LIGO - T880002

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Review of Rai's memo on Laser Power and Cooling Requirements

This is a first review of Rai's memo on Laser Power and Cooling Requirements for LIGO. Let me start with an apology. Being new to this effort I may be naive in my analysis or I may point out problems that are already well understood by the CalTech/MIT group. However this will at least get some of these things down on common paper.

In summary, Rai's memo calculates the power requirements for a facility that would provide shot noise limited strain sensitivity of h = 10^{-21}, for bursts with characteristic frequency scales of 100 and 1000 Hz and treats the cases of recycling and no recycling. He then follows with a discussion of potential efficiencies for Ar^+ and Nd:YAG lasers. Finally he ends with a table of power requirements and operating costs for various scenarios.

I am assuming that this is the first of many reviews of this topic of which only a very few will occur before the hard choices are forced upon us. I therefore propose the following attack on this problem. First, one power requirement for LIGO is that which allows us to attain our target burst sensitivity for the LIGO startup detectors (LIGO1) using currently available large frame ion lasers. Naming any other laser system as the candidate for LIGO1 would look like pie in the sky in a construction proposal. More powerful and/or efficient lasers should be viewed only as one of the trump cards we will play to get to advanced detectors. Therefore the second power requirement is presumably that which would allow us to get to advanced detectors with the power/cooling facilities installed in LIGO1. Some crystal ball analytic continuation must then connect these two points. Where the actual design will fall is mediated by the incremental cost of power/cooling including the effects of the time at which any upgrades are installed. (There is probably a cost savings if the ultimate power/cooling system is put in at initial construction. But this option may be too pricey. If additional capacity is installed as an upgrade it will be more costly, but maybe the cost can be contained if in the initial design we anticipate properly the upgrading we will do.) Last but perhaps most important is the consideration of what we can convince a review committee to give us. This loosely defines the weighting factors. Finally, the constraints are that irregardless of the cost of laser power/cooling, the number of lasers we can install is finite, and if the power estimates include some technology at LIGO startup we will most likely have to prove when the construction proposal is submitted that this technology will work.

To get this review done on schedule I have assumed the validity of the formulae Rai uses for the Fabry-Perot (FP) burst sensitivity. I presume everyone except me is familiar with the derivations. If not I will volunteer to check them. I have checked the arithmetic and concur with Rai's numbers for the FP with and without recycling using Ar^+ lasers.

Power/cooling gets unwieldy very fast as Rai points out. For example at 100 Hz the LIGO1 target burst sensitivity without recycling can be done. Comparable sensitivity at 1000 Hz demands that recycling work well. To review the way things get out of hand, to detect h= 10^{-21} at 100 Hz without recycling requires P_i = 1.2 W of tamed laser input to the cavities. For power/cooling specifications we need P_W, the actual wall power required to get this much tamed laser light. This is given by:

$$P_W = \frac{P_i}{\eta_c \eta_L} \times 2 \times N_D$$

where η_c is the coupling efficiency of getting single line laser output into a FP cavity, η_L is the efficiency of producing electrical to single line lasing output, 2 means each detector is a full length plus half length interferometer, and N_D is the number of detectors/site at the LIGO. Rai proposes $\eta_c = .25$ as reasonable. While the 40 m prototype has only achieved $\eta_c \leq .05$, this may be a reasonable goal. The MIT people are apparently better at using fibers and fibers may or may not be used in this part of the LIGO. $\eta_L \approx 1.1 \times 10^{-4}$ is established fact for large frame ion lasers. Note that I am intentionally neglecting the power expended in cooling the laser. This is because the power requirement for cooling depends on the cooling mechanism which depends on how much cooling is required, etc. This is a renormalization I will do later. Secondly, I have not checked if even this efficiency is reasonably achieved under operating conditions where we can expect an MTBF for the plasma tubes of order one year. We assume $N_D = 3$, a fully dedicated search detector, a developmental detector, and an outside user detector. The result is staggering:

$$P_W = 2.2 \times 10^5 P_i$$

Whether or not we recycle affects the requirement forP_i but not the relation between P_W and P_i. The benchmark target I will take to be for detection of bursts at 100Hz with h $\leq 10^{-21}$ without recycling. This requires $P_W = 2.7 \times 10^5$ W. Engineering proposes $.10/kW-hr as a more realistic cost of electricity than Rai's $.07. Using this price, our expense of running the lasers is $240K/year at each site. The benchmark uses two large frame lasers/detector or six/site. To retain some semblance of sanity in the LIGO1 design we must keep track not only of the laser power budget but also the laser unit budget. In general the number of ion lasers/site can be obtained as:

$$N_L = \frac{6}{5\eta_c} P_i$$

where 6 equals 2 interferometers/detector times 3 detectors, 5 is probably as much single line wattage as we will expect from a single large frame laser, and η_c is the coupling efficiency. Obviously N_L always gets rounded up to the nearest integer. To avoid meltdown there is a further cost for cooling. The Engineering group has advised me to estimate 1/2 W/W for cooling, including pumping and refrigeration. This would bring the total electric bill to $360K, for 400kW. Total nonlaser power consumption at this time is still in flux, but a capacity of 1500kW in addition to laser capacity is a guess at where this will end up. To add a laser capacity of 400kW to this number is certainly reasonable. A further factor which could affect the price of electricity is how we ask for it to be served up. For example, if we demand 1MW the power company will reserve it for us and charge premium prices. If we just use it as available we may get a cheaper price. Typically electric customers who are willing to vary their load at the utility's request get a discount for acting like a storage battery. While we are not an aluminum manufacturer, we should be careful not to "demand" more power than we reasonably need on a demand basis. Also I am not sure that my impression of how utilities bill large power consumers is exact. Clearly some harder numbers on the pricing of electricity are needed.

Should this benchmark power/cooling plan be adopted as our minimum requirement for LIGO1? The answer depends on answering some questions about recycling and vibration isolation. Without recycling, to get the same sensitivity at 1000Hz requires 1000 times the power/cooling requirements and this possibility is safely neglected. I bring up vibration isolation because the low frequency limits to detection sensitivity in the Dec87 proposal were seismic noise and vibration limits. If this is true (I just do not understand where they come from) and if we corner at 200Hz instead of 100Hz, then we up the spec'd power/cooling by eight assuming no recycling. We would then need about \$3M/yr/site for electricity, 48 large frame ion lasers/site. I doubt that we will be allowed to buy this much power, or that many lasers. Note that in the Dec87 proposal the LIGO1 target curve for burst sensitivity bottomed at closer to 300-500Hz. My conclusion is that the above benchmark is not totally out of the question, but we severely limit our prospects unless we design recycling into the construction proposal. Perhaps a more reasonable role for considering the unrecycled case is as a fallback position. If recycling cannot be put on a firm scientific basis by proposal time, we may have to throw the unrecycled case up in the air and pray.

The picture changes drastically when we propose the same power capacity and assume recycling will work up to expectation. At 100Hz we are probably safe in assuming we will need 20 times less power for our target sensitivity. With recycling the same sensitivity at 1000Hz is only 100 times more costly than at 100Hz, or 5 times more costly than the 100Hz benchmark above. So $h = 10^{-21}$ at 1000Hz requires ≈ 30 large frame ion lasers/site with an electric bill of \$1.8M/yr/site, which is probably too large but not out of the ballpark. Also this 1000Hz number assumes 200 recycles and may or may not be reasonable. If we lower the design frequency to 450Hz, the power required drops to the previous benchmark, the number of lasers drops back to 6 and we only need 90 recycles. This target now looks closer to the curve in the Dec87 proposal.

At this point it looks like any except the most modest and risky LIGO1 system will require recycling and that addition of lasers should probably also be written into the design. (At ≤ 6 lasers/site one could get by without addition.) Therefore, for the construction proposal, hard scientific data on recycling will be crucial, and may even outweigh the importance of modest gains in demonstrated sensitivity on the prototypes. I will return to problems on this front later. Progress on laser addition is important but less crucial than recycling. While we could hit a reasonable goal in LIGO1 without addition, a time may come when we are forced to add lasers and a reviewer might balk at our future prospects if we do not prove feasibility in the construction proposal.

Now I would like to get some estimate of the power/cooling requirements of advanced detectors. As an exercise let me adopt as "straw man" the power capacity of the benchmark (namely 400kW) and assume recycling. As an advanced detector target let me specify a burst sensitivity of 10^{-23}, near the standard quantum limit. At 100Hz this represents a factor of 100 improvement over the LIGO1 target without recycling, which I mentioned earlier. The inclusion of recycling buys us a factor of $\sqrt{20} = 4.5$ without affecting power consumption. It is out of the question (with current knowledge) to anticipate attaining the advanced target with Ar$^+$ lasers, as Rai explains in his memo. However it is reasonable that a Nd:YAG system with an efficiency improvement of 100 over current ion lasers could be achieved with a lot of work. This buys us another factor of 10 without increasing power requirements. Combining these two factors we have a shot noise limited sensitivity increase by 45. The extra factor of two could be bought by (1) improving recycling with lower loss optics, (2) increasing our power capacity. The estimated efficiency increase seems reasonble, given Rai's discussion of Nd:YAG lasers. Theoretically flashlamp pumped systems could get there with efficient doubling, but one ought to allow room for dreck effects. However diode pumping should provide enough headroom between theory and laboratory performance. If not, diodes themselves may be developed into reasonable sources in the future. Also while these improved sensitivity estimates are optimistic because they assume things will eventually work as well as they should, they are pessimistic in that they assume that there are no more tricks like recycling to be discovered. If you are willing to buy the efficiency increase, and assume we can recycle well enough to use mirrors a factor of four less lossy than we currently have, then our straw man gets us to advanced detectors. If you do not buy the recycling improvement or you want extra headroom for any failure to get the efficiency increase, we can up the straw man capacity by a factor of 4. This capacity also would allow us in the earlier LIGO stages to add lasers into quadruples, maxing out at 24 lasers/site until the high efficiency product becomes available.

I thus propose a capacity for laser power/cooling of one to four times the straw man number or between .4 and 1.6 MW. The bottom end of the power range is my best guess at the minimum level we can tolerate. I am guessing that the larger number will be comparable to the nonlaser power capacity, and buys us some insurance. The electric bill is in the range of $.4M to $1.5M for the lasers. It may make sense to push the specified capacity for laser power toward the larger number. The incremental cost for substation and wiring is likely to be modest and these capital costs are not driving forces in the construction budget. Hopefully we will not pay for the electricity if we do not use it (provided we are not getting all of our power on a demand basis). This needs more research. If we can install, add, etc., the extra laser power and if other things work well, we could approach the standard quantum limit at higher frequencies. On the other hand we probably will have more power available for running lasers than we spec as capacity, since all of the nonlaser capacity will not be used in everyday operation. For example, the pumping stations require a lot of capacity to pull vacuum in the tubes, but as the pressure drops so does the power drawn by the pumps. The lasers on the other hand will presumably not operate at full power unless vacuum is good. Obviously we need to take a holistic approach to power management. On the other hand we may want to use the holistic approach to reduce the capacity instead.

Another factor to consider is that any point in the power budget range assures us that we can get to some sensitivity level at a given design frequency but also assures that we will not do much better until our efficiency goes up dramatically. The efficiency of our lasers is likely to be a step function in time and we cannot predict when in time the transition will occur. We must face the fact that if we can continuously improve the non-shot-noise interferometer performance we will, at some time, have interferometers that are shot noise limited at a given frequency in the sense that no significant development will be made in sensitivity at that frequency for a long time due to power starvation. Improvements in LIGO will then have to come elsewhere, for example by pushing down the low frequency end of our sensitivity curve. This scenario will occur unless we base our power budget on getting to advanced detectors with Ar^+ lasers, which is ridiculous. Twiddling with the power budget can only affect when the scenario turns on.

Assuming that we adopt a number somewhere in this range for the construction proposal, it is necessary to look at what is required from the scientific teams in the next year. Without recycling and laser addition we are somewhere between being at serious risk and being dead meat. If I were a reviewer I would not accept any construction proposal that did not have a very hard-clad scientific case that (1) our estimates for the efficacy of recycling are valid, and (2) that we really do know how to scale up numbers from the prototypes to the LIGO.

The key scientific factors in my mind are (1) to what extent additional losses in the recycling circuit will limit the number of recycles that are feasible, and (2) can we use the loss numbers we measure in ringdown measurements as the losses we would experience in LIGO. Possible extra recycling losses can occur through (1) failure of AR coatings and scattering on second surface of the FP input mirror, (2) optical path inhomogeneities across the input mirror substrate, (3) birefringence in the mirror substrate, and (4) failure of mode matching due to surface figure errors in the cavity and recycling mirrors (essentially an extra re-injection loss). It is important to realize that although many of these problems can be addressed by say good coatings and compensation plates, there may be important thermal self-focussing effects associated with the higher power densities that come with efficient recycling. My expectation is that problem (3) is potentially the most severe. This is probably because I have routinely made zero order tunable retardation plates by squeezing fused silica slabs of order 1 cm thickness. As for the applicability of ringdown data to the losses expected in LIGO, a simple model convinces me that the losses in a cavity due to surface figure errors depend on the spot and mirror sizes used in the ringdown measurement. In essence, different mode sizes probe different length scales of the surface figure error. I think this bears looking into. I do not know if scattering losses in the beam tubes is a problem. If we can support the recycling promises with data I think the power capacity design looks OK, provided η_c is not unrealistic, and provided we can run lasers at the quoted efficiency for long periods without replacing the plasma tubes all of the time. I hope we can get some discussion on these issues and plan the scientific program accordingly.

How do we get to a final decision on a laser power/cooling budget? Probably the driving factor will be the cost of electricity for the entire facility versus how many dollars of operating budget we can reasonably expect. Therefore an urgent issue is an Engineering definition of exactly how much electricity will cost at the proposed sites. Secondly we will need an operating plan for power consumption. I have already mentioned the possibility of time-multiplexing power between lasers and vacuum pumps. The developmental detector will presumably operate at full laser capacity for only one shift. Perhaps that capacity can be used elsewhere for the other two shifts. Maybe we can use the waste heat from the lasers for some other function (showers?) before we cool it. We might be able to use some such efficiencies to buy more insurance in the power budget for the lasers. Another point is to be sure that we are not fooling ourselves with the efficiency numbers. Are we convinced that, besides being reasonable, we will actually achieve them in the flesh on a routine basis in LIGO1? Finally there is the question of where in the proposed range are we shooting ourselves in the foot, and how much insurance do we think we can afford to buy.

While it may take some time to digest all of this I ask that people please check my arithmetic right away. You can argue with my point of view later. Also if you want to shoot me, please use rubber bullets as I am new on the job.