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Evaluation of Nd:YAG(1064nm) Lasers for Use in the Initial LIGO Interferometers

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Summary

The technical merits and the cost-schedule impact of using a Nd:YAG laser with a wavelength of 1064 nm[1] for the initial LIGO interferometers are analyzed. It is found that except for the cost of commissioning a YAG prototype, there appears to be little penalty to the Project, in terms of cost and schedule delays, if a YAG with adequate performance can be made available by late 1996, and if the decision to use it is made at that time. The technical risk of implementing a Nd:YAG 1064 nm initial interferometers appears low, and there is promise for future improvements in laser sources. We recommend that LIGO enter into a contract with a commercial laser manufacturer in the very near future, with the goal of having a prototype YAG laser in hand in one year. Furthermore, we suggest that a decision on the choice of laser for LIGO be made when this contract is completed and 1-2 months of in-house evaluation of the new laser has been carried out.

If the contract with industry and the subsequent in-house testing can be brought to successful conclusion by November 1996, it appears that the PSL subsystems could be ready in time for installation at the sites by June 1998, according to the current LIGO schedule.

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[1] Henceforth to be called YAG laser

1 INTRODUCTION

The current LIGO Baseline Concept employs Argon ion lasers, emitting 5 W of single frequency, single mode light at wavelength of 514.5 nm. YAG technology has made impressive advances, and it appears that 1064 nm lasers adequate for the initial LIGO interferometers are just a contract with industry away from our labs. For a variety of reasons,[1] there is growing belief that the advanced interferometers will have to use 1064 nm light, thus a switch from Argon lasers to YAGs seems quite likely, raising the issue of finding the optimal point in time for this transition. Given the high cost[2] of rebuilding three operational interferometers operating at 514.5 nm, to accommodate 1064 nm, it is natural to ask what the implications are of switching lasers and wavelength at an early stage, before the first LIGO interferometers enter the Operations phase. Accordingly, Abramovici and Shoemaker were asked to conduct a study addressing the following aspects related to using YAG (1064 nm) instead of Argon lasers:

1. Technical merits of an Argon/YAG change in the Baseline.
2. Examine the LIGO Implementation plans in order to identify the latest possible point in the schedule for implementing the Argon/YAG substitution.
3. Lay out a top-level program to support a decision of an Argon/YAG change in the Baseline.

Section 2 summarizes the comparison between the two types of lasers, in the LIGO context. Section 3 discusses the cost-schedule impact of a decision to use YAG instead of Argon lasers, as a function of decision timing. Section 4 includes a more detailed analysis of the PSL subsystem cost/schedule, under the assumption that it will be possible to order an adequate YAG laser, and that the decision to do so is made by November 1996. Section 5 contains the recommended course of action. Several appendices are included which contain information of a more detailed nature concerning the replacement of Argon laser with YAGs. Appendix A gives the original charge. Appendix B presents the proposed modifications to the LIGO baseline needed to accommodate YAG lasers; Appendix C lists relevant activities in other GW laboratories; Appendix D contains a discussion of the effects of an Argon/YAG switch on the LIGO R&D effort. A draft specification for a YAG laser adequate for the initial LIGO interferometers is presented in Appendix E. References for the technical discussion are in Appendix F.

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[1] A discussion of wavelength choice for the advanced interferometers is beyond the scope of this study.

[2] in money, manpower, and instrument down-time.

2 SUMMARY OF TECHNICAL MERITS

Nd:YAG is expected to be a light source which will be suitable for enhanced and advanced LIGO interferometers. In the laboratory, Nd:YAG and other solid-state lasers exist already which are suitable for engineering into 'enhanced' interferometers (with 40 W of power, equivalent to 20 W of Argon 514 nm light). In contrast, Argon lasers have no promise of more than 20% increases in power. Thus, we see a need to change to solid-state lasers shortly after commissioning of the initial LIGO interferometers.

To first order, then, we wish to anticipate that change and to test if we cannot start the initial LIGO interferometers with a light source and wavelength which would allow an adiabatic change to higher power. This can save schedule, and reduce the net cost, of arriving at an enhanced level of shot-noise limited sensitivity.

A second reason to investigate Nd:YAG lasers at 1064 nm at this time is to evaluate possible performance advantages from the different wavelength. Relaxed mirror specifications, and lower Rayleigh scatter in the substrates, are examples.

In summary, there do not seem to be any aspects of the interferometer performance or engineering difficulty which would be significantly adversely impacted by a change to 1064 nm and Nd:YAG for the initial LIGO interferometers, and all indications that higher power lasers will be in parallel development (driven by a rapidly growing industrial demand). There are a number of places where more in-house effort will be required, to characterize new components, but sharing with laser groups and other GW groups can reduce this burden.

The tables below summarize the differences between a Argon-514nm interferometer and a Nd-YAG-1.06μm laser. Points which can be clearly seen as disadvantages are indicated in *italics*. Details are given in Appendix B. Most categories should be self-explanatory; by 'engineering status' we mean to give a one-line summary of the availability of a commercial solution, the engineering future, the rate of progress in the field, etc.

Table 3-1: Laser Technical Summary

parameter/part	Nd:YAG Merit/*Demerit*	Argon Merit/*Demerit*
power	initial power available, future power assured; *~2x power required for given sensitivity*	initial power available; *no further increases probable*
efficiency	several 10^{-2}	10^{-4}

parameter/part	Nd:YAG Merit/*Demerit*	Argon Merit/*Demerit*
mean time before failure	10,000 MTBF (commercial specification) 10-20,000 MTBF (Byer experience)	8000 MTBF (commercial specification) ~2000 MTBF (LIGO experience)
failure mode	~20% reduction in power	*no light*
raw frequency noise, 90 Hz	10^2 Hz/$\sqrt{Hz}$	10^4 Hz/$\sqrt{Hz}$
raw intensity noise, 90 Hz	$10^{-6}\ \delta I/I\ 1/\sqrt{Hz}$	$10^{-4}\ \delta I/I\ 1/\sqrt{Hz}$
raw intensity noise meets ~100 mW shot noise	3 MHz	~5 MHz
beam jitter	not yet characterized; reported to be small	characterized
engineering status	*~$1M+ 1 year development*	ready
future development	growing market	*static to declining market*

Table 3-2: Modulator (Input Optics) Technical Summary

parameter/part	Nd:YAG Merit/*Demerit*	Argon Merit/*Demerit*
power handling	to 20 watts	to 5 watts
sensitivity	210 volts/π, 1.06 μm	1000 volts/π, 514 nm
frequency range	to 100 MHz	to 60 MHz (in pairs)
engineering status	commercial item	commercial item

Table 3-3: Core Optics Technical Summary

parameter/part	Nd:YAG Merit/*Demerit*	Argon Merit/*Demerit*
mirror size	*back mirror >27 cm*	<25 cm
figure requirements (sample requirement)	Argon $*\sqrt{2}$ $=\lambda_{514}/424$	$\lambda_{514}/600$
required coating uniformity (random errors)	0.1%	0.1%

parameter/part	Nd:YAG Merit/*Demerit*	Argon Merit/*Demerit*
substrate scatter	1-2 ppm/cm	*10-20 ppm/cm*
substrate absorption	1-2 ppm/cm	1-2 ppm/cm
substrate homogeneity	same to 2x better	---
coating absorption+scatter	6 ppm	~20 ppm (1.5 reported)
metrology	commercial	*special interferometer must be fabricated*

Table 3-4: Suspension Technical Summary

parameter/part	Nd:YAG Merit/*Demerit*	Argon Merit/*Demerit*
end FP mirror	*possible additional design type required*	

Table 3-5: Photodetector (Length Control) Technical Summary

parameter/part	InGaAs Merit/*Demerit*	Si (Argon or YAG) Merit/*Demerit*
power handling	150 mA	*15 mA*
quantum efficiency	80-90%	60-70%
surface diameter	*0.5-2 mm*	10 mm
spatial non-uniformity	TBD	$<10^{-3}$
capacitance	15 pf	30 pf
engineering status	*in development*	commercial

3 COST-SCHEDULE IMPACT ESTIMATE

3.1. Scope

- The accuracy of the cost impact assessment is estimated to be at the ±25 % level, or better.
- Schedule impact is defined as the potential delay in entering the Operations Phase of LIGO.

- Schedule impact is evaluated with a resolution of 6 months, assuming that a decision to switch will be made no later than July 1998, when installation of the first interferometer at the Washington site is planned.

3.2. Method

- Schedule and cost impact are plotted versus time. These plots show graphically the steepening impact if the decision to switch laser technologies is deferred to a later date, and will help to determine the latest time beyond which a decision to replace Argon lasers with YAG lasers becomes too costly.
- Impact assessments have been conducted only the following major subsystems, parts of which interact directly with the main light beam:

1. Prestabilized laser (PSL)
2. Input/output optics (IOO)
3. Core optics (CO)

A separate assessment for the R&D activities which are affected was also conducted. We did not investigate the cost impact on the CDS.[1] Indeed, the cost of the CDS part of the PSL is guessed to be a few hundred k$, les than 25% of total PSL cost. The CDS part of IOO and COC was not included in this study because it is independent of wavelength, and therefore any CDS related work already carried out by the time an Argon/YAG switch decision would be made will be simply carried over with no loss.

- Impact assessment is conducted by folding delay estimates into the current Detector Implementation Plan, with proper accounting of schedule floats wherever they are presently available.
- Impact is measured by using a modified baseline description of the initial LIGO interferometer with a YAG laser at 1.06 μm (see Appendix B). This baseline will be modified as our understanding of the technical aspects improves. It is assumed that a single frequency YAG laser with 10 W output power (single mode, single frequency) is needed to provided the same shot noise performance as a 5 W Argon laser.
- The LIGO cost-schedule database were used for input data, wherever possible.
- Costs were evaluated by adding up the cost of effort that needs to be repeated, when the associated expenditures already incurred by building parts for an Argon based system cannot be transferred to a YAG based one.
- It is assumed that to the accuracy of the present evaluation, design activities are ‘color blind,’ i. e. they result in a product which applies equally to Argon or YAG lasers.
- For decision points at or beyond mid-1998, the cost increase is due to the need to maintain

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[1] However, CDS schedule has been folded into the schedule slip estimate.

manpower connected with activities which were supposed to have been completed by that time.

NOTES:

- The method outlined above is likely to yield a worst-case impact estimate, since it rigidly uses the existing cost-schedule structure. It is reasonable to assume that if and when a decision to use YAG lasers is made, one would restructure affected plans in order to minimize costs down the road, possibly resulting in substantial savings.
- It is worth noting that the cost/schedule impact charts shown below should not be taken to accurately represent the actual impact resulting from a decision to replace Argon lasers with YAGs. Carrying out an accurate estimate would have to involve a team of professional cost/schedule experts, well versed in using the advanced professional software appropriate for such exercises. The much less ambitious goal pursued in this section is to achieve a level of accuracy just good enough to show, with a timing resolution of 6 months, where the cost/schedule curves display a sharp upward bend. Possible manpower shortages resulting from letting the schedule for one subsystem slide into a time frame where the same people are expected to work on another subsystem are one example for effects not addressed here.

3.3 Results

3.3.1 Prestabilized Laser Subsystem

The PSL stands out among the major subsystems affected by changing the laser type, as its very core, the laser, would be replaced; it is also the most advanced of Detector subsystems at the present time. The effects and possible timing of this change depend heavily on the availability of an appropriate YAG laser (see Appendix E for a sample YAG specification). Discussions with representatives from Lightwave Electronics, Spectra Physics, and Coherent produced the following information:

- Both Lightwave Electronics and Spectra Physics are interested in entering into a contractual relationship with LIGO which is aimed at building a fully engineered prototype YAG laser based on our specifications.
- Coherent did not express interest in such a contract.
- Both Lightwave Electronics and Spectra Physics believe that they could build the prototype in 12-15 months, for $500k to $1M.

We estimate that once the prototype exists, further units will have approximately the same cost as the Argon lasers included in the current Baseline.

The cost-schedule impact to the PSL subsystem, as a function of the when the decision to switch to YAG lasers is made, is shown in Fig. 2.3.1-1. The somewhat smooth character of the curves reflects the fact that a substantial amount of money and work have already been invested in this subsystem. The steepening impact after November 1996 in the schedule impact graph occurs when the floats built into the current plan are exhausted. An up-front investment of $750k is assumed in the cost curve. This amount is the probable expenditure associated with contracting for a prototype with industry.

3.3.2 Input/Output Optics

The cost-schedule impact on this subsystem is illustrated in Fig. 2.3.2-1. One notable feature is that there does not appear to be much of a penalty if a decision to use YAG lasers can be made before the end of 1996. The schedule has similar behavior, helped by the fact that, according to current plans, there is a half-year float before the IOO needs to be installed at the sites.

3.3.3 Core Optics Components

As shown in Fig. 2.3.3-1, the Core Optics Components subsystem displays a pattern very similar to that of the IOO. The impact could be slightly reduced if a decision were made early to buy 4-5 mirror blanks 28 cm in diameter (rather than the presently baseline of 25 cm). The slightly larger dimension would allow end mirrors usable for either 514.5 or 1064 nm to be fabricated.

3.3.4 R&D

This is a brief summary of the longer discussion in Appendix D. A top-level estimate[1] is that the material costs of characterizing a Nd:YAG source with the Phase Noise Interferometer would be $75K plus the cost of the YAG laser, and its duration would be 6-9 months. It would cost $125k plus the cost of YAG laser to convert the 40m interferometer to 1.06μm, and that an effort would take 8 months.

Most of the useful prototype effort on either the 40m or the PNI could probably be performed with a low-power commercial laser (roughly $25k); much of the required experience with frequency stabilization can also be gained with such a system. High power lasers would be needed on both campuses, but one may be the original prototype and the second an R&D light source. One small laser per campus would be needed. Additional cost, but little manpower, would be needed to establish an infrastructure to allow experiments at 1.06μm. A crude estimate is that $100k between the two campuses would give a solid base to build on, with continuing investment as new experiments are started up.

Thus, the total cost to the R&D program, including ~$500k worth of labor, adds up to about $950k. While this cost is significant, we believe that it depends only weakly on the Argon-YAG decision timing, and therefore does not affect the conclusions of this study. The cost would be distributed over several years. Note that the cost book carries a 'placeholder' budget for Nd:YAG work of 15 Man Months scientist, 2 MM engineer, 30 MM grad student, 4 MM technician, plus

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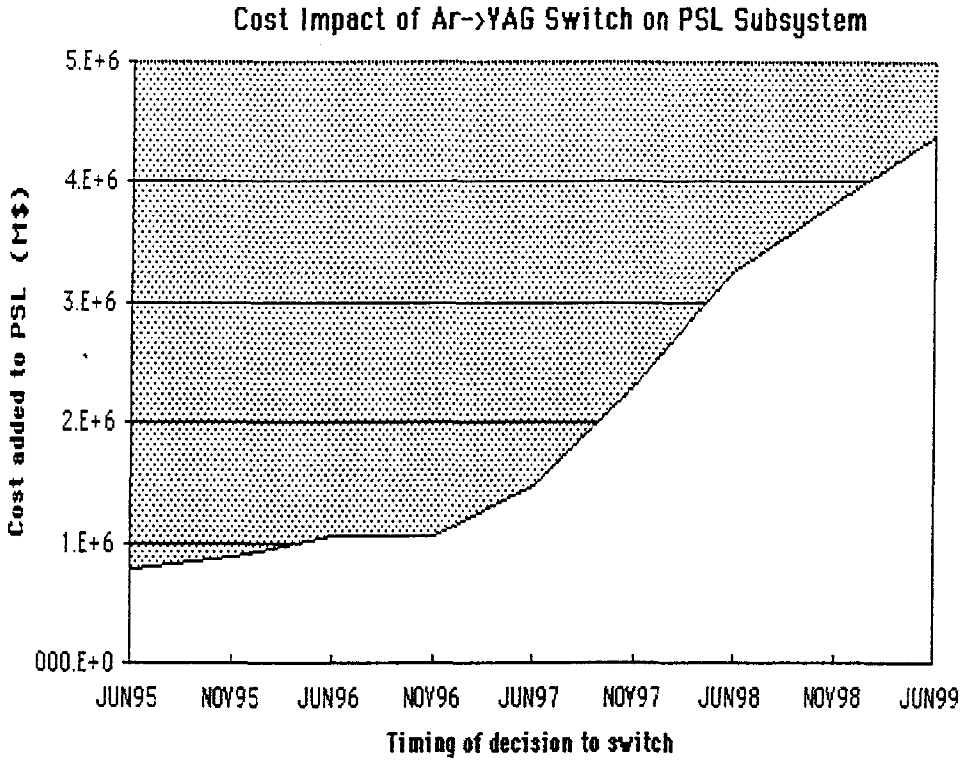
[1] source: Whitcomb

$300k in materials, which is roughly equivalent to 75% the costs estimated for R&D expenses. Whitcomb thinks that some of this effort can not be applied directly to the conversion efforts above, leading to a total R&D impact of about $1.5M with roughly $800k already in the cost book. This 'placeholder' YAG effort was planned for mid-96 through end-98. A commitment of this magnitude would, of course, reduce the flexibility of the R&D program.

3.3.5 Conclusion

Examination of the plots in Figs. 3.3.1-1, 3.3.2-1, and 3.3.3-1, and of the cost summary plot in Fig. 3.3.5-1 indicates that the decision to use YAG lasers will not significantly impact the LIGO schedule, if it can be made before the end of 1996. Any delay after that is likely to cause a steepening increase in cost and a linear schedule slip. The additional cost of ~$750k for the laser development is to be noted; some of the R&D costs are already allocated in the cost book, but there will be an additional cost of roughly $700k, some of which will be 'up-front' investment to get early experience with the technology.

Figure 3.3.1-1: Impacts to the PSL Subsystem



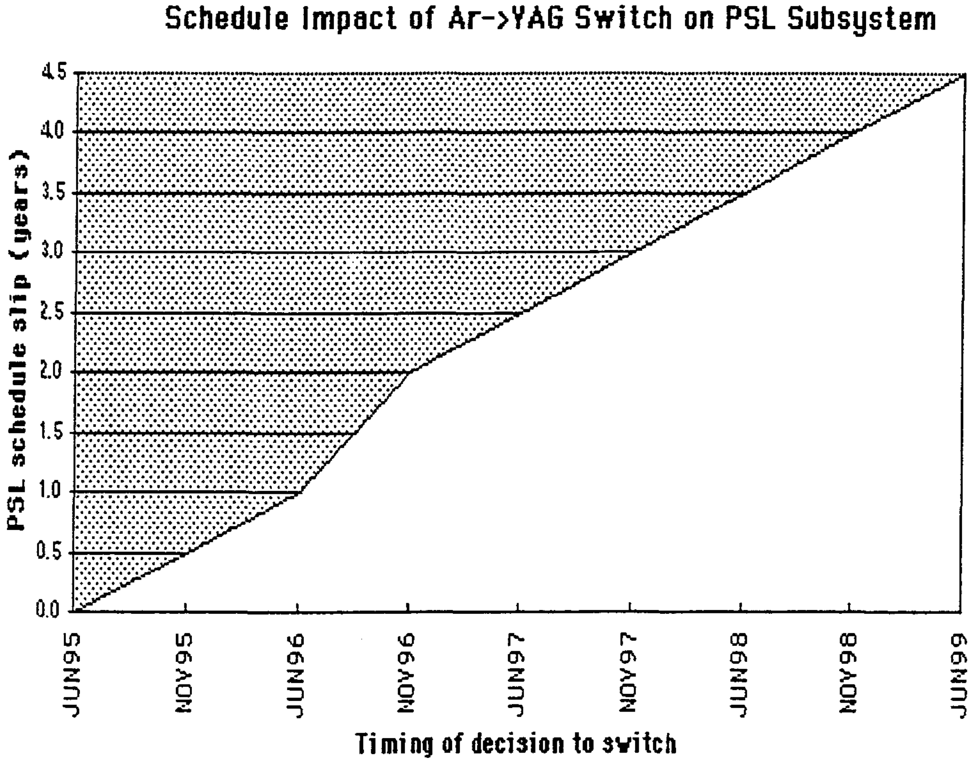
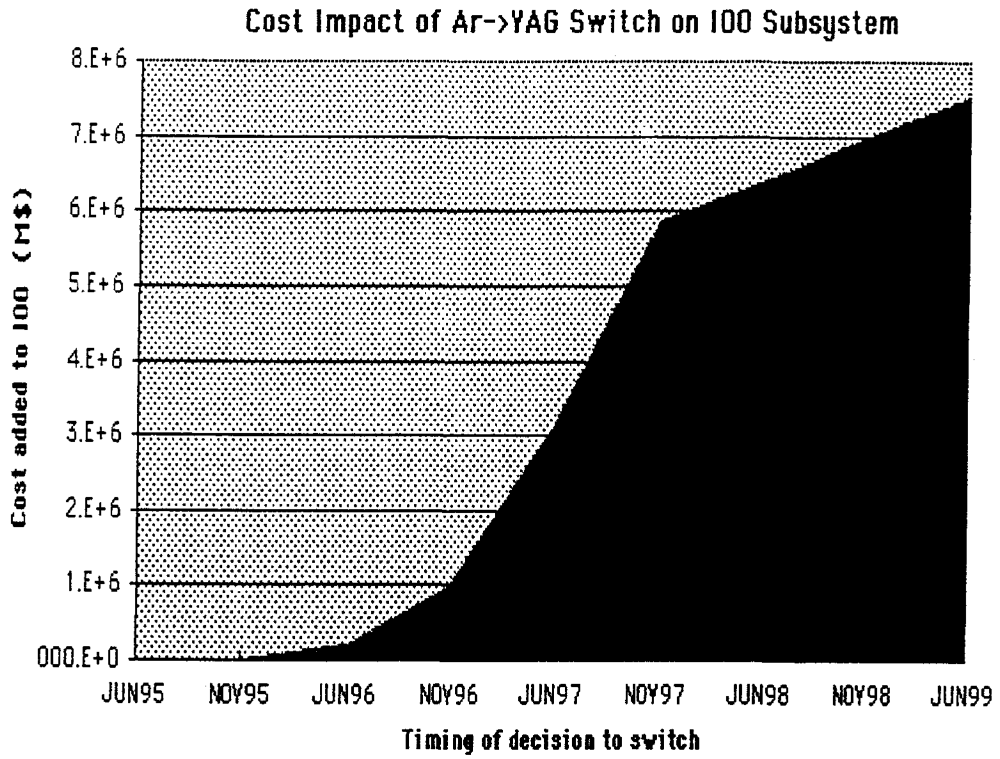


Figure 3.3.2-1: Impacts to the IOO Subsystem



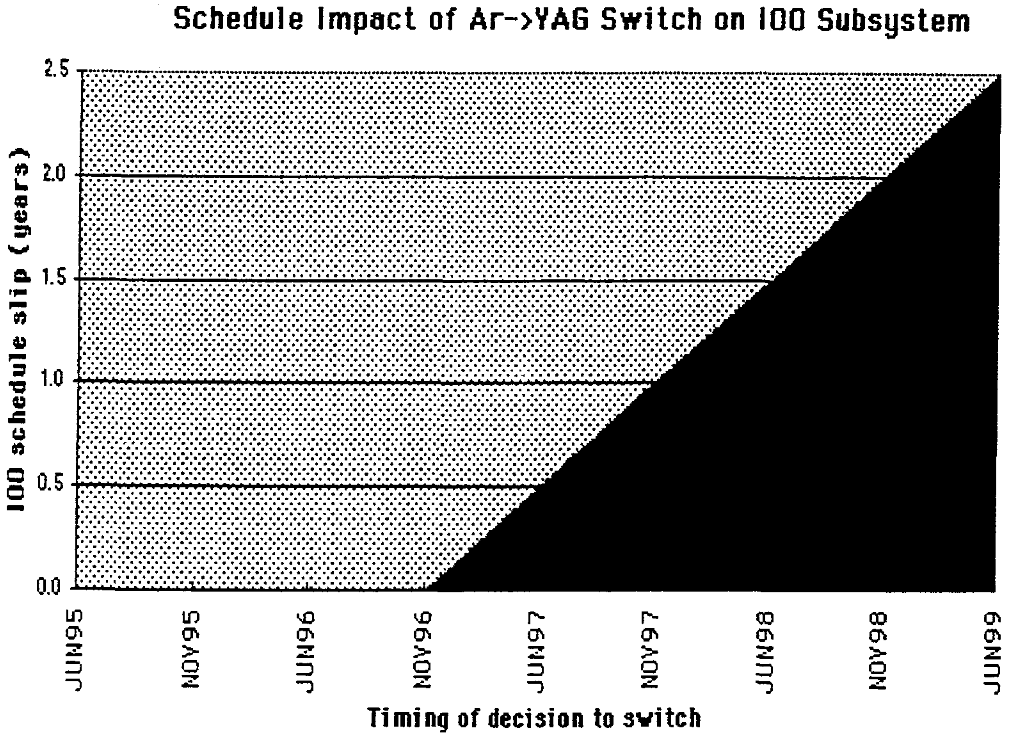
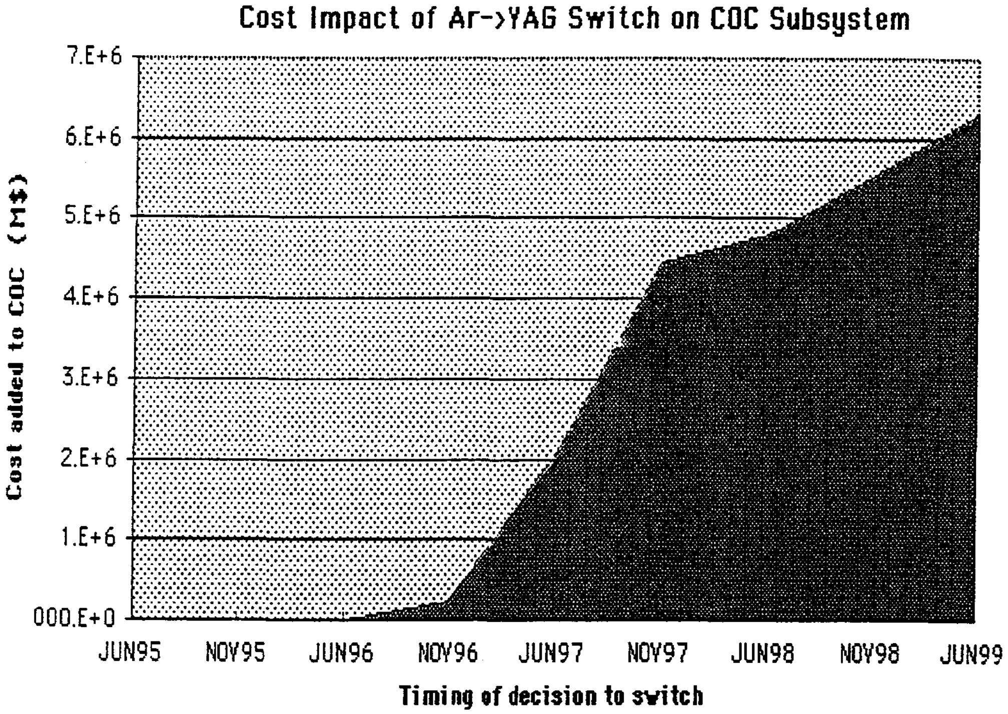


Figure 3.3.3-1: Impacts to the COC Subsystem



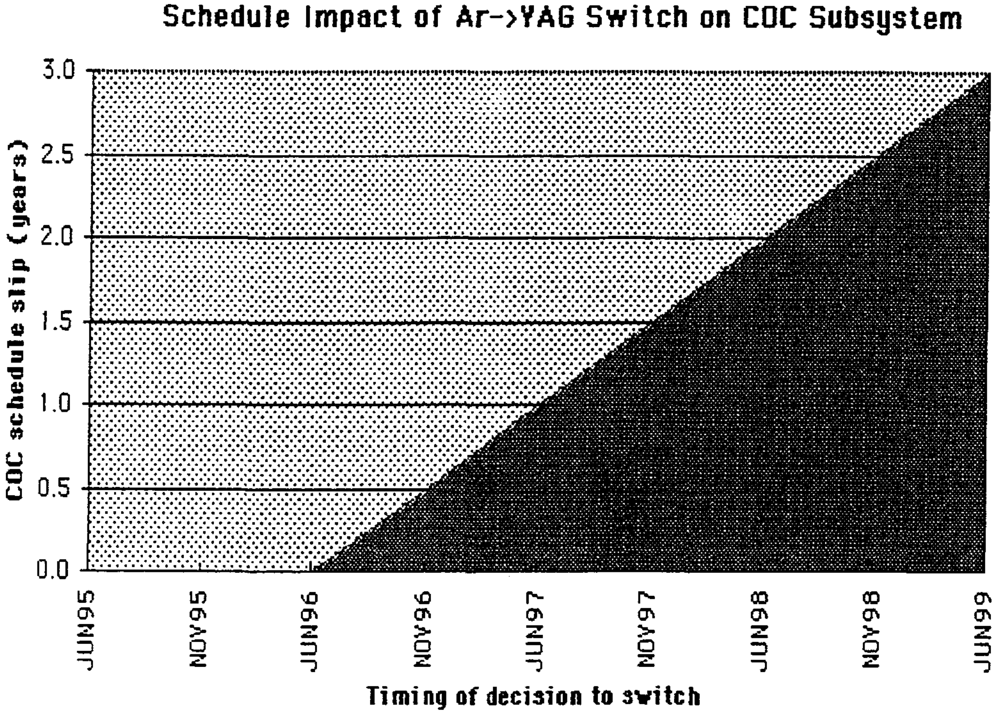
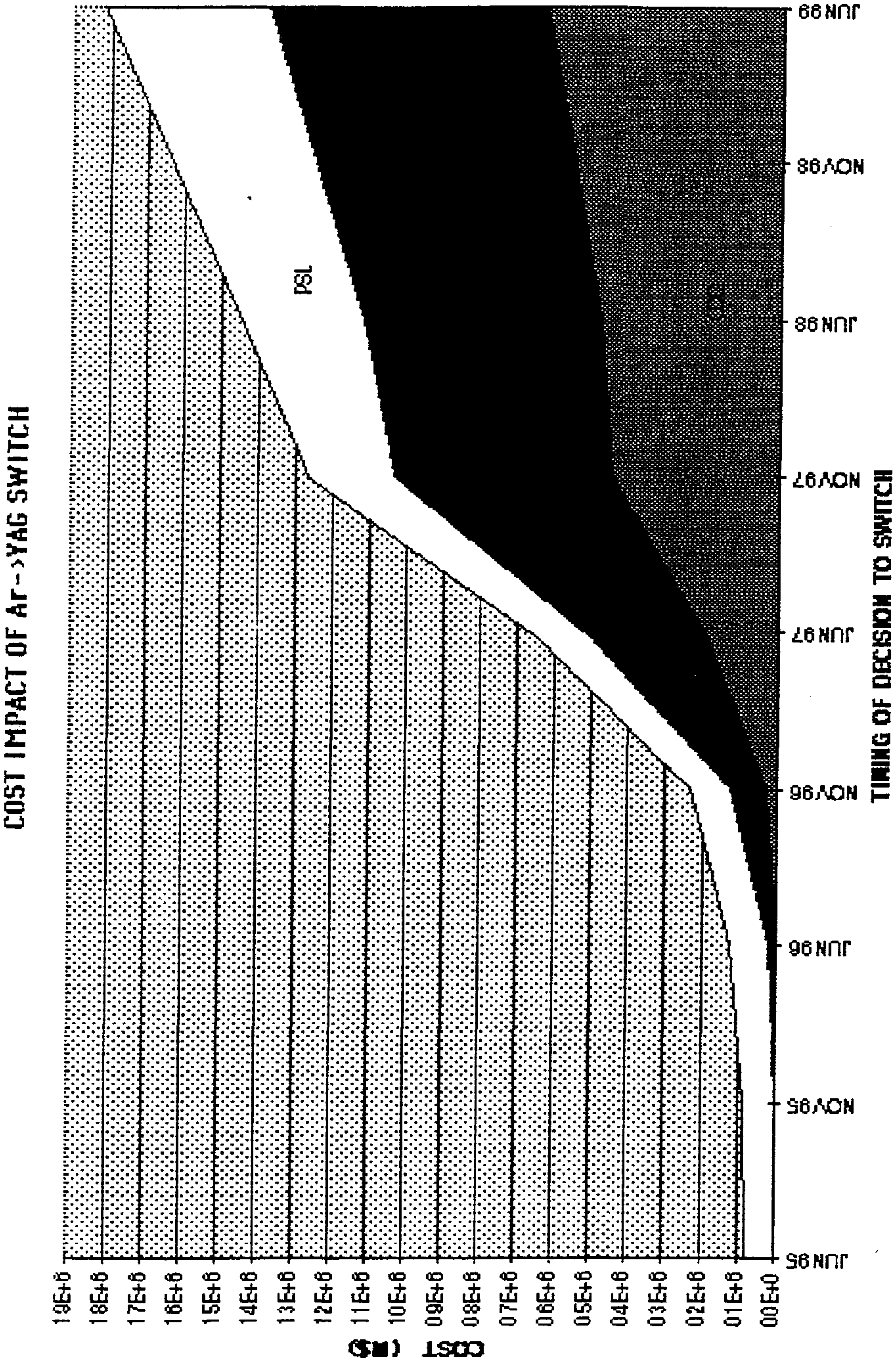


Figure 3.3.5-1: Cost summary over affected Detector subsystems



4 IMPACT ON PSL: A MORE DETAILED ANALYSIS

The conclusion reached in Section 3, that LIGO cost/schedule impact appears to be minor, except for the PSL subsystem, warrants a closer look at the latter. Since a decision to switch to YAG lasers after November 1996 becomes very expensive very fast, the effect of the PSL will be analyzed assuming that such a decision will actually be made at that time. Additional assumptions are:

- Only certain parts of the laser control system will have to be redesigned.[1]
- Following a contract with industry,[2] a 10 W, single frequency YAG laser will be commercially available, for $100k/unit, with a 12 week lead time.
- The start of PSL/CDS procurement/fabrication activities can be synchronized with PSL/IFO fabrication, by delaying the former from May 1996 to September 1997.[3]

Examination of the LIGO cost/schedule database with the above assumptions in mind reveals that the delay caused by switching to a new laser is in part compensated by two factors:

- The YAG laser is procured as a fully engineered, turn-key instrument, which obviates the need for labor-intensive modifications and associated testing.
- The YAG laser is expected to be cheaper than an Argon laser modified in house.

The effect of switching to YAG lasers on the PSL subsystem is summarized as follows:

1. The LIGO cost/schedule database does not indicate the existence of an inherent schedule slip, associated with the switch.
2. The additional work related to integrating YAG lasers will require 5 man-months of engineering and 2 man-months of scientist time.
3. While the human resources may not be available inside LIGO, their cost will be covered by the fact that using YAG lasers will avoid certain costs associated with the need to rebuild the Argon lasers in house.

The most important consequence of the above findings is that the transition to YAG lasers does not appear to cause unavoidable delays in making the lasers available for interferometer integration and shake-down at the sites, by the planned deadline of June 1998.

5 RECOMMENDATIONS

Given the apparent state of readiness of the laser industry on one hand, the high penalty of delaying a decision for the use of YAG lasers beyond late 1996, and the desirability to introduce a more

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[1] The graphic user interface, the remote control and monitoring interface, the slow PZT driver, and the RF photodetector. The fact that the rest of the original PSL/CDS design can be used with the YAG laser is a benefit of the proposed YAG specification (see Appendix E).

[2] For building a suitable prototype

[3] There is no link in the LIGO cost/schedule database to prevent that. However, the database does not allow at this time to examine the effect on the overall schedule, from sliding one item for a given level of available resources.

reliable light source into the LIGO baseline design, we suggest the following approach:

1 Delay a commitment to using YAG lasers in the initial LIGO interferometers until late in 1996.
2. Initiate, as soon as possible, steps to procure a fully engineered 10 W, single mode, single frequency YAG laser prototype from a commercial source.[1]
3. Initiate at once an activity aimed at refining the specification for the YAG laser, using the draft specification of Appendix E as a starting point. Involvement of industry, Stanford, and of our colleagues from Europe, Japan and Australia is likely to benefit this work.
4. Initiate a low level of effort to specify and purchase a low-power Nd:YAG laser and optical components appropriate for 1064 nm to gain familiarity with the system. Examine the R&D effort to identify entry points for 1064 nm conversion of existing programs. As work progresses on the 10 W laser, the priority for R&D tests will be adjusted.
5. Plan for a 1-2 month activity devoted to test in-house the 10W single mode, single frequency YAG prototype, as soon as LIGO accepts delivery from industry. While this activity is necessarily in series with the laser delivery, and thus is a potential cause for schedule slip, this evaluation is necessary to establish confidence in the new technology within the LIGO team. Parallel testing programs of the prototype by a group outside LIGO should be explored and exploited.

APPENDIX A: CHARGE FOR THE STUDY

Subject: Charge for the Study of a YAG Laser Option for the Initial LIGO Interferometer

The study group is asked to study the option for substitution of a 1.06 micron Nd:YAG laser in the initial LIGO interferometer design in place of the existing baseline choice of a 0.514 micron Argon laser. For the purpose of this initial study, a doubled YAG laser option is considered to be a variant of the green Argon laser baseline and is not included as a study option.

1. Assess the technical merits and trade-offs of such a change in the baseline. This study should be organized and documented in summary format.

2. Review the baseline R&D and Detector Implementation Plans and identify the latest possible point in the schedule for implementing this substitution. Coordinate this review with the R&D and Detector Group Leaders.

3. Present a top-level program of needed R&D and alternate detector design activities required to

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[1] Estimated time needed to award the contract, under competitive bidding: 12 weeks

support a decision to change the baseline at or before the schedule date identified in 2.

The study should be carried out and reported in writing for Project-wide review in July. The study group will report to the LIGO System Engineer. Input should be solicited from the R&D and Detector Groups and from knowledgeable groups outside of LIGO.

If the option receives a favorable review, additional exercises will be initiated. These include discussion with the Stanford University group on possible collaboration in development, construction, and operation of a suitable laser, a more thorough study of the LIGO R&D and Detector baseline plans to identify a comprehensive plan for study and resolution of the decision, and consideration of any other laser strategies for LIGO.

APPENDIX B: BASELINE FOR ND:YAG IN INITIAL LIGO

This is a brief description, organized by Detector Subsystems, of the differences from the present baseline (Baseline1) for the initial LIGO interferometers for a sample configuration using a Nd:YAG laser at 1.06 μm as the light source. Additional technical information is included where appropriate.

B.1. Prestabilized Laser Source

B.1.1. Laser Configuration

The laser is a master-slave injection locked system based on modified commercial lasers. This configuration was first suggested as a light source for GW interferometers by Brillet (Man84) and demonstrated in that laboratory on Nd:YAG lasers (Cregut89). Several lasers have been described in the literature which more or less closely resemble this description. See Farinas94 (description also of some of the physics of injection locking), Shine95, and Freitag95. We propose that the laser system be built by an commercial laser manufacturer to our specifications, and that the stabilization then be done by LIGO and/or LIGO collaborators. (This would be the equivalent of contracting for the rebuilt Argon laser but without stabilization electronics.)

Figure B.1.1-1 is a schematic diagram of the laser (after Farinas94).

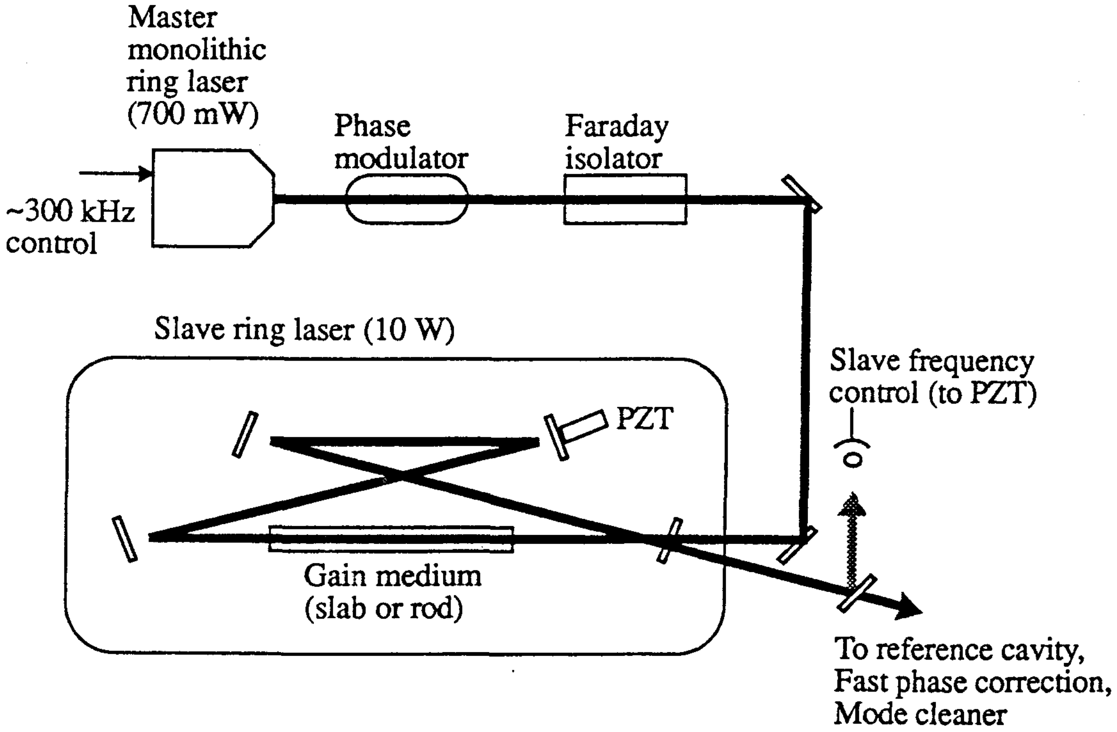

Figure B.1.1-1: Master-Slave Nd:YAG laser configuration

The **master** (low noise) laser is a standard Lightwave 126 non-planar ring oscillator or the equivalent. It produces 700 mW TEM_{00} single frequency 1.06 μm light. It includes inputs for modulating the intensity of the pump diodes (for intensity control) and fast frequency modulation (with several hundred kHz bandwidth, for frequency stabilization). See Kane85 for a description of this laser.

The **slave** (high power) laser is a Lightwave 220 or the equivalent. The commercial version is a cylindrical rod diode-laser side-pumped laser with a simple two-mirror linear cavity. It is designed to deliver 7 W TEM_{00} multi-longitudinal mode. By selecting pump diodes the power can be raised to 10 W without compromising the 10,000 hour MTBF. The rod is placed in a bow-tie ring cavity to allow injection locking; the injection locking ensures single longitudinal mode operation, and sets the frequency and intensity noise at the level of the low-noise master laser described below. See Shine94, Alfrey94, and Freitag95 for descriptions of similar lasers.

B.1.2. Power and Efficiency

A Nd:YAG laser for the initial LIGO interferometers must provide at least the same shot-noise limited performance as the planned Argon laser. The shot noise scales as $\sqrt{P/\lambda}$, and since $\lambda_{Nd:YAG}/\lambda_{Argon} \sim 2$ the laser power must be double that of the present 5 W, *all other aspects of the interferometer being equal*. This leads to a requirement of 10 W for the Nd:YAG laser output power. The optical performance of an interferometer at a longer wavelength is likely to be better (for example, a given surface error results in only half the phase error), as discussed below.

Nd:YAG lasers are much more efficient than Argon lasers, with input electrical power to output luminous power ratios of typically several percent: by comparison, Argon lasers have about 10^{-4} efficiency. This leads to lower operating costs, smaller power supplies and chillers, greater portability, and probable longer lifetimes. Most Nd:YAG designs will fail 'gracefully', leading to a reduction of power when a diode pump laser burns out rather than a complete and sudden loss of light.

The present (mid-95) Nd:YAG lasers with characteristics attractive for LIGO interferometers have maximum output power of 20 W (Freitag95), 26 W (Uehara95b) to 40 W (Shine95). No fundamental problems with significantly increased power are foreseen, and lasers with multi-mode output power of 175 W (Freitag95) are presently available with diode-pumped lasers (much higher power Nd:YAG and Nd:glass flashlamp-pumped lasers are also on the market, but their noise performance makes then unattractive for this application). Byer (Byer95) claims that 1kW diode-pumped lasers will be available by the year 2000. The industry is driven by laser machining needs, although high beam quality will probably continue to be primarily of interest to research.

The future of Argon-ion lasers appears to be limited. Spectra-Physics (Shawn Streeby, telecon28jul95) indicates that they have an engineering effort underway now, driven by LIGO, to produce more power from Argon laser via changes in the bore size and pressure. They anticipate 15-20% increases in the power from this effort, with probable increases in the lifetime of tubes and thus the reliability. There are no plans to make a 2x more powerful Argon laser (because of the maturity of the product, they do not see a technical means); instead, they expect solid-state sources to replace Argon lasers in the green as well as infrared in a 5-year time scale and their engineering is primarily in that direction. Lawrence Livermore proposed to Spectra several years ago to build a 100 W Argon laser, with LLNL providing the engineering funds; after consideration, Spectra decided that they did not want to contract for that goal.

Reliability is cited by manufacturers to be similar for Nd:YAG and Argon lasers. Byer says that his, and Lightwave's, experience with the diode pumped Nd:YAG lasers meet or exceed this specification. Experience in LIGO laboratories is very roughly that one of our six Argon lasers requires attention once a month, and this leads to an estimate of 1,000 to 2,000 hours before the system is unavailable (for a day or so).

The beam quality of the Nd:YAG laser influences the efficiency of the optical system by determining the coupling efficiency into the first cavity along the optical path, but gives some basis for comparison. The 'M' parameter is often used to characterize a beam, but does not lead to an unambiguous calculation of the coupling into the TEM_{00} mode. The Shine (Shine SPIE vol 2379) 40W slab (which has a basically 'square' geometry) laser has an M=1.3. The Uehara (Uehara OL preprint) 26 W laser has an M=1.01 and M=1.1 in x and y. A Spectra-Physics 7 W Nd:YAG has an M=1.1. These should be compared with the specification for Argon lasers; Inova quotes M=1.3

for their large-frame Argon lasers.

B.1.3. Frequency Stabilization

The basic techniques for stabilization are the same as those presently used for the Argon laser. The frequency is measured in a reference cavity (which can be identical to the present design but with mirrors coated for the Nd:YAG wavelength). Phase modulation and reflection locking are used to obtain an error signal, which is then applied to fast and slow actuators in a configuration similar to the Argon pre-stabilized laser. The laser described above is 2-3 orders of magnitude less noisy in frequency than the Argon, so unity-gain frequencies and dynamic ranges can be relaxed from the present requirements. The fast actuator is a Pockels cell (Magnesium-doped Lithium Niobate), probably at the output of the slave laser. The medium-speed correction is built into the master laser (a PZT which compresses the Nd:YAG material, changing the optical path in the master laser; this has a bandwidth of ~300 kHz, and a range of about 20 MHz). The slow correction is with PZT actuators on the mirror mounts of the ring-laser cavity of the slave laser to make the slave laser track the master, and temperature control of the master for long-term control. See Nakagawa94 and Nakagawa95 for frequency control of the master laser.

B.1.4. Intensity Stabilization

The pump diode lasers both produce intensity noise (which then excites intensity fluctuations in the Nd:YAG) and provide a convenient actuator to suppress it. Modulation of the current in the pump diode lasers gives a very-wide bandwidth control over the intensity. Again, the noise level from the laser is smaller than that for the Argon laser, and lower loop gains can be used. See Harb94 for intensity control of this laser. The high-frequency intensity becomes shot-noise limited at 1-3 MHz, allowing our present modulation frequencies to be used.

B.2. Input Optics

Most of the input optics can remain the same in design (size, radii of curvature, etc.). All optics must be coated for 1.06 μm; such low-loss coatings are standard for REO and other coaters. See Core Optics, below.

B.2.1. Modulation System

The crystal used in the Pockels cells must be changed to one which is transparent at 1.06 μm. Magnesium-doped Lithium Niobate is the best choice. Commercial units from New Focus can be used at 20W (Shine95), and have the same crystal size as the Gsaenger cells presently used. They are specified for a smaller beam diameter, because measurements show that this gives better uniformity of modulation (presumably also true for the Gsaenger cells presently used at 0.5 μm).

A coincidental advantage of the MgO-doped LiNbO is that its loss tangent for RF modulation is much smaller than that of ADP or KDP (the presently used materials) and its electro-optic coefficient much larger (hundreds of volts per λ instead of thousands). This allows easier electronic design with probably greater phase stability with temperature, lower radiation from modulation circuits, and, most importantly, the possibility of employing higher modulation frequencies which may ease some interferometer configuration difficulties.

There is experience showing that the electro-optic to piezoelectric coupling is stronger for the Lithium-based modulators (Weiss85). The success of efforts to stabilize Nd:YAG lasers in frequency, using these modulators, suggest that these problems have been solved or are not relevant to practical applications.

B.2.2. Faraday Isolators

Faraday isolators for 1.06 μ m are commercially available. They are specified as >90% transmission, and >30dB attenuation (thus resembling 514 nm isolators), with <95% transmission and >35 dB attenuation observed in practice. The material itself (Terbium Gallium Garnet) absorbs 0.4%, with the remaining lost in AR coatings and polarizers. Devices with up to 45 mm free aperture are available (at 85% transmission) (Electro-Optics Technology, Inc.).

B.2.3. Other Optics

Many optics companies have a series of beamsplitters, polarizers, waveplates, etc. designed for 1.06 μ m.

B.3. Core Optics

Size: This proposed configuration adopts the same *g=0.3* factor as the present 4 km arm-cavity design. This leads to beams $\sqrt{\lambda_{1.06}/\lambda_{0.514}} = \sqrt{2}$ larger everywhere in the interferometer. Because the present near test masses and recycling mirror are oversized, no change in diameter or thickness of those components is required. The far test masses and the beamsplitter must be made larger. All optics must be coated (Rmax, 3%, AR) for 1.06 μ m, a standard wavelength for REO and other coaters.

Thermal noise: Saulson has pointed out that a larger beam radius-to-mirror radius can reduce the thermal noise contribution from internal modes, with a linear dependence (Raab95); however, a larger mirror will have lower resonances and a greater mass, so that the scaling is not simple. A test-mass size and aspect-ratio optimization (thermal noise from substrate and pendulum, diffraction loss, mode mixing by the edge, fabrication ease) should be performed for either a Argon or Nd:YAG design. The small changes in diameter proposed here will make small changes in the thermal noise, as the thermal noise goes as the square root or slower of most of the parameters.

Coating uniformity, scatter and absorption: Studies of the performance of mirrors at 1.06 μ m show that the absorption and scatter performance available is as good or better than that obtained with coatings at 0.5 μm. Published measurements of loss (Uehara95) and informal reports (Boccara95, Brillet95, Willke95) indicate total losses < 6 ppm are achievable. Comparisons between 0.5 μm and 1.06 μm of measurements of correlations between substrate preparation and the scatter give mixed results, but show either similar or better (as would be predicted by simple theories of scatter as a function of wavelength for fixed workshop practice) performance for longer wavelengths (Hickman93, Watkins93). REO (Lalezari95, telecon 1Aug95) indicates that there are equally good results seen for their coating system at 1064 and 514 nm, and that they have no preferences for one wavelength. The coating errors tend to be proportional to the thickness, so that a fractional precision of (say) 0.1% is maintained independent of the wavelength of the coating. REO can coat right to the edge of the substrate, with errors growing to 1% in thickness at the edge of the coating (whether this is at the edge of the substrate or in from the edge a cm or so). Hiro Yamamoto (Yamamoto95, calcs) has shown that 0.1% uniformity of coating is sufficient for the initial LIGO if coating errors are random, and 0.02% if 'accordion'-like.

Note that the phase noise from a given level of stray light is 2x greater for the 2x longer wavelength. The net impact is due to a combination of factors, where the 10x reduced Rayleigh scatter in the substrate and the likely reduced mirror source scatter mitigate. No estimate has been made for the total.

Thermal distortions: The power level will be twice as high in a 1064 nm interferometer, leading to (for a given wavelength-independent coating absorption) larger thermal deformations from surface absorption. However, the net result cancels (Strain94): While the optical path distortion due to heating grows linearly with the power, and the required power linearly with the wavelength, the effect on the interferometer performance falls linearly with the wavelength, so that the two effects cancel. This, with the fact that at present the best 1064 nm and 524 nm mirrors show roughly the same absorption, makes for no difference from this effect.

Substrate homogeneity, scatter and absorption: Silica substrates have Rayleigh scatter at 1.06 μm on the order of 2 ppm (Boccara95), as compared with scatter at 0.5 μm of 10-20 ppm (Winkler93, Shoemaker93). The absorption in substrates appears to be similar for the 1.06μm and 0.5 μm, at 1 to 2 ppm; this will not be a factor in the initial LIGO interferometers, where deformation from the surface absorption will dominate the thermal focussing budget (which itself is expected to be negligible). Homogeneity and birefringence effects in the substrate will be smaller for the longer wavelength for the part due to density variations; index variations will lead to the same effect on the two wavelengths.

Contamination: We do not have experience with contamination of mirrors at 1064 nm. In general, the lower energy per photon will probably lead to less destructive contamination (Byer, talk 1Aug95), but unfortunate resonances could make contamination at 1064 nm worse than 514 nm. We feel that we do not have a thorough understanding of contamination at 514, and have planned to study it; this certainly holds true for 1064 nm as well. Groups familiar with low-loss 1064 mirrors (JILA) may be able to help us with this.

Effect of surface figure: The change in optical phase for a given mirror surface error (from the substrate surface or the coating) is 1/2 as large at 1.06 μm as at 0.5 μm. This advantage may be offset by the fact that larger beams sample longer spatial wavelengths on the optical surface, and this is in general a rapidly growing spectrum toward longer spatial wavelengths.

Using the FFT optics propagation code and standard LIGO FFT optics model to explore the impact using 'real' mirrors (the statistically duplicated HDOS reference flat), the optical power throughout the interferometer and the signal-to-noise ratio has been calculated for 1.06 μm light (Bochner95). No re-scaling of the substrate surface errors was made, in the assumption that the polishing techniques for a 28 cm mirror would be the same as for a 25 cm mirror. For mirror diameters kept at their nominal 12.5 cm diameter (as for the 0.5 μm runs, the net effect of larger beams is an improvement in the contrast (because given surface errors are less at the longer light wavelength) and a consequent reduction in the power on the photodiode for a given input power.

Another run was performed for the mirror diameters here proposed for 1.06 μm: We assume effective coated diameters of 23 cm for the near FP mirrors and the recycling mirror, and 28 cm for the end mirrors and the beamsplitter (an aperture of 19.8 cm was used for the beamsplitter, due to the 45 degree incidence; this refinement was not used for the Argon run, which had a very large effective beamsplitter). Several key parameters are shown in the table; the 'bottom line' is that somewhat better performance is obtained with Nd:YAG (once the power is doubled for the shot-noise equivalence). The improvement is due to better optical performance of surfaces and coatings at the longer wavelength leading to a smaller contrast defect, lower modulation index, and less power on the photodetector per input watt of light.

Table B.3-6: FFT Optics model results for 1.06μm

Parameter	Nd:YAG	Argon
Laser wavelength	1.06 μm	532 nm
Mirror radii: recycling, flats	11.5 cm	12.5 cm
beamsplitter	9.9 cm	12.5 cm
FP back mirrors	14.0 cm	12.5 cm
Laser power (at recycling mirror)	5 W	2.5 W
Assumed loss/bounce on all mirrors	100 ppm	100 ppm
Optimum recycling gain	34	31
Contrast defect (1-C)~2 (I_{min}/I_{max})	3×10^{-4}	1.3×10^{-3}
Optimum modulation	0.34	0.47

Parameter	Nd:YAG	Argon
Photodetector power	260 mW	240 mW
h (below cavity pole frequency)	$5.7\times10^{-24}/(\sqrt{\mathrm{Hz}})$	$6.2\times10^{-24}/(\sqrt{\mathrm{Hz}})$

Metrology: It may be less expensive to hire and easier to find precision metrology houses for the 1.06 μm wavelength, as some commercial manufacturers (Zygo, Wyko) offer interferometers for this wavelength as standard items.

B.3.1. End Test Masses

The end test masses should be increased from 25 to at least 27 cm diameter (28 was used in the FFT analysis). This leads to 2 ppm/bounce diffraction loss (Spero92, Spero95) if the surface to the edge is usable (to be compared with the nominal present requirement of 1 ppm/bounce, which is exceeded by 25 cm mirrors). The additional loss is not important from the point of view of lost power; the impact due to additional scatter needs to be evaluated, but since reduced scatter from microroughness is anticipated, no net impact is expected. No difficulties in polishing the larger masses is anticipated; the coating chamber must be large enough to hold the larger diameter, but the coating requirements can be relaxed at the edges (true for Argon and 25cm as well, of course).

B.3.2. Beamsplitter

A minimum 26 cm beamsplitter is recommended to meet the above diffraction requirement and to allow walkoff beams to be separated (Abramovici95). To ease manufacture of substrates and coatings and suspensions, the same size beamsplitter and end test mass are recommended, thus 28 cm is the point-of-departure baseline. Note that the beamsplitter for the Argon case must probably be larger than the present nominal 25 cm test mass design.

B.3.3. Baffle Reflectivity and Scatter

The scatter from the mirrors can be reflected or backscattered from the tube walls and baffles and then recombine to make excess phase noise. The prospective baffle materials and the tube walls have been characterized at both 0.5 μm (Whitcomb95) and at 1.06 μm, and preliminary results show that the backscatter for baked stainless steel is lower by roughly a factor 2 at 1.06 μm, but that the reflectivity is higher by about the same factor. There may be a compensating lower scatter from 1.06 μm mirrors, but neither the baffle data nor the scattering data are yet definitive.

We are committed to making the LIGO installation compatible with near-infrared light, independent of our initial configuration, and the initial interferometer will not be limited by this scatter (in either the Argon or Nd:YAG wavelengths). Mirror technology is expected to improve, and the influence of scattered light falls with the square of the mirror scatter, leading to optimism that changing the mirrors will allow significant changes in the LIGO system sensitivity to scattered light when more sensitive interferometers are installed.

B.3.4. Suspensions

B.3.4.1 End Test Masses

The larger end test mass mirrors will require a larger suspension. The same design rules used to generate the present two (or three) suspension designs are extended to a ~10% larger diameter; we can contemplate reducing the mirror size for the near test masses and the recycling mirror. Again, the beamsplitter in the Argon design will probably require a larger mount; the beamsplitter and end mirror design could be the same.

B.4. Length Control System

B.4.1. Photodetector

The same silicon photodetectors now used for Argon can be used at 1.06 μm, with a change in the doping and silicon wafer thickness to improve the quantum efficiency (the absorption length for 1.06 μm light is of order 1 mm in Si, making it more difficult to simultaneously require good conversion efficiency from photons to electron-hole pairs, and to collect those pairs before recombination takes place). The EGG part YAG-444 has very similar specifications to the presently used SGD-444, with a lower capacitance (helping signal to noise in the diode-amplifier combination) and a greater responsivity (0.45 A/W at 1.06 μmm compared to 0.2-0.25 A/W at 0.5 μm). The net quantum efficiency is similar at both wavelengths. We will probably use several photodiodes in a shared aperture configuration with cascaded photodetectors (electrical parallel, before or after conversion to voltage) to collect the approximately 300 milliwatts of light at the interferometer output. If the light not converted is reflected, the later photodiodes can be used to increase the efficiency of the total photodetector (Fox93). We may choose to place the detectors at a non-optimum Brewster angle to intentionally distribute the current collection uniformly over a number of photodiodes.

Alternative photodetectors exist (InGaAs) which have a high quantum efficiency, and some devices with higher power-handling have been developed (Harris95, Intevac Advanced Technology Division). The higher quantum efficiency and lower energy per photon lead to roughly 1 A/W for InGaAs diodes at 1.06μm, and present devices are linear to 140 mA (1 dB compression); they have an inconveniently small active area (0.5 mm diameter). Most of the industrial interest is in 1.3 μm, and one manufacturer of InGaAs (Olsen95, Sensors Unlimited) recommends staying (at least presently) with Si for the YAG wavelength.

APPENDIX C: ACTIVITY IN OTHER RESEARCH GROUPS

Short descriptions of some of the other efforts to produce laser sources, optics, and detection systems for GW interferometers is given below. At present, all of the plans for moderate- or long-baseline interferometers call for laser-diode pumped Nd:YAG lasers at 1.06μm using the master-slave approach describe above.

C.1. STANFORD

C.1.1. Laser

There is a great wealth of experience with solid-state lasers at Stanford (Gustafson95). The Lightwave NPRO monolithic laser used widely as a master laser comes from this laboratory. A slave laser using a zig-zag slab geometry has been made and characterized (Shine95) which produces 40W in a linear cavity (multi-longitudinal-mode). Injection locking of a 5W slab laser to a NPRO showed very good agreement with the theory of injection locking, with the frequency noise and intensity noise of the injection locked slave laser being effectively identical to the master (Farinas94).

C.1.2. Input Optics

No detailed information.

C.1.3. Core Optics

No detailed information.

C.1.4. Length Sensing/Control System

There is activity in fundamental research (Harris95) and in device development (Yamamoto, in conjunction with Hamamatsu) in the domain of InGaAs photodiodes for high quantum efficiency, high current handling capability.

C.2. VIRGO (France, Italy)

C.2.1. Laser

A description is found in the VIRGO design document, section 4100; further details from Brillet95. The Master Laser is manufactured by Laser Zentrum Hannover (See GEO-600 below). The Slave laser is manufactured under contract by BMG and is designed in collaboration with the Orsay group and is to be delivered in August 95. Presently, the plan is for the injection locking to be performed in the Orsay lab, with a completed laser by October 95. The initial goal ('VIRGO 97') is for a 10W 1.06 μm laser, with a plan for 20 W in 1999. Frequency stabilization is as described for the LIGO YAG baseline, with particular attention paid to the mechanical properties of the triangular rigid reference cavity.

C.2.2. Input Optics

Modulators are as described for the LIGO YAG baseline.

C.2.3. Core Optics

The optics will be manufactured by some combination of REO and the Lyon coating group of Mackowski, where the goal is to apply a variable-thickness final coating to correct for surface, coating, and substrate errors. The metrology is to performed largely in-house by Boccara in Paris.

C.2.4. Length Sensing/Control System

A Hamamatsu InGaAs photodiode is used, and although only specified by the manufacturer to be useful to 3 mW, performs to their satisfaction at 100 mW (or about 70 mA of photocurrent).

C.3. GEO-600 (Germany, Great Britain)

C.3.1. Laser

Laser Zentrum Hannover produces a monolithic ring laser similar to the Lightwave design, with 700 mW available. It uses temperature and PZT tuning. See Freitag93, and Harb94, for details; intensity stabilization has been successfully researched, but no data on frequency stabilization. The Slave laser is also made in-house at LZH using a rod (not slab) geometry with radial pumping; it produces 20W single-frequency. A complete injection-locked system has been characterized, but no published results on frequency-stabilized high-power operation exist.

C.3.2. Input Optics

No detailed information.

C.3.3. Core Optics

Laser Zentrum Hannover has coating facilities which have produced 2 ppm absorption and 5 ppm scatter 1.06 μm mirrors on small substrates. There is a traditionally close cooperation between Zeiss and the GW group. No recent information on this front.

C.3.4. Length Sensing/Control System

No detailed information.

C.4. TAMA (Japan)

C.4.1. Laser

There are active groups at the University of Electro-communications (Ueda et al.) and at the University of Tokyo (Nakagawa et al.) doing laser development and characterization for GW ifos. The master lasers used are Lightwave. Using pairs of suspended cavities in vacuum, very good frequency stability has been achieved and independently measured (Nakagawa94, Nakagawa95) for the master laser.

C.4.2. Input Optics

Careful studies of the loss of mirrors for 1.06 μm manufactured by the Japan Aviation Electronics Industry have been made (Uehara95). They show 6±6 ppm of total loss ($L = 1 - (R + T)$ for mirrors of 1.4×10^{-3} transmission; the cavity formed of two such mirrors showed a transmission on resonance of 99.14±0.86 % for the TEM_{00} mode. These mirrors will be used to form a mode cleaner for the 20m interferometer at the National Astrophysics Observatory.

C.4.3. Core Optics

No detailed information.

C.4.4. Length Sensing/Control System

Multiple InGaAs photodiodes in optical series (using beamsplitters) has been used to collect high total photocurrents (Uehara 94a) in a shot-noise limited Pound-Drever locking of a Fabry-Perot cavity.

APPENDIX D: IMPACT ON LIGO R&D

We break down this description by the major R&D installations.

D.1. Phase Noise Interferometer

The Phase Noise Interferometer (PNI) research program is designed to test both the phase measurement system (modulator, photodetector, pre-amplifier) and the laser source (frequency, intensity, and beam position noise) as well as sources of excess phase noise (e.g., mirror scatter). A test of a 1.06 μm Nd:YAG system on the PNI appears to be the shortest route to verification of this technology for LIGO's needs.

Many problems and solutions along the path to a successful experimental demonstration will be similar for the Argon and Nd:YAG cases, so that adding a test of Nd:YAG at the end of the Argon effort will allow problems specific to Nd:YAG to be solved. Should we choose to abandon the Argon demonstration in favor of Nd:YAG, the exact time of switch-over to the other wavelength is not critical.

A number of components would need to be changed.

- The Nd:YAG laser with stabilization of frequency and intensity must be in place. The laser should be given pre-installation tests to minimize down-time on the PNI.

- New optics for all suspended masses would need to be fabricated, setup for suspension, and suspended. As this is in-vacuum, delicate work, this presents the largest configuration change. In addition, optics fabrication often suffers longs delays compared to promised delivery, so that these components should be ordered, and then tested, well in advance---these can be test pieces for the coating process.
- The modulator (presently external to the vacuum system) would need to be switched with any changes in the drive system implemented.
- The high-power photodetector system for Nd:YAG must be put in place.

The test program once the system is together will resemble the one for the argon laser, but with no need for the staged approach planned for the Argon; one would immediately use the full recycled system with Mode Cleaner in place. This would also represent the test of a 1.06 μm Mode Cleaner.

The Byer group has expressed interest in being involved in such a test, and has proposed to contribute manpower both to get the hardware prepared and to aid in the installation and experimentation.

A crude timetable for such a test program is:

- laser source to be ordered as early as possible; frequency and amplitude stabilized (in the OTF, or possibly at Stanford) and characterized off-line
- Mirrors:
    - mirror substrates to be ordered at least 9 months before the start of installation
    - precision metrology on the polished substrates to follow
    - coating and repeat precision metrology, other off-line tests
    - preparation for hanging (magnets, fins, baking)
- other components ordered to allow initial off-line tests
- Installation of laser and mirrors, other optics: 3 months
- Tests: 6 months

If we assume that the present PNI research is completed as planned in mid-96, and that the preparations are timely, then the research would be wrapping up in March 97; the information on the research would come later than the optimal time for a choice of wavelengths for the full-scale LIGO mirror coatings. The delivery time for a full-power laser source does not allow the schedule to be shifted much earlier.

An alternative would be to use a master laser alone for the initial research. This would make the primary delay the acquisition of suitable optics, with the frequency stabilization of the master laser in parallel. The present PNI research schedule concentrates on measurements without a mode cleaner until December, 95; it is possible to consider a switch at that time to Nd:YAG. This would lead to significant experience with Nd:YAG by mid-96 at the cost of extending the overall PNI program.

The manpower for the installation and research phase is estimated to be at the present targeted PNI level of 2 FTE scientist and 2 full-time graduate students for 9 months.

The MIT laboratory plans to move from Building 20 to a new experimental space some time in early-to-mid 1997. This constraint needs to be considered as plans become firmer.

D.2. 40m Interferometer

We do not anticipate that the change of laser would impact either the operational length control system or the lock-acquisition strategy (assuming either that no fast servo look to the frequency is central to the locking scheme, or that the servo behavior of the laser can be characterized adequately separately from the interferometer). It is possible the it would impact the test-mass displacement in ways which are not evident, or that the complete system with Fabry-Perot cavities would show up shortcomings or interactions not seen in the Phase Noise Interferometer. A more important purpose for a 1064 nm test of the 40m is for system integration test of the YAG PSL. The timing of such a change has not been studied.

D.3. Optics Test Facility

A number of off-line tests can be performed in the OTF for YAG-1.06 μm components and assemblies to gain experience and to qualify components. This could be done under the rubric of R&D or Detector.

- 1.06 μm mirror tests: loss, scatter, uniformity, susceptibility to contamination
- modulator tests: transmission, efficiency, uniformity
- photodiode tests: uniformity, linearity, damage threshold
- stabilization of Master and/or or complete Nd:YAG lasers

A crude estimate of the manpower involved is 0.5 FTE for one year of scientist and a full-time graduate student. For a *complete* change-over of the OTF from 514 nm to 1064 nm, FJR provides an estimate of 15 MM scientist and 15 MM engineer. Note that in addition to components specifically purchased for tests, there is the additional cost of establishing an infrastructure (at both east and west coast LIGO) to allow experiments at 1.06 μm: lenses, mirrors, waveplates, polarizers; CCD cameras, infrared viewing scopes, fluorescent cards; safety glasses.

Note that if Byer's group is involved in our effort, many of these tests could be performed (and/or may have already been performed) at Stanford.

APPENDIX E: YAG LASER SPECIFICATIONS

E.1 GENERAL

The present specification for a 10 W, single frequency Nd:YAG laser is intended to support the procurement of a laser appropriate for the intial LIGO interferometers, to be installed at the LIGO sites begining in June, 1998. The resulting laser should be a self-contained turn-key system, with a minimum level of required adjustment and maintenance. It is desirable that the design ensures easy maintainability, by technical personnel with average training level in operating and maintaining lasers.

E.2 LASER LIGHT

E.2.1 General Properties

6. Wavelength: 1064 nm, single frequency
7. Output power: >10 W in TEM_{00} mode
8. Beam quality: less than 1 W in higher order modes
9. Polarization: linear, within 1^{o} of vertical, extinction ratio >500:1

E.2.2 Reliability

1. MTBF: >10,000 hours.
2. Minimum stretch of continuous operation, between required maintenance events: 500 hours.

E.2.3 Stability

1. Warm-up time: <1 hour. Stability specs Points 2,3,4 below refer to warmed up laser.
2. Power: long term variation < 5%
3. Frequency drift $<10^{-6}/^{o}C$, free running
4. Pointing drift $<10^{-5}rad/^{o}C$ p.t.p., free running
5. Beam diameter stability: within 5%

E.2.4 Noise

1. Relative power fluctuations $<10^{-5}/Hz^{1/2}$, above 100 Hz
2. Relaxation oscillation: critically damped or overdamped

3. Frequency fluctuations: $<10^4 Hz/Hz^{1/2}$ at 100 Hz, $<10^3 Hz/Hz^{1/2}$ at 1 kHz
4. Pointing: TBD

E.3 OUTPUT CONTROL

1. Frequency control:
    1. Slow tuning over >1 GHz range, over time spans corresponding to room temperature changes
    2. Fast tuning over >10 MHz range, at rates up to 100 kHz
2. Output power control: TBD by vendor

E.4 INTERFACES

E.4.1 Electrical

1. Mains: 110V-60Hz, single phase
2. Controls and inputs
    1. Local and remote (TTL) ON/STAND-BY/OFF switches
    2. Local and remote output power control
    3. Local and remote output shutter operation
    4. Local LOCAL/REMOTE switch selector
    5. Inputs for frequency control sugnals 3.1.1 and 3.1.2 above.

3. Outputs
    1. ON/STAND-BY/OFF status
    2. Output shutter status
    3. Power level
    4. Head temperature

4. Connectors:
   Items which are commercially available from multiple sources are strongly preferred. To be selected by vendor, subject to consultation with and approval by LIGO.

E.4.2 Mechanical

1. The laser beam will be 14 cm above the plane defined by the support points.
2. The laser will be supported on three legs, attached to the rigid resonator frame.
3. The rigid resonator frame will extend 10 cm outside laser enclosure, 10 cm below the output beam, parallel to the beam and horizontally centered on it. This extension will be provided with 1/4-20 threaded utility holes, number and pattern TBD.
4. Support points for lifting and other handling will be provided.

E.4.3 Cooling

1. Cooling capacity and type (air, water) to be set by interaction with vendor.

2. The laser cooling unit will be separate from the laser head.
3. The cooling unit will be operated on 110 V, self-contained, and connected to the facility only through the power cord.

E.5 MAINTENANCE AND SERVICEABILITY

Laser subsystems that need periodic maintenance will be designed as modules, kinematically attached to the frame whenever needed, and easy to access, remove and replace.

E.6 SAFETY

1. The laser will be provided with all safety arrangements required by applicable regulations, e. g. an output shutter.
2. All control inputs will be internally protected against overload damage.

APPENDIX F: TECHNICAL REFERENCES

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