LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
--LIGO—

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LHO 2K suspension wire breakage incident

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Introduction

This report summarizes what is known concerning an event that damaged a mirror in the input optics to H2 (2-kminterferometer at Hanford) and lead to postponement of science run S1. Many people worked hard to provide the information summarized here. I have referenced the relevant e-log entries for various topics, allowing the reader to browse the actual log entries to get a literal sense of the details behind this event, its investigation and its outcome. I would like to acknowledge the special effort by Doug Cook to comb through the logs to collect together these references.

H2 Suspension Wire Breakage Incident

On Friday, June 28, 2002, following the onset of ground motion traced to an earthquake on the Russian-Chinese border, the damping loops on SM2 (one of the steering mirrors in the input optics) became unstable. After some failed attempts to recover control, this problem was fixed by increasing the side-damping gain setting from 1 to 30. Approximately 6 seconds later, at 18:57:25 UTC, mirror MMT2 shifted dramatically.

Further investigation showed that all sensors but UL were no longer recording reasonable motion. UL sensor did show effects of excitation, but a measurement showed the mirror's natural frequency had shifted from approximately 0.5-0.75 Hz to 7.37 Hz. A ring-down measurement yielded a Q of 250. Clearly the restoring forces on the mirror had risen more than 50-fold and there was significant friction experienced by the optic. A swap check of electronics confirmed our suspicion that there was mechanical interference.

We guessed that the interference might have arisen from a static charge that might have been picked up by the mirror striking the earthquake stops. Such an event once was observed in H1 and was remedied by venting the chamber, which evidently discharged the optic. We made the decision to vent HAM8. When a first vent failed to release the optic we pumped down and then vented again, this time with greater flow rate. We had spotters watching the mirror during these vents with bright lights illuminating the chamber. In the second vent the spotters (Betsy Bland, Robert Schofield) could clearly see the glint from a free suspension wire waving in the flowing purge air.

We notified Gary Sanders that we would be unable to run H2 in the scheduled science run, S1. Mark Guenther then locked out the light pipe between the PSL and HAM7. We then began preparations for an entry into the vacuum system for repairs of MMT2. While preparations were underway, we assessed the health of the other optics so we could identify any other optics that needed repair. All other optics were not damaged.

First Vacuum Entry for Repair of MMT2

We planned an incursion into HAM8 to fix the broken suspension wire on the MMT2. Provided there were no other problems with this suspension except for the broken wire (i.e., no broken magnets), we planned to enter HAM8, fix the wire, and resume pumping on this volume within one work day. If magnets were in need of repair, we planned to pull this suspension out of the chamber for a 1-2 week reprocessing in the optics lab. We planned to close and re-pump the chamber during this reprocessing.

HAM8 was vented for about 3-4 hours on Tuesday morning, 7/2/02, for repair of MMT2. Inspection showed that magnets had been broken off the mirror, so the damage was photographed and the mirror was removed to the optics lab for repair.

Forensic Investigations

It was immediately obvious that two separate failures had occurred. The wire was broken and the earthquake stops failed to protect the magnets. The cause of the second failure was also immediately obvious: the springs in the earthquake stops were far too soft to limit motion sufficiently in the presence of 1-g accelerations. When the wire broke, the weight of the mirror compressed the spring stops enough to allow the sensor/actuator heads to shear the magnets off the falling mirror.

Work focused on finding the cause of the wire break. We subjected the wire to visual inspection under a microscope to characterize the break, being careful to minimize contact between the wire ends and other materials. Under the microscope it was clear that the wire end had been drawn to a narrower diameter near the break and at least one end showed indications of melting. The wire ends appeared to be rounded – suggesting shaping of a liquid surface by surface tension – and one end had small rounded "droplets" of metal adhering to its surface. Unfortunately, we were ill equipped to clamp this wire under the microscope in the optics lab and these blobs were inadvertently wiped off when the wire "sprang" into a clean wipe.

We entertained two hypotheses for the melting: that the laser light had melted the wire or that plastic deformation at the time of breaking had generated enough local heating to melt the wire. Some experiments were done with loaded sample wires to ascertain whether the wire was hot or cold when the break occurred. Wires were broken by slowly loading them either when they were hot or at room temperature. These tests were not overwhelmingly conclusive, but the wire ends of hot-broken wires were more similar to the MMT2 wire than were the cold-broken wires.

Rai Weiss presented a calculation showing that melting by the laser light was a likely cause of the break. Shortly thereafter, melting of a wire in air by the laser in Livingston was demonstrated. Calculation and demonstration showed that this fine wire, exposed to several watts of laser light in a beam comparable to the beam diameter at MMT2 will exceed, in a fraction of a second, the temperature at which the tensile strength of steel is a minimum. Since the suspension wires are loaded to 40% of yield stress at room temperature, such a laser exposure must result in breakage of the wire. The degree of melting which occurs will depend on the details of the exposure. This melting hypothesis was supported by electron microscope examination, made at the MIT Surface Laboratory by Libby Shaw and Megan Goldman.

The Repair

We decided that we could prepare the MMT2 spare for installation into HAM8 more quickly than we could repair damage to the mirror removed from HAM8. This was done, and MMT2 was designated as a spare after rehabilitation. Since the earthquake stop design was faulty, we decided – in consultation with Dennis Coyne – that, when we re-installed MMT2, we would remove all springs in the earthquake stops that were easily accessible in the MMT2 and MC2 suspensions. Finally, we fabricated and vacuum-prepped two new baffles to protect the free wires on MMT2 and MC2 from exposure to the laser light in HAM8.

On the morning of Wednesday, 7/9/02, we re-entered HAM8 to complete in-vacuo repairs. Baffles were installed on MC2; the newly outfitted MMT2 was installed into HAM8; as many springs as were accessible were removed from the earthquake stops on MC2 and the earthquake stop screws were adjusted inwards. We decided to trust our reference stops in HAM8 and our alignment procedure to get us within bias range of a good IO alignment, rather than try to run light through the MC in air. Raab made this decision after consultation with colleagues at the weekly commissioning meeting, to minimize water and dust contamination of the optics. We were able to get the diagonal section pumping again by 19:35 UTC (12:35 PST). We were quickly able to recover an input optics alignment with good transmission through the mode cleaner, up to the recycling mirror and back through the Faraday isolator onto the REFL photodiode and REFL video camera.

After frequent consultations between John Worden, Fred Raab and Rai Weiss, it was decided to open the gate valves isolating the diagonal section on Monday, 7/22/02. Subsequent measurements of water vapor outgassing showed that we could leave the gate valves open.

With gate valves opened, we rapidly aligned the optics to obtain flashing fringes on the Y arm. To make best use of the H2 downtime, we had installed a new optical layout on ISCT10 (the H2 antisymmetric port). With the gate valve open and the IOO and ITMY in reasonable alignment, the task of aligning the ISCT10 optics began.

The Root Cause of Damage to MMT2

The initial earthquake did not damage MMT2 directly. Ground shaking due to this earthquake was typical of events that occur several times a month at Hanford. The earthquake did drive the controller for steering mirror SM2 unstable. The motion of SM2 was noticeably ringing up within 2 s of the arrival of the quake at Hanford. The mirror was exhibiting large swings – basically being driven rail to rail – for approximately 1.5 hour after the earthquake. In the process of trying to regain control, the bias sliders were set to zero, at approximately 20 minutes before MMT2 failed. This did not correct the problem with SM2. Eventually, SM2 was brought under control by adjusting the side-damping gain to its maximum value. Approximately 5 s later, the final jump in the MMT2 alignment occurred.

The likely scenario for this failure is that the earthquake induced an instability in SM2 control. SM2 was then swinging wildly, but the swings were not delivering significant power to the MMT2 suspension wire to cause damage. Sensors show no unusual motion of MMT2 during this time. It is likely that reducing the alignment biases on SM2 to zero placed the center of the alignment swings of the light near the MMT2 suspension wire. Some twisting of the MMT2 alignment began after this bias change. Finally, damping the alignment swings of SM2 allowed the temporal overlap of the light on the wire to increase until the wire temperature rose high enough and the tensile strength of the wire could no longer support the load. The wire then broke and the optic pressed on the earthquake-stop springs, which were too soft to limit the motion sufficiently. The magnets were broken off the mirror as the springs compressed and the magnets struck the sensor/actuator heads.

Recommended Actions

This incident identified a need to protect the MC2 and MMT2 optics from illumination by several watts of laser light in a tight beam (few mm diameter). These are the most vulnerable mirrors. The most fail-safe protection for these mirrors would eventually require that baffles be placed to prevent this from occurring, as was done for H2. **Baffles for H1 and L1 should be prepared in advance, so they may be placed in chambers at the next reasonable opportunity.** It appears that most other optics are less likely to have their suspension wires cut by laser light. The core optics are relatively immune because the light intensity that can be delivered to their suspension wires is relatively low. Although there are very high intensities in the aligned arms, these cannot be sustained in misaligned arms. The mode-cleaner mirrors can also not deliver sustained intensities to their suspension wires. **It should be checked by calculation that the remaining input optics cannot receive harmful irradiation by the light.**

It is undesirable to vent the chambers for H1 and H2 solely for this remedy, because of scheduling impacts to the commissioning and science runs. We are installing software remedies for H1 that should significantly mitigate risks from high-intensity light beams. The first remedy recognizes that the required fluctuating coil drives to optics are much smaller once the interferometer is locked in a stable configuration. The DSC software is being modified to implement significantly tighter clamping of RMS coil currents once the interferometer is locked. These dual-mode watchdog settings prevent large orientation kicks to the mirrors, caused by loss-of-lock events, from being sustained. Watchdog levels can be reset once the interferometer transitions back to “acquire” mode after a check that no optics have lost control. The second remedy recognizes that the input optics controllers allow a large alignment bias adjustment, but that this is not required once the initial alignment has been set. (The large range was meant to accommodate tolerances in optics installation.) EPICS software for IOO optics and recycling mirrors should accommodate upper and lower limits about the nominally aligned values on the bias adjustment sliders. These should be set to prevent alignment biases being applied that could steer a high-intensity light beam onto a suspension wire. Intentional misalignments should only be accomplished by programmed excursions that are known to place the beam in a safe place. Overriding these software protections should be accompanied by an alarm in the control room and a visually obvious indication on the relevant control screens. **Dual-mode watchdog and bias adjustment limiting software should be extended to H2 and L1 as the digital controllers are installed to limit large continuous bias changes.** This will prevent the system from being maintained in a risky alignment state.

A final mitigation strategy is to have EPICS monitor the excursions of alignment through optical lever and/or shadow sensor channels to determine when an optic exceeds nominal alignment values sufficiently to cause a significant risk of damage. This should then trigger a response that (1) unlocks the mode cleaner; (2) disables the mode-cleaner auto-locking script; and (3) triggers an audible control-room alarm. With the mode cleaner unlocked, light levels within the vacuum system pose no hazard to hardware. **EPICS**

interlocks should be implemented on all interferometers to disable the mode cleaner when optics exceed safe alignment bounds. This will decrease risks to hardware from receiving extended, unplanned exposure to laser light caused by a fault in the control system.

The earthquake stops did not limit motion sufficiently to prevent breakage of the magnets on MMT2. **The soft spring tip design for earthquake stops should be reviewed and design changes that mitigate risk of magnet damage in a similar incident should be evaluated.**