surface. The out-coupling coating is designed to maximise the power build up in the cavity, allowing for the substrate absorption and losses due to the AR coating on the ITM and compensation plate. The End Test Mass (ETM) is made from m-axis sapphire, has a 720m radius of curvature with a high reflectivity (HR) coating.

Gingin test 1 will use a 10W Nd:YAG laser developed by the University of Adelaide. It is expected that around 7W of laser power will be delivered to the cavity, this will generate approximate 5kW inside the cavity. The ITM substrate will absorb 2W of this power changing the radius of curvature of the ITM from flat to 350m. This will change the size and position of the cavity waist. The waist size will change from 8.75mm to 6.62mm in radius and it will move from the HR coating in the ITM 56m to the centre of the cavity, which will reduce in about 20% the power inside the cavity. As seen in section 6, a fused silica lens mounted in a compensation plate has been designed to restore the power inside the cavity. A simplify diagram of this test can be seen in Figure 6.a. The compensation plate will be heated from outside by a specially designed mount that can deliver heat power to the edge of the compensation plate. This will counteract the thermal effect of the ITM substrate by creating a temperature gradient opposite to the one in the ITM. In parallel at the input test bench a variable radius of curvature mirror will be used as part of the mode matching telescope for adaptive mode-matching[25]. The aim is to dynamically correct the laser beam profile before entering the cavity. The final result of

the combined optical effect between the ITM and the compensation plate will be a virtually flat test mass. This plus the adaptive mode-matching will set the cavity waist and mode-matching back to the cold cavity values, thereby restoring its power.

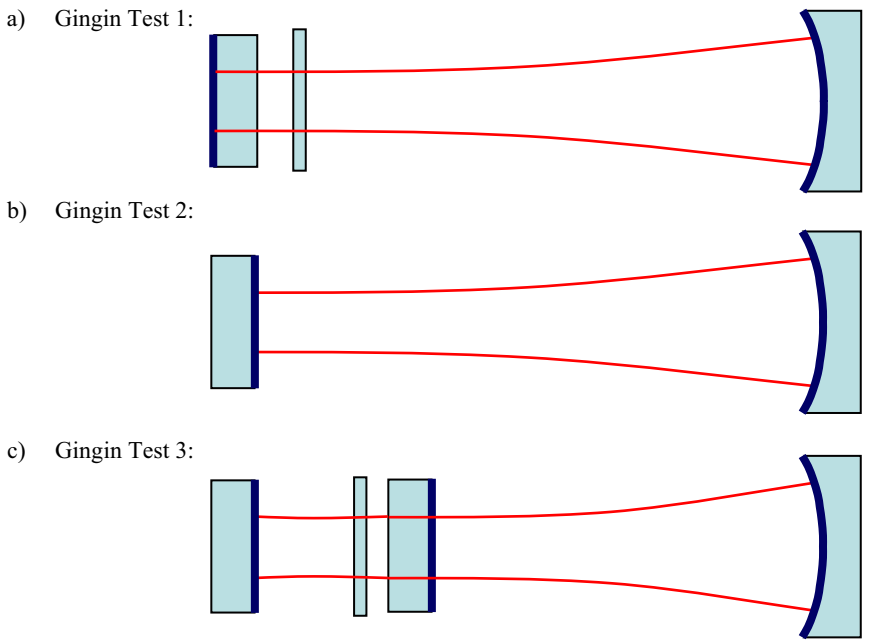

Figure 6: Gingin tests are design with different purposes. Test 1 is to quantify and correct thermal lensing effects using two sapphire test masses and a fused silica compensation plate. Test 2 will use the same test masses but with the coating inside the cavity. Test 3 will add a fused silica power recycling mirror in order to increase the intra-cavity power for further study in thermal effect on the test masses and the compensation plate inside the power recycling cavity.

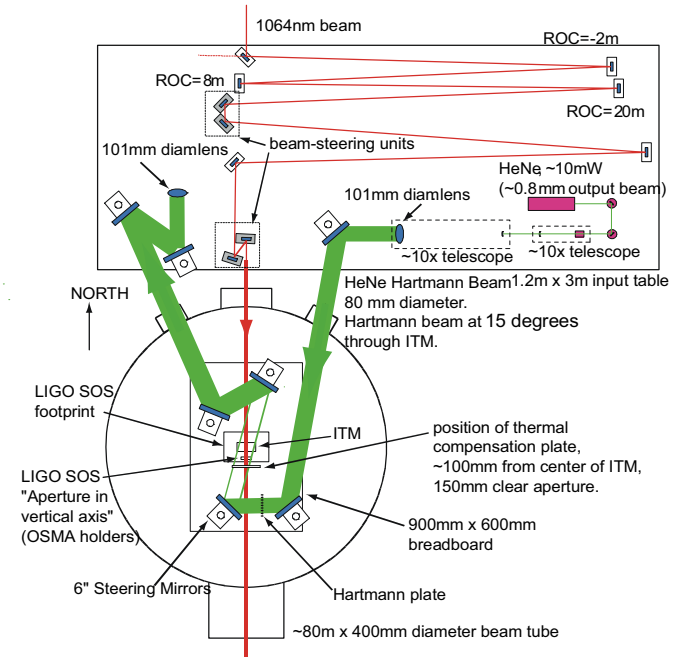

Figure 7: Schematic diagram that shows the distribution of the input test bench including the ITM and the Hartman sensor inside the vacuum tank.

As part of the input test bench we will include a Hartman sensor inside the ITM vacuum tank as seen in Figure 7. This sensor will be used to measure the wavefront distortion in the ITM. This test mass is designed to suffer the strongest thermal effects. The ETM will also suffer a small thermal effect but almost negligible compared to the ITM. An important aspect of this project is the vacuum enclosure where this experiment will be installed. It is formed by two 3.3m height and 1.6m diameter tanks connected by a ~80m pipe. Figure 8 shows the intermediate tank already installed inside the main lab. This tank will be used during the third test, which includes a power recycling cavity. In this tank we will install the ITM adding a fused silica power recycling mirror in the first tank. The whole vacuum enclosure has been pumped down to $2x10^{-7}$ mbar with $8x10^{-10}$ mbar total partial hydrocarbon pressure[26].

Figure 8: View of the main lab, where it is possible to see the ITM vacuum tank and the intermediate tank, where the ITM will be installed for Gingin test 3. At the actual ITM tank we will mount the power recycling mirror.

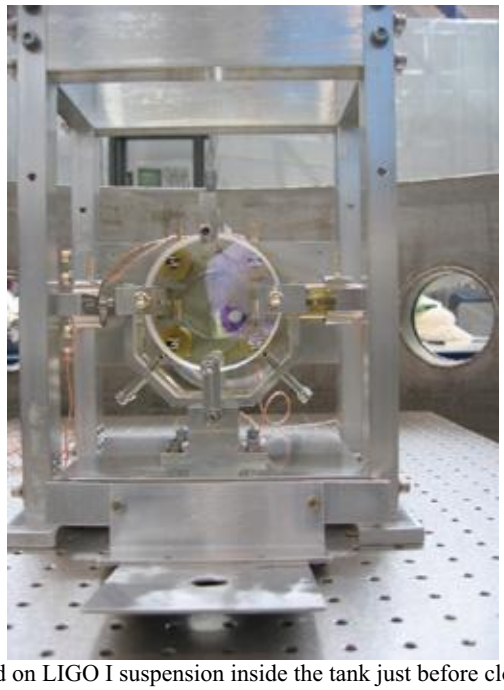

Figure 9: BK7 input test mass mounted on LIGO I suspension inside the tank just before closing it. The picture was taken from the high reflection coating side, where it is possible to see the magnetic actuators behind the mirror.

Preliminary tests leading up to the Gingin test 1 use BK7 optics and LIGO suspensions for the ITM and the ETM. Figure 9 shows the mounting of the ITM on its LIGO suspension. These are mounted on top of optical tables in order to characterise the optical system and lock the cavity using a 500mW laser, which later on will be replaced by a 10W laser. The addition of a complete AIGO suspension system will be installed as soon as its digital control system is demonstrated. Then the LIGO suspension will be mounted as the last stage shown in Figure 10.

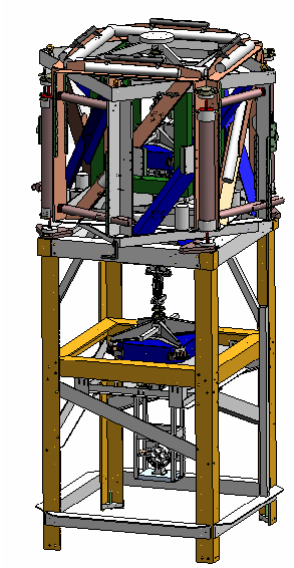

Figure 10: Complete AIGO vibration isolation system with LIGO I suspension and test mass as the last stage.

At the south arm of the HOPTF we have mounted the ITM and the ETM both in their LIGO suspensions inside the tanks under vacuum. A 500mW Nd:YAG laser that has been pre-stabilized is being beamed into the cavity, in order to test the alignment and control system. Figure 11 shows both test masses inside their respective tanks.

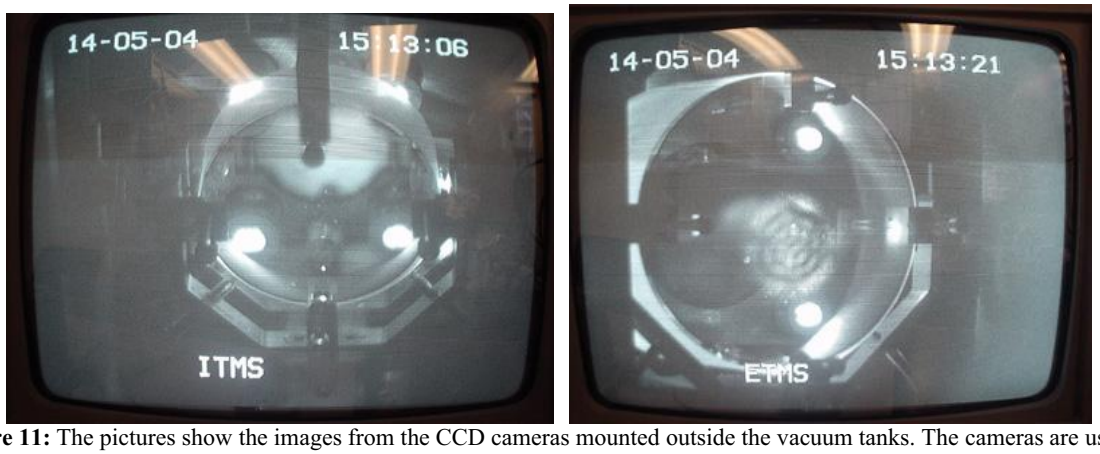

Figure 11: The pictures show the images from the CCD cameras mounted outside the vacuum tanks. The cameras are used to monitor the test masses during locking and operation. At the south end test mass (ETMS) we can see the higher order modes oscillating inside the 80m cavity.

For Gingin test 2 the main objective is to test the effects of high power in the test masses HR coating. For this test the laser power will be increased from 10W to 50W. In order to do this, the same test masses will be used, but this time the substrate of the ITM will remain outside the cavity (Figure 6.b). As a consequence the power will be mainly absorbed in the coating of the test mass instead of the substrate.

Gingin test 3 will work at even higher levels of power with the addition of a fused silica power recycling mirror (PRM) to create a power recycling cavity just before the main cavity as shown in Figure 6.c. This configuration will allow us to study the effects of high power dynamics. The compensation plate and the adaptive mirror will be used again to restore the power inside the cavity (most probably an improved version once the results of Gingin test 1 have been analysed). This new configuration will also allow us to investigate radiation pressure and optical spring effects.

10. SUMMARY

ACIGA's High Optical Power Test Facility current state was presented. These tests have been designed to demonstrate and measure the effects of high power lasers, necessary for advanced gravitational wave detection. To prepare these tests different approaches and techniques are being developed in collaboration with the international community and the group members of ACIGA. As part of this collaboration ACIGA's research included different fields like vibration isolation, thermal lensing, radiation pressure and optical spring, high power lasers and auto-alignment. These results will help ACIGA to turn AIGO into the first Advanced Gravitational Wave Interferometer of the southern hemisphere, a key component of the international network of GW interferometers.

11. ACKNOWLEDGEMENTS

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