LIGO-T880001

#01

List of 3/1/89

MEMO7688b

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CONCERNING: Laser, interferometer efficiency and LIGO power, cooling requirements.

REQUIREMENTS

The gravitational burst sensitivity goal of the initial LIGO receiver has been projected at an rms strain of h = 10^{-21} in the 100 Hz to 1 KHz band. The rms burst sensitivity for a Fabry-Perot receiver limited by photon shot noise for a burst with $\tau \simeq 1/f$ is given by

$$h_{shot} = \left(\frac{2h\lambda}{\eta P_{in} c}\right)^{1/2} \left(1 + (f/f_0)^2\right)^{1/2} \frac{f_0 f^{1/2}}{2}$$

without recycling and by

$$h_{shot} = \left(\frac{2h\lambda}{\eta P_{in} c}\right)^{1/2} \left(\frac{2A}{\pi \tau_{tr}}\right)^{1/2} \left(1 + (f/f_0)^2\right)^{1/2} \frac{(f_0 f)^{1/2}}{2}$$

with recycling. Both relations assume that A, the mirror loss, is much less than 1 and that $f < 1/\tau_{tr}$.

The definition and some typical values for the parameters are

$$\lambda = 5.145 \times 10^{-5} \quad \text{optical wavelength in cm.}$$

$$\tau_{tr} = l/c = 1.33 \times 10^{-5} \quad \text{light transit time in seconds}$$

$$\tau_{st} = \text{cavity energy storage time}$$

$$f_0 = \frac{1}{4\pi\tau_{st}} \quad \text{Fabry} - \text{Perot corner frequency}$$

$$\eta = .9 \quad \text{photodetector quantum efficiency}$$

$$A = 1 \times 10^{-4} \quad \text{mirror loss}$$

$$L_{cavity} = \frac{8A\tau_{st}}{\tau_{tr}} \quad \text{cavity optical loss}$$

The corresponding relations for a delay line Michelson receiver are given by

$$h_{shot} = \left(\frac{2h\lambda}{\eta P_{in} c}\right)^{1/2} \frac{f^{3/2}}{2\sin(\pi f \tau_{st})}$$

without recycling and by

$$h_{shot} = \left(\frac{2h\lambda}{\eta P_{in} c}\right)^{1/2} \left(\frac{A\tau_{st}}{\tau_{tr}}\right)^{1/2} \frac{f^{3/2}}{\sin(\pi f \tau_{st})}$$

with recycling. The storage time is given by

$$\tau_{st} = b\tau_{tr}$$

where b is the number of beams in each cavity.

The optimization of the shot noise in the receiver types depends on the style of operation (with or without recycling) and on the highest frequency spectral component of the pulse, which in this simple model is assumed to be at frequency f. The Fabry-Perot is optimized for bursts when $\tau_{st} = \frac{1}{4\pi f}$. This is strictly true in the recycled case only but not far off in the unrecycled Fabry - Perot as well. The delay line is optimized in the unrecycled case when $\tau_{st} = \frac{1}{2f}$ and in the recycled case when $\tau_{st} = \frac{1.1656}{\pi f}$. To achieve the projected sensitivity, the light power at the input to the interferometer, P_{in}, is given in the table below. I assume that the contrast of the interferometer fringes is close to 1.

POWER INTO INTERFEROMETER AT 0.5 MICRON WAVELENGTH

Receiver	100 Hz	1KHz
FP no recycling	1.3W	1260W
FP with recycling	0.06W	6W
DL no recycling	0.63W	630W
DL with recycling	0.083W	8.31W

The optical input power requirements depend on the highest frequency spectral component of the pulse as f^3 in the unrecycled case and as f^2 in the recycled case. (If it weren't for the noise from stochastic forces, gravitational wave astronomy would be easier at lower frequencies.) The power also scales as $1/{h_{rms}}^2$.

The power required for the same sensitivity at 1 micron is twice as high as the numbers given in the table. The numbers for the recycled case are optimistic in that the only optical losses assumed in the interferometer are in the cavities. No allowance has been made for losses due to optical inhomogeneity, birefringence and other factors which distort the wavefront of the recombining beams. In general, the optical losses and wavefront distortion are wavelength dependent and would favor the operation of the interferometer at 1 micron rather than .5 microns.

The optical input power to the interferometer, listed in the table above, is not the raw laser output power which must be higher by a factor $1/\epsilon$. ϵ is the optical efficiency of the system used in transforming the laser output beam into a matched, spatially controlled, frequency and amplitude stabilized input beam to the interferometer. The optical efficiencies of the prototypes, at present, range from .3 and to .02. The Michelson systems happen to be more efficient than the Fabry- Perot systems at the moment, although I don't believe there is a fundamental difference between them in this regard.

What could be a reasonable optical efficiency to use for estimation? Mode matching cavities or optical fibers are essential coupling elements into the interferometers and will probably be used as output couplers to reduce the influence of scattering. The cavities can be improved over the present ones with better mirrors, so can the fibers, especially if larger core diameter fibers are used but I will assume that we will never do better than .6 in these devices. Every system we have envisioned requires optical isolators and modulators, pickoff beam splitters, beam steering optics at the input and possibly at the output. Even if all surfaces used at normal incidence are V coated and all components, that can be, are used at Brewster's angle; it is hard to imagine that we will not loose another .6 in the remaining optics. For estimation purposes I will assume that we can attain an overall optical efficiency of .25. This means that all the optical powers in the table should be multiplied by 4.

What is the laser power required to achieve the initial goals? Assume Fabry-Perot receivers and .5 micron light. A moderate estimate assumes that recycling will work as well as indicated in the table (a recycling factor of 200), that we will be shot noise limited at 1 KHz and that there is paydirt at an h_{rms} of 10^{-21}. This would require 24 watts of laser power per interferometer. A pessimistic estimate would assume that we will not get recycling to work any better than a factor of 50 (the present best experience) so that we will need 96 watts of laser power per interferometer. An optimistic estimate would assume that recycling will work better than indicated in the table since mirrors with .3 times less loss have been coated and it is conceivable that the optical inhomogenieties will not become a problem, we are then talking about 8 watts of laser power per interferometer.

The LIGO is being planned for more than one interferometer. The present expectation is that each receiver will have both full length and 1/2 length interferometers. The two interferometers should have similar shot noise sensitivities, otherwise one cannot be an effective veto for the other. One complete receiver doubles the above estimates. The possibility that we will be testing an advanced receiver while searching for gravitational wave signals with another doubles the instantaneous laser power requirement again. Finally, if the full up facility is contemplated from the beginning, a third receiver system would be operating. The overall laser power estimates could run from: optimistic = 48 watts, moderate = 144 watts, pessimistic = 570 watts. The goals for the advanced receivers are h sensitivities that are 10 to 100 times smaller, should the technology of mirrors not improve over the estimates for the initial receivers given here, the demands on laser power could grow by a factor of 10^2 to 10^4 (which is outright unreasonable).

LASERS AND PROJECTIONS FOR THEIR EFFICIENCY

ASSUMPTIONS

1) The lasers will be operated CW in a single longitudinal and single spatial mode.

2) The present choice of LIGO beam tube diameter will not change substantially, so that the optical wavelength is restricted to shortward of 2 microns. This assumption eliminates the efficient CO_2 and chemical lasers.

3) The laser power supplies will not use switching regulators. This is not a serious issue in overall laser efficiency, factors of ≈ 1.2, but is important in reducing the inevitable problems with RFI.

4) For planning purposes I assume that Argon ion and/or optically pumped solid state lasers such as Nd:YAG lasers are the most likely laser sources to be used in the initial

LIGO. Other candidate systems are copper vapor laser pumped dye lasers, now used at Livermore for isotope separation and the direct use (rather than as pumps for solid state lasers) of semiconductor diode lasers which are being developed at Lincoln Lab. Both of these systems look promising but appear to need even more development than Nd:YAG to adapt them to LIGO requirements.

THE ARGON ION LASER

1) PRESENT PERFORMANCE

Typical numbers for large frame Argon Ion lasers at present are given by the properties of the Coherent Inc INNOVA 200-25 (or Spectra Physics 2030-20). This laser produces 6 Watts CW at $.5145\mu$ single longitudinal and spatial mode when driven by a line voltage of 480 Volts and 65 Amps/leg of a 3ϕ power supply. The input power is 54 KW giving an electrical to optical power efficiency of 1.1×10^{-4}. The water cooling requirements are $\approx$ 20 liters/minute. The smaller frame lasers are still less efficient. There is little expectation that the laser manufacturers will make any but small factor, say 2, advances in the Argon Ion laser efficiency in the future, in part since there is no strong impetus for it, but also because they are beginning to come up against fundamental physics problems in the discharge tubes.

2) SOME PHYSICS CONCERNING THE EFFICIENCY OF THE ARGON LASER

The scaling of and a reasonable upper estimate for the Argon laser efficiency can be determined by simple reasoning. The $.5\mu$ lines (photon energy of ≈ 2 eV) in the Argon ion laser originate from an excited state of the Argon ion ≈ 35 eV above the atomic ground state. The ionization energy of the atom $E_{+} \approx 15$ eV. The electron energy in the discharge tube is clamped in a Maxwell distribution with average energy $\approx 1/2 E_{+}$ until the gas is fully ionized. As a consequence the electronic excitation of the upper laser state must be produced by a multi collision process, ionization followed by excitation. At low electron current densities it is a two step process. The optical output power of the laser per length of discharge under saturated conditions is

$$P/l = E_{\gamma} R_{exc} A.$$

E_{γ} is the photon energy, R_{exc} is the rate of excitation of the laser upper level per volume, and A is the discharge column cross section. The excitation rate is given by

$$R_{exc} = \sigma_{exc} n_e v_e n_{+}$$

where σ_{exc} is the excitation cross section of the ionic excited state from the ground ionic state,n_e and v_e are the electron density and velocity (the electron number current density $j_e = n_e v_e$) and n_{+} is the ion density. The ions are lost to the discharge by migrating to the walls where they both lose kinetic energy and recombine with electrons. This is the dominant energy loss mechanism in the discharge. Let the average lifetime of an ion be τ, the equilibrium density of ions is

$$n_{+} = \tau n_0 \sigma_{ion} n_e v_e$$

where σ_{ion} is the ionization cross section and n_0 is the density of neutral Argon atoms. The maximum light output will occur at the highest electron number current density which occurs when the gas becomes fully ionized. The ionization probability becomes 1 when the current density is

$$(n_e v_e)_{max} = \frac{1}{\tau \sigma_{ion}}$$

The power dissipated by the ions per length of tube is

$$P_{ions}/l = \frac{E_{ion} n_+ A}{\tau}$$

where E_{ion} is the energy per ion deposited at the tube wall. The maximum efficiency of the laser is finally given by the ratio of the optical power to the power lost to the walls

$$\epsilon = \frac{E_\gamma \sigma_{exc}}{E_{ion} \sigma_{ion}}$$

$E_\gamma \approx 2$ eV, $E_{ion} \approx 20$ eV, $\sigma_{ion} = 3.2 \times 10^{-16}$ cm^2 and $\sigma_{exc} \approx 3 \times 10^{-18}$ yielding an upper limit for the efficiency of $\approx 10^{-3}$.

There has been experimental research on higher power and more efficient Argon Ion lasers in university and government laboratories. A useful reference is "*Ionenlaser hoher Leistung*" Herziger,G. and Seelig,W., Zeitschrift fur Physik, 219,5,1969 in which a 2 meter long, large bore diameter (1.2 cm), laser is described that produced 120 watts multimode all blue and green lines with a 90 kW electrical input yielding an efficiency of 1.3×10^{-3}. Such a discharge tube used as an oscillator with a large TE$_{00}$ mode volume or as a multipass amplifier might have an efficiency of 3×10^{-4} operating single spatial and longitudinal mode in the green. This is close to the theoretical efficiency. I don't suggest that we embark on the development of such a system. In 1984 I discussed the development of such a laser with Coherent, Spectra Physics and Mathematics Northwest (since bought out by Spectra Physics), they all recommended against it.

THE Nd:YAG LASER

1) PRESENT PERFORMANCE

At present no *commercially* available Nd:YAG laser fulfills the requirements of operating in a single spatial mode at a single frequency with adequate power at either the fundamental wavelength of 1.06μ or at the frequency doubled wavelength of 0.53μ. The marketed products lag the developments in the research laboratories. In this regard the situation is different than with the Argon laser where no research development is being carried out except to improve reliability and reduce costs in marketed products.

Most of the commercial Nd:YAG systems are being marketed for high power industrial process such as laser welding, machining and materials annealing. These systems, operating at 1.06μ, use Nd:YAG rods pumped by Krypton discharge tubes in water cooled enclosures and oscillate in linear resonator cavities. The better units have a beam quality, limited by thermal distortion in the Nd:YAG rods, to 5 or more spatial modes. There is no need (and therefore no effort expended by industry) to make these systems oscillate in a single longitudinal mode. The output power ranges between a few watts to 1 kW with an overall efficiency between 1 to 4×10^{-2}.

There are several commercial products that have relevance to the LIGO

a) Discharge tube pumped rod lasers operated as mode locked oscillators (pulsed with a repetition rate $f = \frac{c}{2l} \approx 100MHz$ for a 1 meter cavity) are available, for example the Quantronix 416. This system produces an average power of 20 watts into a single spatial mode with an efficiency of 5×10^{-3}. The mode locked laser is a suitable light source for an equal arm delay line Michelson interferometer but is not straight forward to modify for a Fabry - Perot interferometer or for recycling.

b) Discharge tube pumped Nd:YAG slab laser heads can be purchased from GE which have developed 750 watts CW at 1.06μ in a few spatial modes when used in a linear cavity oscillating in multi- longitudinal modes. This system is expected to develop 250 watts in the TE_{00} mode with an efficiency of 1×10^{-2}. The relevance of this head to the LIGO is that it can be used as an amplifier or injection locked oscillator driven by a lower power stable oscillator.

c) Single spatial and longitudinal mode, laser diode pumped, Nd:YAG monolithic ring lasers are now commercially available from Lightwave Electronics. The highest power device, at present, develops 40 mW at 1.06μ with an overall efficiency of 7×10^{-2}. Except for the low power, these lasers fulfill the requirements for the LIGO and have the lowest demonstrated intrinsic amplitude and frequency noise of any laser on the market.

Research is being carried out in several areas. One direction is to develop higher power laser diode pumped oscillators and amplifiers. This is clearly the best approach to improve reliability, maintain low noise and to achieve high efficiency. The major limitation, at present, is the high cost of the laser diode pumps, $\approx$ \$1000/watt in large quantity purchases. As will be discussed below, a 20 watt 1.06μ system pumped by laser diodes would cost about \$60K just for diode pumps alone. Hopefully, the costs will come down but this will not happen until there is a market for the laser diodes. Lincoln Laboratory and McDonald Douglas under SDI contracts are developing two dimensional diode arrays and heat exchangers for pumping slab lasers. The aim is to develop a 100 watt diode pumped oscillator for space communications.

An alternate direction that is being taken is to mix technologies, to use low power diode pumped oscillators that are amplified by or injection lock higher power discharge tube pumped slabs and rods. This approach is being taken by GE and Livermore. Although it is a more economical means of achieving higher power systems at present, the amplitude and frequency noise induced by cooling the slab or rod is a worry.

The status of frequency doubling will be the subject of another memo to you when I know more about it. What I do know is that high conversion efficiency, $P(.5\mu)/P(1\mu)$, has been attained in two regimes: 1)low duty cycle ($\delta \approx 10^{-4}$) pulsed operation with high peak power and an average power of a few watts where conversion efficiencies of .7 have been achieved and 2) CW conversion at low power (52mW 1.06μ) has been demonstrated with an efficiency of .56. The principal difficulty in attaining high average power conversion is in the heating of the doubling crystal. Efficient doubling requires a well controlled single spatial mode 1.06μ beam and should become more efficient with higher fundamental power since the non linearity in the doubling crystal is driven harder. Development of higher power stable Nd:YAG at 1.06μ must preceed doubling.

2) SOME THEORETICAL PREDICTIONS CONCERNING THE Nd:YAG LASER The host crystal is $Y_3Al_50_{12}$ which has a cubic structure. The oscillating ion, Nd^{3+}, is an impurity which replaces about 1% of the Y^{3+} before the crystal becomes distorted. The Nd ion energy levels in the host form a true 4 level laser system. The upper lasing state is populated by optical pumping from the ground state to absorption bands (when laser diode pumped) that lie $.8\ \mu$ (≈ 1.5 eV) above the ionic ground state. About 0.8 of the ions excited into the pump bands arrive at the upper laser state. Of these 0.6 participate in the induced emission at $1.06\mu(\approx 1.1$ eV) under saturated conditions. The lower laser state lies ≈ 0.24 eV above the ground state and is therefore not thermally populated at room temperature. Scattering losses in the crystals are determined by the reciprocal scattering length $\alpha \leq 2 \times 10^{-3}$ cm^{-1} at 1μ so that a scattering loss as large as 1% could occur in an optical path 3 cm long. The maximum efficiency defined by the ratio of optical power in to laser power out is .35.

The remaining efficiency factors are determined by the pump light source and the geometric overlap of the pump light distribution with the laser mode volume in the crystal. For laser diodes at room temperature the the absorption coefficient of the Nd:YAG crystal in the main pump band at $.8\mu$ is $\alpha = 8$ cm^{-1} so that there is no difficulty in getting unity absorption in the crystal, in fact some care must be taken to tailor the absorption by varying the diode wavelength to match the $1.06\ \mu$ mode shape within the crystal. The conversion efficiency of multi stripe GaAlAs diode lasers defined as optical power out over electrical power in is .3. If multi mode optical fiber are used to couple the laser diodes to the crystal the coupling efficiency is not likely to be better than .7. One should not have to pay a further price in the geometric overlap when using fibers. The overall theoretical efficiency for diode pumped Nd:YAG in terms of optical power out of the laser to electrical power in would be 7×10^{-2}.

The breakdown for Krypton discharge lamp pumped systems is: ratio of lamp optical power spectrum absorbed by Nd:YAG to electrical input power $\approx .15$, the geometric overlap and lamp cavity coupling efficiency $\approx .4$. The overall theoretical efficiency optical power out of laser to electrical power in would be 2×10^{-2}.

There are several factors that should be considered in these predictions. First no additional losses have to be included to make the laser single longitudinal mode. The fact that the laser lines are homogeneously broadened implies that the laser output power should be the same whether running multi longitudinal mode or single mode, all the ions contribute to the single oscillating line. We are now sure of this from our own experiments. On the other hand thermal distortions in the crystals which perturb the laser wavefront may cost in efficiency. This is certainly the case in discharge tube pumped rod lasers and is one of the major motivations for the slab geometry. At one time it was thought that conjugate optics would cure this problem in rods but wavefront conjugation does not cure polarization distortion. The reduced thermal loading of a diode pumped slab is expected to make this an unimportant concern.

Theoretical predictions for the efficiency of frequency doubling are harder to come by. The absolute maximum efficiency with perfect mode coupling in the doubling crystal is given by the Manley - Rowe relations as one $.5\mu$ photon out for two 1μ photons in, a power conversion efficiency of unity. I am not ready to make a more reasoned theoretical estimate.

SUMMARY

As you can see there are many considerations one has to take into account to answer the question of how to configure the power and cooling system for the LIGO lasers. This document will clearly not be the last word. The table below summarizes my best guess at the requirement on the assumptions that a full up facility will be operating and that we will do moderately well with recycling. The estimates for frequency doubling are shear quesses.

system	optical power	wavelength(μ)	efficiency	electrical power	cost/yr($.07/kwh)
argon	144 W	0.5	1.1×10^{-4}	1.3×10^{6} W	8×10^{5}
Nd:YAG(dp)	288 W	1.06	5×10^{-2}	5.76×10^{3} W	3.5×10^{3}
Nd:YAG(dp)	144 W	0.5	1×10^{-2}	1.44×10^{4} W	8.8×10^{3}
Nd:YAG(lp)	288 W	1.06	1×10^{-2}	2.88×10^{4} W	1.76×10^{4}
Nd:YAG(lp)	144 W	0.5	2×10^{-3}	7.2×10^{4} W	4.42×10^{4}