PLT
PEOPLE LASER TECH

About Flashlamps

A flashlamp provides the optical energy required to make our system work. It delivers short powerful bursts of optical energy to the laser rod.

A word of caution about these flashlamps.

First, they are connected to a very high-energy power supply that will deliver a fatal dose of electricity to anyone who comes into contact withy the electrical path (e.g. at the ends of the flashlamp). Second, these flashlamps produce a light pulse so powerful that not only will they immediately blind you if they are allowed to discharge in anything but a tightly closed pump chamber, but they will peel the paint right off of your walls and can even set your place on fire. Be careful with these things. They look small and unimposing but they are exceedingly dangerous.

The trick with flashlamps in an Nd:YAG system is to deliver as much energy as possible in the shortest time possible and then be immediately prepared to pulse again as soon as all laser energy has been evacuated through the OC. It turns out that properly designed flashlamps are complete lycapable of such a task but are limited by the performance of the connected power supply. Flashlamp selection is critical in Nd:YAG systems, since system efficiency, output power, and beam quality are all affected by the laser rod-lamp match-up.

Flashlamps get very hot, as does everything else in the general proximity of the flashlamp. Water is used to cool the flashlamp but as we will see in a moment, the flashlamp must be compatible with fluid flow and the fluid has some very special requirements.

High efficiency flashlamps convert approximately 50% of the electrical energy applied to them into white light. Only a small portion of this light is actually absorbed by the laser rod. All energy not absorbed by the laser rod is converted to heat and must be carried away from the pump chamber to prevent damage to the cavity's components (e.g. flashlamp and laser rod).

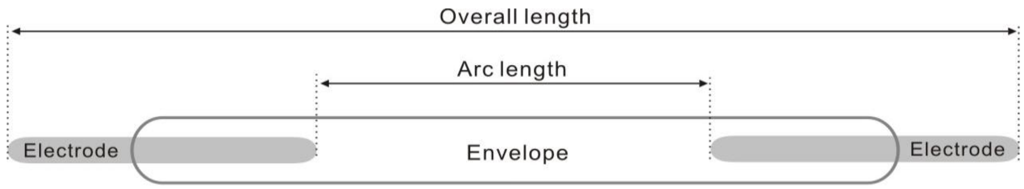
There are literally thousands of flashlamp designs, most of which will not work in your system, so before you just go out and buy that surplus flashlamp, it would be a good idea to understand a few things about them. Next, ask yourself if this laser is something that you intend to use for along time or just a challenge to design and construct and will soon find its place in the "I did it" pile. If it is something that you intend to use often, then forget about surplus flashlamps. Buying a new flashlamp will effectively increase your power output by a facto of 2, not because the flashlamp will be more powerful, but because you can design a circuit that optimizes the flashlamp of known values rather than designing a circuit for an unknown flashlamp.

Using an unknown flashlamp is just taking the chance that it might output the right amount of light in the right spectral bands, operate properly with the power supply that you design, not explode on the first pulse, not rust apart in your cooling fluid, won't solarize your flashlamp, and is common enough that you will be able to replace it with the identical type when it requires replacement.

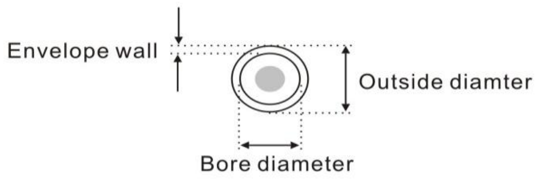
You don't want to completely redesign your system when your flashlamp burns out (and it will before too long) just because you got a discontinued item or one that you do not know the specs for.

A branch of science called plasma physics covers the theory of flashlamp operation. Its complexity presents some significant hurdles to understanding this theory but I shall make an effort to explain the main points.

A flashlamp is comprised of a long quartz tube (envelope) that seals around electrodes (cathode and anode) on opposite ends and contains a noble gas such as xenon. When the cathode is presented with negatively charged electrical potential (voltage) and the anode is presented with a positively charged potential and the gas inside the envelope is excited (e.g. by a trigger pulse - explained later), negatively charged electrons begin to flow from the cathode to the anode and positively charged ions flow from the anode to the cathode.



SIDE VIEW



END VIEW

The negatively charged electrons are more mobile than the positively charged xenon ions and deposit themselves in large concentrations on the interior surface of the quartz tube causing the interior wall of the tube to become electronegative (the quartz tube becomes negatively charged). This charge sets up a powerful attraction for the positively charged ions and they soon find their way to the quartz tube where they recombine with the electrons. This recombination causes a release of photons, which we see as light. At the same time, the impedance (resistance) between the electrodes decreases dramatically as the xenon gas becomes electrically conductive. At the peak of light emission from the typical flashlamp; the voltage drop form cathode to anode is less than 15 VDC (volts direct current). The center of the envelope extending from the cathode to the anode heats up toward 10,000° K (17,540° F), about twice the temperature of the sun's surface) and is the cause for most of the thermal heating of the flashlamp walls, and electrodes.

Now that we understand a little bit about flashlamp theory, let's spend some time really getting to know flashlamps and their components. First, let me dispel a common myth that began when Theodore Miaman released pictures of the first laser ever made. This laser looked so space-age with its helical flashlamp, that since then, everyone seems to think this is what a laser should look like. Forget about cool looking.

When friends see your laser, it will only look like a rectangular enclosure to them since, as I will repeatedly stress throughout this text, your laser must be hermetically (light tight) sealed. Opening the enclosure for any reason will be accompanied by hours of cleaning. Dust in, means less (or no) power out. Dust loves laser optics, nobody know why, but once you build this thing, you don't want it contaminated with dust particles.

The point of all this is, nobody but you will ever know what your flashlamp looks like. The helical flashlamp despite looking cool has no application for high power pulse operated lasers. The only flashlamp you should consider is the rod type. It gives you the most efficient transfer of electrical power to absorbed power in the laser rod. Also, the cavity we will design requires the rod type of flashlamp rather than other designs such as the loop or the helical design.

When you look at a flashlamp, you will notice that it is little more than two opposing metallic electrodes enclosed in glass (envelope) with some sort of invisible gas inside. Believe if or not, engineers have found 100 ways to make a flashlamp with different envelopes, seals and electrodes and with different gasses inside. When you hold them in your hand, they all look about the same.

Envelope Materials

The term envelope in reference to a flashlamp is used universally to describe the body or jacket surrounding the electrodes necessary to contain the flashlamp's filling gas and to provide rigid support for the electrodes. The chosen material must be transparent and able to transmit the useful light or radiation produced by the flashlamp. It must be impervious to air, the filling gas and to whatever liquid is chosen to cool the flashlamp. It must withstand high temperatures and have good mechanical strength.

Laser flashlamps are almost exclusively enveloped with transparent fused quartz better described as clear fused silica. As you look around at flashlamps, you might see the envelope material referred to as vitreous silica or quartz glass or fused glass or silica quartz, which are all the same thing. There are at least 3 basic variants as follow:

- **Clear Fused Quartz** : This material has an Ultra Violet (UV) cutoff (blocks wavelengths shorter than the cutoff value from leaving the envelope) of 220nm. It has good strength and provides an optically clear path for light to leave the flashlamp. It does well in high heat situations and provides relatively good electrical insulating properties. Unfortunately, this material solarizes (changes color when exposed to the high levels of UV produced by the flashlamp).

  This is especially true when repeatedly exposed to very high peak pulses as it would be in our laser so is an <u>unsuitable material</u> for us.

- **Doped Quartz** : This material provides for the control of UV cutoff by introducing a dopant to the material when it is formed. These variants are often used for Nd:YAG lasers to prevent damage to the laser rod, reflector, plastics and o-rings. There are a few primary types of dopant used.

- **Cerium doped Quartz** : This envelope is a clear fused quartz material doped with cerium oxide. The UV cutoff for this material is 380nm. This material eliminates UV and as a side benefit, it converts some of this UV into visible light, absorption lines for Nd:YAG. The envelope seems to be immune to solarization and thus has very long-term stability. This material is the most desirable material for an Nd:YAG pulse operated system.

- **Titanium Doped Quartz** : We won't waste our time with this material, as it is very susceptible to solarization and not suitable for our use.

- **Synthetic Quartz** : This material is far too expensive for us to consider and offers no advantages over any of the others discussed. It is primarily intended for the emission of UV light.

- Envelope wall thickness is customarily 1mm for the size laser systems we are designing but thicker for larger size flashlamps (e.g. 1 meter in length). For our purposes, the flashlamp wall thickness will be 1mm. This thickness offers a good compromise between mechanical strength and flashlamp thermal properties.

Seals

A flashlamp must provide a hermetic seal so that the gas inside doesn't escape. This seal isn't all that easy to achiever given the differing natures of quartz and the metallic electrodes since these elements expand and contract at different rates given the same thermal conditions. These flashlamps must function in a wide range of temperatures from room temperature to more than 300°C. The flashlamp manufacturer can't simply seal the envelop around the metal electrodes without doing something special.

I introduce this topic because different seals have benefit for specific applications. We are looking for a flashlamp with a seal designed for thigh thermal loading, able to withstand significant shock from the violent nature of pulsing the flashlamp, able to withstand significant amount of electrical current and high voltage. There are 3 basic types of sealing methods employed in the manufacture of flashlamps as follows:

- **Ribbon Seal**: In this design, quartz is bonded directly to a thin strip of molybdenum foil. Flashlamps sealed with this method exhibit a very strong and robust bond between the metallic electrodes and the quartz. These seals have a seemingly unlimited shelf life and they allow the designer to minimize dead volume (that interior space between the electrode tip and the seal). Unfortunately, this seal cannot survive the immense current applied to the electrodes required in a pulsed laser system and therefore cannot be used in out flashlamps used for this project.

- **Solder Seal**: This method allows a bond to be made between a circular band of invar and the quartz tube. The seal is made using lead indium solder with a melting point of 350℃. This technique reduces dead volumes, it provides a rigid mounting of the electrodes to the quartz tube, has high strength and has the best current handling capability of all the sealing methods. Unfortunately, this sealing method has a low service temperature of less than 100 ℃ and has a questionable shelf life. Another poor choice for our project.

- **Rod Seal** : The term " rod seal" is used to describe a sealing method whereby quartz is directly fused to the metallic electrodes in a very tight bond. This can be accomplished through the use of extreme heat and/or pressure at the seal. There is no actual " rod " involved. This sea method is used extensively in solid-state pulsed lasers such as the one we are about to construct.

This seal method has high reliability, high peak and RMS current capability, handles relatively high temperatures and offers the full potential of silica thermal handling capabilities which is to say that it can handle a significant amount of heat without breaking down. In fact, the seal typically get tighter the more heat the seal absorbs. We must assure however, that the long-term temperature does not exceed 300 ℃. In summary, the rod seal is the proper choice for our system.

Electrodes

The purpose of the electrodes is to deliver high-energy to gas stored in the quartz envelope. There are two electrodes in a flashlamp and each is different form the other. The cathode receives a negative charge from the pulse-forming network (PFN) and emits electrons through the gas to the anode, which is connected to the positive side of the PFN.

A voltage in the neighborhood of 800VDC is applied across the flashlamp for normal operation but this doesn't set the flashlamp off. To ignite the flashlamp, we must either achieve the self-ignition voltage of the flashlamp (series method), which is quite high, or ionize the gas inside the tube through a high voltage spark in the proximity of the tube. Since we will surround the flashlamp with cooling fluid (water), our only choice for initially triggering the flashlamp is the series method.

Now getting back to the electrodes, if you were to place an ohmmeter across the electrodes, you would notice that the flashlamp has absolutely no conductivity at the meter's sampling voltage level. The impedance of these flashlamps is extremely high until they begin to arc and then suddenly, the conductivity increases toward infinity and the impedance drops toward 0 (e.g. they become a short circuit).

You can expect this to cause us a design concern when we begin work on the capacitor charging power supply and the pulse-forming network. Imagine short-circuiting a high voltage, high current delivery power supply. We can make use of this low impedance effect however, using a simmer circuit. Once the impedance of the tube drops to a very low level due to the arc, it doesn't require much current to sustain this arc. The simmer does this exactly and by dong it; we significantly increase the life expectancy of the flashlamp and receive much higher reliability from it.

OK, a few words of warning– if you connect the flashlamp to your power supply backwards (e.g. positive to the cathode and negative to the anode), you will quickly end the useful life of your flashlamp. If you flash this flashlamp in anything other than a tightly sealed enclosure (e.g. a hermetically sealed laser pump chamber), you will likely never see again. If you mismatch the pulse forming network, the flashlamp with either be under-utilized giving you poor performance or will be over utilized dramatically shortening its service life.

Filing Gas & Pressure

There are two basic gases used for flashlamps– xenon krypton. Krypton can be used at low power densities for Nd:YAG systems and is desirable for such systems because of the more suitable match between the krypton spectral lines and the YAG absorption bands. Xenon however, will be our choice for this project even though its output doesn't match any of the YAG absorption bands. Xenon overwhelms the laser rod with intense energy throughout the spectrum. Nd:YAG absorbs almost all visible and near-infrared wavelengths and absorbs a good portion of the xenon output. You simply couldn't deliver this much absorbed energy with a Krypton flashlamp despite it producing energy in the Nd:YAG absorption bands.

Fill pressure (the pressure of the xenon gas inside of the flashlamp) is an extremely important specification for flashlamps. Generally, the higher the fill pressure, the higher the efficiency will be for laser pumping (e.g. more favorable ratio of electrical power-in to total optical power-out). For pulsed flashlamps, the highest practical pressure is approximately 3000 torr ("torr" is the measure of gas pressure equivalent to millimeters of mercury approximately equal to 0.02 PSI). Above this, triggering can be a major problem.

Below 100 torr, cathode sputter and envelope contamination can become a major problem. We will want our flashlamp to have a xenon fill pressure of approximately 450 torr (8.7 PSI). I make this statement based on mathematical calculations that are inappropriate for this text. For those interested in such calculations, please see " Solid-state Laser Engineering by W. Koechner".

Dead Volume

Dead volume is that space inside of a flashlamp between the electrode tip and the seal – the non-active internal area of our flashlamp. We care about this dead volume because a flashlamp with a large dead volume will not attain a higher pressure during operation. We count on this higher pressure caused by gas heating and expanding to increase the efficiency of the flashlamp. This goes back to the statement made in the Fill Pressure section about the efficiency of the flashlamp being higher with greater fill pressure. Every flashlamp is rated as to its cold fill pressure. As current flow through the flashlamp increases, so does the gas pressure due to heating effects of the xenon gas. The more gas inside the flashlamp envelope, the greater will be the gas expansion and therefore, the greater will be the pressure at higher temperatures. Dead-space inside the flashlamp provides a place for expanding gas to expand to and the overall pressure increase is diminished. The higher the pressure inside the envelope, the more efficient the flashlamp will be.

Flashlamp Impedance

The impedance (resistance to current flow) of a flashlamp (denoted by the symbol K_o) is dependant on the arc length (distance between the electrode tips) and the internal (bore) diameter (e.g. the envelope volume). It is also determined by the gas fill, gas type and is influenced by the flashlamp's dead volume. The impedance will increase with longer arc lengths and decrease with increasing tube diameter. As implied earlier, impedance also increases as the fill pressure is increased.

The respective values for impedance of the cold vs. the hot flashlamp are important for the proper design of a power source to operate the flashlamp. We will revisit this concept again when we discuss pulse forming network design.

Spectral output

Flashlamps emit an optical spectrum that covers a wide range of wavelengths. These wavelengths extend from the UV (ultra-violet) range to the IR (infrared) range. The radiation produced by a flashlamp is primarily dependent on current density (amount of electrical current flow) and to a lesser degree on the gas type and fill pressure. The conversion of electrical energy to optical energy in a xenon flashlamp is a relatively efficient 50%.

The efficiency improves with current density and gas fill pressure providing the power source that drives the flashlamp matches the impedance of the flashlamp. Regardless of the electrical to optical efficiency of a flashlamp, true system efficiency is the measure of "electrical energy-in" to "laser energy-out".

This is affected greatly by the spectral match between the flashlamp output and laser rod absorption. The principle pump (absorption) bands of Nd:YAG are located from 0.73 to 0.76 ㎛ and 0.79 to 0.82 ㎛. It turns out that xenon has no major line radiation (light at a specific wavelength) in these bands; so pumping is primarily due to continuum radiation (the full spectrum of white light). Fear not, we have a solution to this problem in the form of a dye (Rhodamine 6G) added to the coolant that fluoresces in the primary pump bands when presented with certain wavelength emissions not otherwise useful to Nd:YAG. This dye will increase our system output levels by as much as increase our system output levels by as much as 50%. I will discuss this dye in better detail, later in this text.

Cooling Considerations

We will accelerate hear removal from the flashlamp and laser rod with circulating fluid through the pump chamber. As I state this, we should begin to consider our flashlamp that must accommodate such flow.

I received one of our lasers back from the field for having failed completely and when I disassembled the cavity, I knew the problem immediately. The operator had replaced one of our flashlamps with a generic brand that was not designed for operation in a liquid cooling environment. Soon after placing the flashlamp into the cavity, the caustic coolant began to destroy (rust) the electrodes. Soon the fluid was fouled and before long, the flashlamp disintegrated (the ends rusted off) and the flashlamp failed in a spectacular way fouling the entire cavity. The user somehow extracted all of the glass pieces from the cavity and installed the proper flashlamp and was surprised when the laser wouldn't function. The laser rod was unable to absorb enough light to initiate a population inversion, the cavity reflector had a coefficient of reflection of precisely zero.

Once you design your system with a power supply that is a match for your flashlamp, record the flashlamp manufacturer and model number somewhere so that you can replace the old flashlamp with one made for your system. Write this information down on a sticker and affix this sticker to your pump chamber.

Use flashlamps that are specifically designed for cooling fluid operation. These flashlamps have electrodes that will not rust when exposed to the corrosive coolant fluid for long periods of time.

Don't use a flashlamps whose specifications you are not sure about for the initial design or for a replacement later.

Our coolant system will be described later in this text. In this section, I will focus on the general principles of cooling the flashlamp.

Gases, such as air, have poor thermal conductivity and absorption. For low power, low repetition laser systems, air circulation provides sufficient cooling for the flashlamp. Our design attempts to create a very high-power laser system using high- energy flashlamps that produce significant quantities of heat. We must remove this heat or we will suffer damage to the flashlamp, pump chamber, laser rod and anything else unfortunate enough to be in or near the heat generated by these things. Even the cleanest cooling water fouls easily in a closed system so we mix it with ethanol. I will discuss fluids later.

To provide sufficient cooling for our system, we should provide a flow rate of 4-10 liters of cooled fluid over the laser rod and flashlamp each minute. We will perform the calculations in chapter 9. the fluid carries enough of the heat away from the flashlamp so that heat doesn't build up to a critical point.

We place temperature-monitoring sensors inside of the pump chamber and in our coolant lines along with control circuitry to maintain an acceptable pump chamber temperature. We design fail-safe circuitry that shuts the entire system off in cases where the temperature inside the pump chamber begins to go into thermal runaway (this is a condition where our cooling system can no longer remove heat at the same rate as heat is produced). Compare the laser cooling system to your automobile coolant system. Without sensors, temperature monitoring and control, the engine in your car would burn up just as your laser will without similar sensors, temperature monitoring and controls.

A side benefit to fluid cooling, besides hosting the dye I mentioned earlier, is that fluid cooling is clean and doesn’t contaminate the pump chamber with dust as forced-air cooling does.

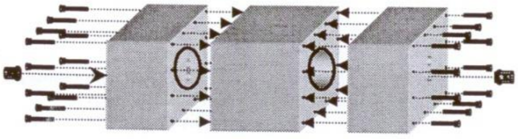
Tap water is unsuitable as a coolant since it conducts electricity and will short our flashlamp out. It also provides a dangerous electrical path to everything the water touches (e.g. enclosure metals). Tap water is also very conducive to biological growth, which would coat the fluid pathway, laser rod, flashlamp and everything the coolant comes into contact with. This growth buildup would quickly inhibit light transfer from theflashlamp to the laser rod. It would also cause severe electrolysis of the connectors that are in constant contact with the coolant.

This electrolysis would destroy even the highest-grade electrodes.

In this text, I provide you with two options for constructing the pump chamber. The first option is the flooded version; the other option is the flow-tube version. It will be entirely up to you which version you produce. The flow-tube version has the advantage that it can be cleaned without complete disassembly whereas the flooded version has the advantages of simplicity and efficiency. I will introduce these pump chambers here and describe them in more detail later.

- ## Flooded Pump Chamber

The flooded pump chamber is simple since it primarily consists of three sections of drain, a few o-rings and two flashlamp terminals. Figure 5.2 illustrates the design of such a system and figure 5.3 illustrates the coolant path.



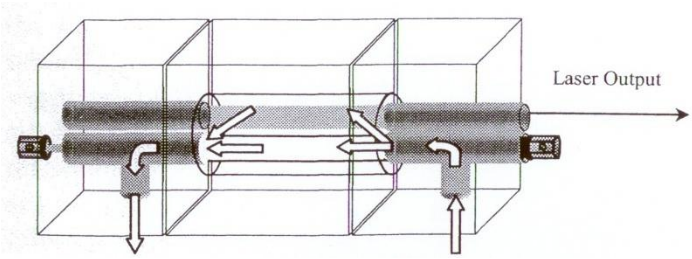
< Figure 2 >

Flooded Cavity Design

The cavity and end-blocks must all be made from a material that will not contaminate the coolant fluid or conduct electricity. The material must also have a relatively high melting point. White drain plastic is an excellent choice for this project.

I favor the flooded cavity for its simplicity and efficiency advantages over the flow-tube design. As you will see shortly, you can place the laser rod and flashlamp much closer in the flooded design than in the flow-tube design, and you can wrap the cavity reflector around the flashlamp and laser rod much tighter. Bringing the laser rod and flashlamp closer and tightening the reflector will make a big difference in efficiency, as much as 50% over the flow-tube design.

Cooling is simple and straightforward in the flooded cavity design in that coolant fluid flows in one block and out the other unrestricted. You can see from figure 5.2, that the center section (cavity) has a big hole in it to host the cavity reflector. The cavity reflector is made from either gold- plated, marine-grade stainless steel or from a highly reflective ceramic.



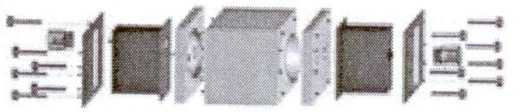
< Figure 3 >
Flooded Design Coolant Flow Path

Coolant flows from the heat exchanger and enters the right-side end-block from the bottom. This coolant flows along the flashlamp to the cavity, it floods the cavity, and flows along the other end of the flashlamp, through the bottom of the left end-block and back to the heat exchanger. Since the laser rod also exists in the cavity, it is cooled, as is our reflector.

This is a simple design that works extremely well. It is effective in accelerating heat removal from flashlamp, laser rod and reflector. The flow-tube design only cools the flashlamp and laser rod. Care must be taken with materials used for the flooded pump chamber since it is exposed to very corrosive de-ionized water, ethanol and Rhodamine 6G dye. All of the materials used to construct the pump chamber must be very resistant to corrosion by these fluids, must not release contaminants into the fluid and must not ionize the fluid.

Flow-Tube Pump Chamber

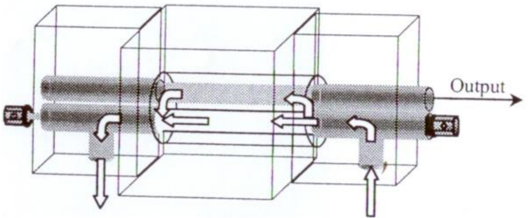
In the flow-tube design, we have a little more flexibility in the materials we use. For example, we can use materials such as aluminum, brass or copper for some of the components so long as we do not use these elements in anything that the fluid comes into contact with. Figure 5.4 illustrates this design and figure 5.5 illustrates the coolant flow path.



< Figure 4 >

Flow-Tube Design

In this design, the flow tube is typically a piece of quartz very much like a test tube with the bottom cut off. We place the flashlamp inside of one flow tube and the laser rod inside another flow tube. We seal the ends of each flow-tube to the pump chamber and to the laser rod or flashlamp. We design a channel to each, so that fluid can flow unrestricted in one end and out the other without air pockets or turbulence from the fluid flow. The coolant enters the chamber from the right end-block, flows across the flashlamp end to a junction where some of it continues along the flashlamp and some of it along the laser rod, all the while, constrained within the boundaries of the flow- tubes.



< Figure 5 >

Flow-Tube Cavity Flow Path

The end caps extend the pump chamber out to accommodate the flashlamp, which has an overall length of at least twice the laser rod. The arc length (distance between the anode and cathode tips) is the same length as the laser rod. The overall flashlamp length is substantially longer than the arc length and laser rod length so it isn't unexpected that we would need to extend the pump chamber to accommodate the flashlamp.

Because of the large concentration of highly charged electrons associated with the electrical energy we place across the flashlamp, we will want to be sure that our cooling fluid has very low conductance. It is interesting to note that pure water is an insulator (e.g. it doesn't conduct electricity). Water will conduct electricity however if it contains metal particles such as copper, brass, or aluminum and easily becomes ionized (conductive).

We must never allow our cooling fluid to come into contact with copper, brass, aluminum or any other ionizing material or with components such as gauges, transducers, valves, sensors, or pipe that contains ionizing material. Our fluid path must be constructed from glass (flow tubes), drain or high-grade stainless steel (end- blocks) and Teflon (hoses).

Although the pump chamber body can be constructed from aluminum, brass, copper, etc., any portion of it that our coolant comes into contact with must be constructed from a non-ionizing material, such as stainless or drain. Pump chambers are typically constructed from a large block of aluminum to help absorb some of the heat trapped inside (e.g. helps to cool the cavity reflector).

The design uses a “pump cavity” (large block in the center) to host the reflector, a flashlamp extension block on each end of the cavity to host the flashlamp and encapsulate the flow-tubes. Coolant form the heat exchanger enters one of the flashlamp extension blocks from the bottom, flows through the block and around the flashlamp to a junction where the fluid splits; half going through the flashlamp flow-tube andthe other half going through the laser rod flow-tube. The fluid merges at the other flashlamp extension block, finds its way through the bottom and returns to the heat exchanger.

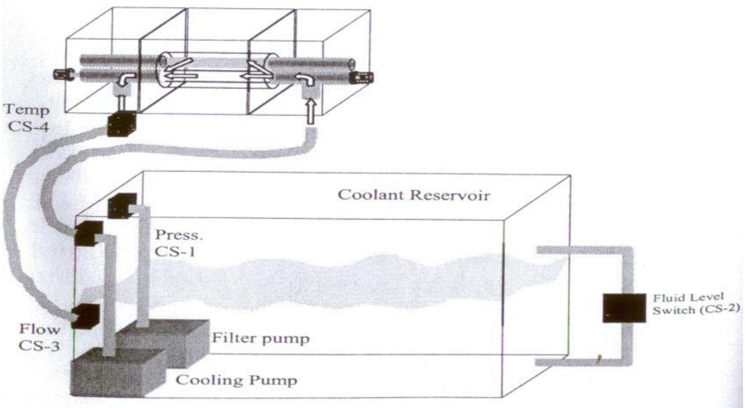
Notice that the fluid never touches the cavity reflector or the pump chamber. It only touches the end- locks, flow tubes, laser rod and flashlamp. This means that we can use a material of our choice for the reflector and chamber but must use a material not harmed by and not harmful to the coolant for the flashlamp extension blocks. As I stated earlier, this design has the advantage that it does not require disassembly for cleaning (all pump chambers must be cleaned periodically). All one needs to do is remove the flashlamp and laser rod through easy-out ports for cleaning. The flooded design would require a complete disassembly and realignment when cleaning is required.

This design does a very good job of cooling the laser rod and flashlamp but does nothing for the cavity reflector. It could be argued that nothing needs to be done for the reflector but I will tell you, this reflector becomes extremely hot, so hot in fact, that not cooling it means that the chamber must be made from something that will not melt (e.g. not from soft plastic. Also, if a gold- plated reflector is used, the gold plating must be able to withstand severe heat.

- Coolant & Temp Monitoring

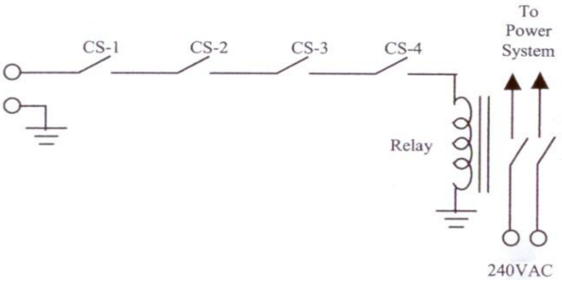
As discussed earlier, we will need to monitor the temperature inside the pump chamber during operation and build in electronic control circuitry to automatically disable power to the flashlamp when the temperature becomes too high. Likewise, we will need to monitor the temperature of the flashlamp electrodes, coolant fluid temperature, and coolant fluid flow rate. If any of these values fall outside of the safe operating range, our system must shut off promptly. I designed this control circuitry for you and hope that you implement it into your design. This circuitry isapplicable for any pulse-operated, solid-state laser system. These controls add to the cost and effort of this project but are essential to the sustained operation of your laser.

< Figure 6 >
Coolant Sensor Mechanical



Figures 5.6 and 5.7 illustrate the placement and interconnection of this circuitry. I will provide a more complete discussion of the design later in this text and more complete diagrams can be obtained from the support website (www.Buildalaser.com). From figure 5.6, you should note thatwe will monitor the temperature at various places and will monitor coolant pressure and flow. We do this since it is very possible to have coolant pressure without flow (e.g. an obstruction in the line). It is likewise possible to have coolant flow without pressure (broken line spilling fluid all over the floor). It is also possible to have good pressure and flow but be unable to control the pump chamber temperature within safe operating limits (on a very hot day)

< Figure 7 >
Coolant Sensor Electrical



We design our system so that the laser will not turn on until there is coolant pressure and flow. It also will not operate when the temperature is too high. The system shuts downautomatically when the temperature exceeds a set point, when pressure of flow drops, or when the coolant fluid level drops below a set level.

Figure 5.7 illustrates that the sensors and transducers individually control an associated switch that simply breaks the circuit when any one of them fall outside of a parameter that we control. An example of this is the flow switch failing open when there is no coolant flow. With the coolant flow switch in the "open" position, electricity is unable to energize the power relay. Since the power relay fails open, the entire system shuts down and remains shut down until we cause the coolantflow switch to close, and therefore, the power relay to close.

If the "closing " and "opening" of these circuits seems confusing, fear not. I will cover the electronics in much better detail later.

A point of warning to you; If these concepts seem strange-get electronic help with this project. We are currently discussing the coolant monitoring and control system, which by comparison to the power supplies and q-switch control system that we will discuss later, is extremely basic. If you are having difficulty understanding the switches, you will find it impossible tounderstand the power supplycircuitry and will place yourself in very real danger if you attempt to work in the power supplies without help.

Selection Considerations

Here are some of the basic flashlamp selection criteria. Choose a flashlamp made for high peak power and medium average power. As we already determined, we want a xenon flashlamp with an envelope constructed from cerium-doped quartz that incorporates a rod seal and electrodes designed for very high-density pulse operation. It should have fill value of 450 torr.

Choose one with an arc length that matches your laser rod length. We will be using a simmer supply, so you will want to make certain that the flashlamp you select is rated for simmer operation (e.g. the simmer). Also, your flashlamp ends will continually contaminate your DI coolant (I'll explain DI later) with rust and will fail prematurely when the ends literally fall off.

We already covered the envelope material and seal. Make certain that your flashlamp complies with these specs. When you buy a flashlamp, there will be specifications listed by the manufacturer for operating impedance. We will need this specification when we design the PFN. Also, a proper elliptical reflector assumes that the outside diameter of your flashlamp (bore diameter) is the same as the diameter of your laser rod. This is important, since it will be difficult to design a cavity reflector that optimizes the transfer of light from your flashlamp to laser rod if these diameters are greatly different.

Glossary

Arc length (L_A)	Arc length measured between electrode faces (mm)
Bead centre (L_B)	The distance between the centre of the lamp seas (mm)
Bore (d)	Internal diameter of the lamp (mm)
C	Capacitance (F)
CFQ	Clear Fused Quartz
CDQ	Cerium Doped Quartz
CW	Continuous Wave – a term used to describe continuous lamps
Damping coefficient (∝)	A damping factor for the resonance of the PFN circuit including the lamp – should be between 0.6 and 1.0 – ideally 0.8
Dome-to-dome	An alternative term to describe Bead Centre. (mm)
Dc	Connector diameter (mm)
Dp	PEI sleeve diameter (mm)
Eo	Pulse energy (J)
Ex	Energy required at a specific pulse duration for lamp life to equal one firing (J)
Fill pressure	The cold fill pressure of gas which is pumped into the lamp during manufacture (Torr)
IGBT	Insulated Gate Bi-polar Transistor
Kex	Lamp explosion energy constant. Kex can be used to calculate Ex for any pulse duration
Ko	Lamp impedance constant ($\Omega A^{1/2}$)
L	Inductance
Lc	Connector length (mm)
L_L	Lead Length (mm)
Ls	Stripped length (mm)
Lp	PEI sleeve length (mm)
Max-non flex	For lamps with flexible leads, this is the distance between the outer edges of the leads once they have been bent at right angles (mm)
Maximum average power	Maximum level of Average input power to the lamp (W). This figure is based on the maximum continuous wall dissipation of the quartz
O	Offset (mm)
O-ring centre (L_R)	The distance between the centre of the anode and cathode O-rings (mm)
Overall length (OAL, Lo)	The length of the lamp form the end of one connector to the end of the other (mm)
P	Pressure (Torr)
PFN	Pulse Forming Network
SCR	Silicon Controlled Rectifier
SFQ	Synthetic Fused Quartz
T	Full Pulse width measured at 1/3 pulse height (seconds)
t	Time constant of the circuit (seconds)
TDQ	Titanium Doped Quartz
Zo	Electrical impedance of the circuit (Ω)
Z_L	Electrical impedance of the lamp (Ω)

Lamp formula

General

Impedance constant

$$(\mathrm{Ko}) = 1.28\,\frac{\mathrm{Arc\ length}}{\mathrm{Bore}}\left(\frac{\mathrm{Fill\ pressure\ in\ Torr}}{\mathrm{Constant}}\right)^{0.2}$$

Constant = 450 for Xenon and 805 for Krypton

Adjustments

Nominal Pulse lamp calculations are based on 1mm wall Clear Fused Quartz.
For other materials and thicknesses, refer to figure 17 on page 15.

Square Wave power supply

$$\text{Pulse voltage (V)} = \mathrm{Ko}\,l^{1/2} \qquad \text{Pulse energe (Eo)} = \frac{V^3 T}{\mathrm{Ko}^2}$$

$$\text{Pulse power (W)} = \mathrm{Ko}\,l^{3/2} \qquad \text{Current (I)} = \left(\frac{E}{\mathrm{Ko}\,T}\right)^{2/3}$$

PFN

$$\text{Time constant of circuit (t)} = (L\,C)^{1/2} \qquad \text{Explosion energy (Ex)} = K_{EX}\,t^{1/2}$$

$$\text{Capacitance (C)} = \left(\frac{2\,\mathrm{Eo}\propto^4 t^2}{\mathrm{Ko}^4}\right)^{1/3} \qquad \text{Voltage (V)} = \left(\frac{2\,\mathrm{Eo}}{C}\right)^{1/2}$$

$$\text{Damping factor } (\propto) = \mathrm{Ko}\left(\frac{C}{V\,t}\right)^{1/2} \qquad \text{Life as a function of explosion energy} = \left(\frac{\mathrm{Ex}}{\mathrm{Eo}}\right)^{8.5}$$

$$\text{Average power} = \mathrm{Eo}\,f \qquad \text{Full pulse width at 1/3 height (T)} = 3\,t$$

$$\text{Impedance (Zo)} = \left(\frac{L}{C}\right)^{1/2} \qquad \text{Peak current } (l_{MAX}) \text{ approximation} = \left(\frac{\mathrm{Vo}}{2\,\mathrm{Zo}}\right)$$

$$\text{For changes in fill pressure, new Ko} = \text{old Ko}\left(\frac{\text{new pressure}}{\text{old pressure}}\right)^{1/5}$$

$$\text{For changes in Ko, new pressure} = \text{old pressure}\left(\frac{\text{new Ko}}{\text{old Ko}}\right)^{5}$$

Conversion factors

Length

mm → inches	x by 0.039
inches → mm	x by 25.4

Temperature

℃ → °F	x by 1.8, then add 32
°F → ℃	subtract 32, then x by 0.556

Volume

Litres → UK Gallons	x by 0.22
UK Gallons → Litres	x by 4.54
Litres → US Gallons	x by 0.26
US Gallons → Litres	x by 3.78

Pressure

Pascal → Torr	x by 0.0075
Torr → Pascal	x by 133
psi → Torr	x by 51.715
Torr → psi	x by 0.0193
millibar → Torr	x by 0.75
Torr → millibar	x by 1.33