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MAGNET SWAP REVIEW FOR ENHANCED LIGO

TO:	Jay Marx and Albert Lazzarini
FROM:	Norna Robertson on behalf of members of the Enhanced LIGO Magnet Swap Review Committee: Doug Cook, Dennis Coyne, Joe Giaime, Mike Landry, Brian O'Reilly, Janeen Romie, Norna Robertson (chair), David Shoemaker, Daniel Sigg, Stan Whitcomb.
SUBJECT:	Report on the review of the proposal to replace the initial LIGO ETM magnets (made of NdFeB) with CoSm magnets in order to improve the expected Enhanced LIGO performance below 100 Hz.
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1. Introduction

At the schedule update review for enhanced LIGO held on 4th September 2007 (see report M070346-00-M) the possibility of replacing the ETM magnets with CoSm magnets to reduce noise associated with the coil/magnet actuators was discussed. The proposed work was not part of the original baseline plan for enhanced LIGO. The review committee recommended at that time that this topic be reviewed at a later date. That review has now taken place and we present our report below. In section 2 we present a summary of the main findings. In sections 3, 4 and 5 we give more details on our findings addressing particular sections of the charge. The charge to the committee is given in Appendix A and the agenda for the review telecon is given in Appendix B. Appendix C gives a list of activities with the committee's estimated time for completion of the magnet swap.

On the final page of the report we append comments received from Rai Weiss on 11th March 2008.

Note: throughout we refer to Enhanced LIGO as eLIGO and Advanced LIGO as aLIGO.

2. Main Findings

2.1 The committee supports the proposal to swap the NdFeB magnets attached to the back of the ETM mirrors on H1 and L1 with CoSm magnets.

2.2 The scientific case, as presented, is not totally unambiguous. However there is general consensus that this is a noise source which is at or close to the noise level achieved latterly in S5 in the 40 to 100 Hz region, and, if it is not dealt with, making any further improvements will be difficult. Addressing it allows one then to tackle other noise sources. Revealing other noise sources could help with commissioning aLIGO. If this noise source is not addressed, it is likely to impact projected S6 sensitivity especially for BH-BH coalescences.

2.3 There will be some impact on the eLIGO installation/commissioning schedule and on the aLIGO prototyping schedule which should be explicitly recognised. The latter can be minimised by using observatory personnel not currently contributing significantly to aLIGO. The eLIGO schedule can be relaxed to reflect the delayed aLIGO start.

2.4 The proposed procedure in general looks workable. There are risks, but steps can be taken to mitigate these.

2.5 The possibility of replacing the ITM magnets should be reviewed in the future if and when appropriate, after the outcome of replacing the ETM magnets has been investigated.

3. Scientific Justification

In this section we address the first two items in the charge.

- Scientific justification for this change; what happens (to eLIGO projected performance) if we do nothing?
- The experimental evidence that points to the limiting effects of the current magnets; is the evidence clear and unambiguous?

We also include a response to part of charge 3) in this section.

- What is the projected performance if we do carry out the proposed work?

3.1 Summary

There is general agreement within the magnet review committee that upconversion noise is a primary noise source below 100Hz that should be mitigated via swapping out magnets. However, not all the evidence is unambiguous. Nor is it clear that swapping the magnets will make a marked improvement in sensitivity. The committee does agree however that mitigation of this primary low frequency noise source is necessary progress for eLIGO and ultimately, aLIGO.

3.2 What happens to the noise if we don’t swap the magnets?

Barkhausen noise has been identified as the leading explanation for observed upconversion noise in LIGO interferometers. If this noise source were not mitigated by a swap of NdFeB magnets for CoSm ones, the committee expects that the eLIGO goal of ~30Mpc reach for binary neutron star inspirals (angle averaged over sky position and source orientation) will not be achieved (a possible exception to this would during times of extremely low seismicity). How much we would miss the goal of 30Mpc is not well understood, but estimates range from 3% (see G070054-00), up to a rough maximum of

25%: the upconversion noise is a limiting noise source below 100Hz. Additionally, astrophysical sources that predominantly radiate at lower frequencies such as binary black holes would be further impacted by upconversion noise in S6 if mitigation is not attempted, or not successful. Lastly, additional noise mitigation without replacing magnets (e.g. additions or refinements to PEPI or HEPI) are expected to produce only minimal, if any, gains.

The committee are concerned that, if the magnet swap does not take place, future noise hunting may stall out, as the standing belief will likely be that upconversion noise in the form of Barkhausen dominates.

3.3 Expected Improvement

The clearest benefit to the mitigation of Barkhausen noise is that it may reveal new and previously unanticipated noise sources, salient for both eLIGO and aLIGO. New noise terms at or just below the upconversion level cannot be assessed and mitigated unless the latter problem is addressed. At some level, no work on low frequency noise can proceed until the 'gorilla in the room' is mitigated.

Furthermore, there may be a genuine reduction in the noise level of the interferometers below 100Hz, although this is less understood and less certain.

3.4 Is the evidence clear and unambiguous?

Evidence for the limiting effects of upconversion noise, and its association with Barkhausen noise in the NdFeB magnets, is included in the eLIGO wiki,
http://lhocds.ligo-wa.caltech.edu:8000/mLIGO/Magnet_Swap

The case for Barkhausen noise is not conclusive however – there are several experiments that do not reconcile completely with evidence given at the eLIGO wiki. These include:

- Some examples of excess noise at LLO during times of earthquakes and high microseism fall like $1/f^3$, instead of $1/(f-f_0)f^3$ as expected from upconversion. Indeed, with reference to p14 of the presentation from Rai Weiss and Sam Waldman, G080068-00-I, (Barkhausen noise scaling) the match is questionable.
- The nature of upconversion as a function of drive frequency is not understood, and does not match up with simple model.
- In another test made at LLO, upconversion appears for only one sign of the DARM control signal, whereas it is expected in either sign. This is not understood.
- Noise scaling as a function of PAM gap spacing does not match a simple model: LHO ITMs with ~4mm PAM gaps should show, for example, a factor of 4 worse upconversion noise than measured. A more complicated model (based on extended (3mm) magnets instead of simple dipoles) produces agreement only at the factor of 2 level.

3.5 Additional suggestions

- If the ETM magnet swap proves successful and reliable, and if good evidence indicates that Barkhausen noise still dominates the noise below 100Hz, we could consider a similar magnet procedure for ITMs (at the very least, for HEPI-less LHO). A natural time frame for such work would be coupled to the fall vent intended for the 99:1 HAM4 beamsplitter, arm-cavity and septum baffles, etc. This should be reviewed at a later date after the results of doing the ETM swap have been assessed.

- Instead of effecting the magnet swap at both sites, it has been suggested that the swap be performed at LHO, and then the value assessed. The procedure would only be done on L1 if it was shown to be of value on H1. This plan was conceived as potentially halving i) the risk to core optics, and ii) the time required on the procedure, in the event that no improvements in noise were obtained. The committee was not unanimous, but a majority felt that proceeding with both swaps without waiting for the results from the first was the preferred option.

4. Proposed Solution

In this section we address the third item in the charge.

- The proposed solution with the new magnets; is this realistic? What are the risks involved? What happens if one or more of the risk factors do, indeed, occur? What are the recovery plans?

4.1 Summary

Any disturbance to the TMs in initial LIGO is a concern to the committee and should be undertaken only with care. That said, the record to date for successfully removing and installing TMs is near perfect and there is good reason to believe that the magnet swap will have a similarly near perfect record.

The procedure proposed at the review uses well known procedures, experienced staff and the proven tooling to remove and replace the SUS cages with optics. We recommend that well known procedures be used as much as possible. The team should make sure the schedule is not overly aggressive.

Processing the optic would likewise follow proven methods. The main difference is in the magnet removal. The committee likes the proposed setup to wick solvent up to the magnet from underneath, allowing a full soaking about the bond. Testing of this method on some sample parts is planned and encouraged by the committee.

The committee suggests that the team that is doing the work should be given reasonable latitude to define the procedure they prefer rather than having the committee define the procedure details. The committee, however, would like the team to consider the following in deciding whether to schedule the work to be able to bake the optics together:

- The proposed procedure involves one additional move/installation/removal of the lazy susan/lift-table, per chamber, with a corresponding increase in the resources required by the task.
- There is some risk in each bake operation. Baking the two optics separately increases the risk that one optic might be damaged by a bake oven failure, but decreases the risk that both will be. The latter could be a very difficult situation to recover from.

4.2 Risk

The main risk is damage to one of the ETMs. If that happens, then we should swap in one of the spare ETMs, rather than put a damaged optic back in. Damage to an optic would introduce a delay (not estimated by the team, but one member of the committee estimated one month), with added resources diverted to the replacement, but given past experience, this is sufficiently low probability that it should not, in the committee's view, prevent us from going forward with the swap.

The next most likely risk is that an ETM does not return to its proper pitch after magnet installation and re-hanging. A wire replacement at that time might help that, but removal and replacement of the side magnets and stand-off may be needed. The schedule hit for this (not estimated by the team, but one member of the committee estimated two weeks) is significant, but still acceptable, in the committee's view.

The committee does recommend that if there is an significant glitch in the H1 magnet swap (such as a damaged ETM or a failure to return to proper pitch), that the L1 replacement be put on hold until a committee of suspension experts and one or two grey-beards meet to understand what happened and to recommend to management whether to continue with the L1 replacement.

4.3 Additional suggestions:

1. The team should take steps in advance to assure that we can maintain our in situ alignment fiducials in the event of an optic replacement or rehanging.
2. Add a step of wire inspection for signs of kinks where it went over the standoffs.
3. Please consider putting first contact on the face of the optic while the magnet de- and re-bonding work is happening.
4. The first team to perform this replacement <u>(at LHO)</u> should brief the second team on the lessons learned/lessons remembered. It may also be beneficial for staff from LHO to travel to LLO to assist with some of the procedures.
5. It was suggested that we install the new earthquake stops in the lab as the ETMs are re-hung to prevent silver from the old screws flaking onto the optics if replaced in situ. This would require a new style TFE cap placed over the glass tips on the EQ stops for transporting to and from the optics lab. The team should assess the risk of flaking versus the risks of new procedures/parts.

5. Schedule, Manpower and Cost Issues

Here we address the final item in the charge.

- The schedule and required manpower; is it realistic? What, if any, are the cost impacts? What, if any, are the manpower impacts on aLIGO?

A more detailed accounting of the manpower is needed to assess the impact on other activities in eLIGO, aLIGO, and Observatory operations. For example we need to recognize that drawing in personnel contributing to aLIGO efforts (R&D completion or the start of the project) will have a significant impact on those efforts. We should seek to minimize the impact, to the extent possible, by using observatory personnel who are experienced with LIGO suspensions and optics but not at present contributing significantly to aLIGO. However, as the staff who can put their hands directly on the effort are currently fully occupied, we have to expect that pursuing the magnet swap will cause other efforts to slip in schedule.

If we pursue the magnet swap, we recommend a change be made in the schedule to draw out both eLIGO installation and aLIGO development, worked out in discussions with the impacted teams (Observatory staff, aLIGO suspensions/management, eLIGO organization). The detailed list of activities given in Appendix C can form a basis for that discussion. We propose that the eLIGO schedule be relaxed to reflect the delayed aLIGO start. We propose that the swap duration should be extended to at least 7 weeks per observatory (not including pump down time). We also recommend the notion of working on one ETM at a time both for leveling the impact on other activities and to reduce risk.

There are no cost impacts due to the current plan. However we recommend that we consider hiring additional 'touch' labor at the observatories to help handle the additional labor needs (filling in for more experienced people working on the magnet swap); this would appear as an Ops charge, and so is in competition with other needs for Ops funds. The labor could be continued to ALIGO if the labor profile is right.

The committee estimates that the total labor required to carry out the magnet swaps is from 5 to 8 person-months per observatory (without contingency). In Appendix C we present a detailed list of activities, from the procedure E080064, that document our estimated minimum required labor and schedule.)

Appendix A

Charge to Enhanced LIGO Magnet Swap Review Committee

The LIGO Directorate hereby charges the eLIGO Review Committee with the review of the proposal to replace the initial LIGO ETM magnets from NdFeB to CoSm in order to improve the expected eLIGO performance below 100 Hz. In consideration of this proposed increase of eLIGO upgrade scope, the committee should review/consider the following elements:

1) Scientific justification for this change; what happens (to eLIGO projected performance) if we do nothing?

2) The experimental evidence that points to the limiting effects of the current magnets; is the evidence clear and unambiguous?

3) The proposed solution and the projected performance with the new magnets; is this realistic? what are the risks involved? what happens if one or more of the risk factors do, indeed, occur? What are the recovery plans?

4) The schedule and required manpower; is it realistic? what, if any, are the cost impacts? what, if any, are the manpower impacts on aLIGO?

Appendix B

Agenda for magnet swap review.

Telecon held on 21st Feb 2008

1) Introduction (Mike Z)	13.05 - 13.10	(5 mins)
2) Case for swapping magnets (Rai W/Sam W)	13.10 - 13.40	(20 mins + 10 mins quns)
3) Procedure for magnet swap (Mike Z)	13.40 - 13.55	(10 mins plus 5 mins quns)
4) Further discussion/questions etc	13.55 - 14.25	(30 mins)
5) Summing up (Norna)	14.25 - 14.30	(5 mins)

Appendix C

Estimated Time for Completing the ETM Magnet Swap per Observatory per E080064

	number of		cummulative	
A. ETM Removal Procedure	people	hrs	days	
0. Prep end station, transport tooling	4	24	3	
1. Establish pre-vent alignment fiducials	2	4	3.5	
2. Seal, lock and tag gate valves, annuli and pump apertures as required to isolate BSC volume	2	4	4	
3. Vent first ETM BSC and remove door per M980133, E000120 and E000062	4	4	4.5	
4. Inspect and log EQ stop gaps and PAM magnet screw extensions	2	2	4.75	
5. Immobilize ETM with EQ stops	2	0.5	4.8125	
6. Install alignment reference jigs on SEI interface	2	0.5	4.875	
7. Install BSC LOS installation/removal jigs and tooling per E000062	4	4	5.375	
8. Remove LOS w/ETM to transport tooling	4	4	5.875	
9. Transport LOS to optics lab for processing (next section)	3	4	6.375	
10. Deinstall LOS install/removal tooling, perform exit QA	4	4	6.875	
11. Reseal BSC and repump temporarily during COC reprocessing	4	4	7.375	
12.a Move install/removal tooling to second ETM station	3	4	7.875	8 days
12.b. repeat steps 0 - 11	1	210		
B. Core Optic Reprocessing Procedure (in optics lab)				
0. Prep optics lab, gather fixtures/tooling	2	16	2	
1. Erect LOS in optics lab and test equilibrium hanging level per E970154. Record results for post-process comparison.	2	2	2.25	
2. Remove ETM from LOS leaving suspension wire in place.	2	2	2.5	
i. Loosen the upper barrel and bevel stops and raise the lower barrel stops evenly to slacken the wire.			2.5	
ii. Slip the wire aft past the lower barrel stops one at a time and dress upward past the face magnets. Avoid kinking or catching on magnets.			2.5	
iii. Tie suspension wire out of the way before attempting to withdraw the ETM.			2.5	
3. Rotate ETM to horizontal position with face magnets upward and lay in holding fixture	2	0.5	2.5625	
4. Level ETM holding fixture using shims so upper face is horizontal within +/- .010" over face (to control liquid migration)	2	0.5	2.625	
5. Drip a single droplet of methylene chloride around base of each face standoff	1	0.5	2.6875	
6. Replenish solvent periodically at a rate sufficient to compensate evaporation (do not form puddle)	1	4	3.1875	
7. Continue to maintain local solvent pools for at least 4 hours (TBR)			3.1875	
8. Test for softening of the glue using clean razor blade. If glue remains firm, resume solvent soak. DO NOT apply significant force to blade or attempt to lever or pry the standoff away.			3.1875	
9. When all face standoffs have debonded, locally clean each attachment point using methylene chloride on folded lens tissue held in hemostats.	1	1	3.3125	
10. Change tissues and renew solvent after each wipe. Continue until all visible glue residue has been removed.			3.3125	
11. Repeat local cleaning of bonding zones with spectroscopic reagent grade acetone and lens tissue.	1	1	3.4375	
12. Prepare ETM surface for face magnet gluing per specification in E970154.	1	1	3.5625	
13. Prepare jigs, epoxy, SmCo magnets and standoffs per E970154.	2	2	3.8125	
14. Prepare gluing fixture D990158-A for face magnet attachment. However substitute special optical noncontact sighting adapter in place of side magnet gluing fixture.	2	1	3.9375	
15. Install the ETM in the gluing fixture per E970154. However use the sighting adapter to orient the side magnet as it was originally attached, without touching it. This will insure the proper relative positions of face magnets.	2	1	4.0625	
16. Attach SmCo face magnets and standoffs per E970154. Take care to observe proper magnet polarity.	2	1	4.1875	
17. Bake out the ETM per E970154 to cure/degas VacSeal.			4.1875	
i. move optic into and out of chamber	2	2	4.4375	
ii. Perform bake and RGA scan	1	2	4.6875	
18. Resuspend ETM in LOS per E970154. Check that pitch angle repeats within PAM/bias adjustment tolerances (it will be constrained by existing guide rods).	2	4	5.1875	
19. If suspension wire is replaced, insure that length and roll angle are replicated to required tolerances.			5.1875	5 days
20. Repeat steps 0 - 19 For the other ETM	1	73.5		
C. Reinstallation Procedure				
0. Transport the LOS to the end station	3	4	0.5	
1. Seal, lock and tag gate valves, annuli and pump apertures as required to isolate BSC volume.	1	4	1	
2. Vent ETM chamber & remove access door per M980133, E000120 and E000062	4	4	1.5	
3. Reinstall LOS installation tooling per E000062	4	4	2	
4. Install LOS using alignment fiducials and positioning jigs to replicate prior orientation	4	4	2.5	
5. Repeat installation PAM adjustment	2	2	2.75	
6. Replace EQ stops with quartz-tipped screws per procedure T070257	2	2	3	
7. Clean ETM face per procedure E990035	2	2	3.25	
8. Remove LOS tooling, perform exit QA, seal and pump chamber	4	8	4.25	
9.a Move installation tooling to second end station (or into storage)	3	4	4.75	5 days
9.b repeat steps 1 - 9a	1	108		
10. Follow vacuum QA and degassing protocol prior to reexposing chamber to beam tubes.	2	4	0.5	

GRAND TOTALS (work time, not calendar time):	hrs	815	36	schedule days
	months	4.7	7.2	schedule weeks

Comments on the report received from Rai Weiss, 11th March 2008

1) There is far less uncertainty in the up-conversion spectrum than implied by the report. All the direct measurements both in the test rig and in the in-situ direct measurements show 1/((f-f0)*f**3) spectrum when driven by a sinusoidal excitation at f0.

2) The uncertainty in predicting the up-conversion from the spectrum of the current in the coils comes primarily from how best to do the convolution with the current. The non-linear dependence (I^^3/2) is part of the problem and the fact that some of the Barkhausen noise is coherent (always the same for the same current) while another part is incoherent adds to the difficulty. Given this somewhat difficult analysis problem I am amazed how well the projections actually work. A good thesis for a motivated undergraduate.

3) The point about the complicated model of the Barkhausen up-conversion with with close magnet spacing that was discovered at LHO, is not quite on the mark. I used a wrong model in the original calculations (the point dipole model) never expecting that there would be a PAM/control magnet spacing as close as that found at LHO. It was only after the meeting with your committee and the unexpected skepticism, that I felt it necessary to calculate the magnet/magnet interaction properly having been satisfied with the qualitative agreement that the mass with the closest spacings had the largest in-situ up-conversion. I was very happy to find that the correct calculation even allowed the prediction to work well (better than a factor of 2 if you include the uncertainty in the measurements of both the spectrum and the gap spacing).

4) I do not understand the comment about the mystery of the single sided up-conversion at LLO. It certainly does not appear that way in the in-situ measurements.

I do agree with committee assessment that if we do not fix the magnet noise problem we will never make much progress on improving the sensitivity of the instrument in the binary BH region. This would be an enormous pity since this is the most likely source we could observe in S6.

Also I want to make sure that the committee realizes that the NS/NS inspiral probability will only by weakly improved by the magnet swap as under quiet times I do not expect the noise above 150 Hz to be strongly influenced by the magnets. The noise at LHO with strong winds and at LLO with strong microseism will be very much improved so there will be an improvement in duty cycle for the NS/NS coalescences.