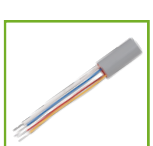
High-Power Water-Cooled Flashlamps



Introduction

Excelitas Technologies® Xenon or Krypton Flashlamps produce microsecond to millisecond duration pulses of broadband light with high radiant intensities and repetition rates.

For high-power and UV applications, our robust quartz envelope materials are recommended. For lower-intensity applications, hard glass or borosilicate offer better economy without sacrificing performance.

Excelitas offers an extensive assortment of lamp shapes for a range of applications and integrations. Comprehensive plug-in custom solutions... lamps, sockets and integrated trigger coils... are also available upon request. Exceptional stability and life characteristics make our flashlamps series the ideal source of pulsed or continuous light for your application.

Much work has been undertaken in recent years to further improve lamp technology in new, demanding applications. A great deal of lamp development work is concentrated at the cathode, where rigorous service conditions are encountered when lamps are operated at high average powers and pulse durations in the millisecond regime. Excelitas utilizes it's company-wide diagnostic techniques to aid this research. Techniques such as finite element analysis and x-ray analysis are tools that play a significant role in lamp development.

Excelitas actively participates in the advancement of flashlamp technology through its connections with research establishments throughout the world, both at university and commercial levels.

PAST, PRESENT AND FUTURE

Solid state laser systems have historically used pulsed and CW (DC) xenon or krypton filled arc lamps as excitation for pump sources. In 1960 T.H. Maiman demonstrated the first practical pulsed laser system at Hughes Reseach Labs. At this time, the technology and understanding of flashlamps was very basic and mostly used for photography and related applications. In fact the Maiman ruby laser was pumped by a small, hard glass helical lamp, made by General Electric, intended for studio photography.

Throughout the 1960's lamp and laser development progressed and matured. During this period the quartz/tungsten rod seal flashlamp was developed, perfected and extensively adopted for high average power laser pumping. Specialist laser lamp manufacturing companies were also set up, adding to the development and advancement of high technology laser lamps.

Lamp production has now progressed to the point where many advanced high performance designs are routinely available off the shelf or can be built in small quantities at short notice. Although production runs can be for several thousand lamps, they are still universally assembled using basically hand crafting techniques. It is because of this hand crafting that small production runs of specialized devices can be undertaken economically.

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Lamp Construction and Material Selection

ENVELOPE MATERIALS

The term ‘envelope’ is universally used to describe the body or jacket surrounding the electrodes necessary to contain the filling gas. The chosen envelope material has to be transparent and able to transmit the useful light or radiation produced by the lamp. It must also be impervious to air and the filling gas, withstand high temperatures and be mechanically strong. The material universally used for envelopes in the construction of flashlamps and arc lamps for laser pumping is transparent fused quartz. It meets all, or most of the stated requirements, is easily worked and is available in a wide range of sizes.

Hard glass or pyrex is used extensively for lamps operating under conditions of low average power. This includes signal beacons, low power stroboscopes and low power photographic applications, such as camera flash guns. Under the high power conditions required for laser pumping, glass simply cannot withstand the high thermal loading. Stress cracks will rapidly develop within the tubing leading to lamp failure. Quartz however is highly tolerant to thermal shocks. At red heat it can be plunged into cold water without damage and has a high softening point (1300°C). Pyrex softens at approximately 600°C.

There is frequent confusion surrounding the terminology used in quartz based products. Although the term quartz is frequently used, its usage is somewhat incorrect as it describes the basic mined, unrefined ore, not the final product. The correct term is clear fused silica. It is also referred to as vitreous silica, quartz glass, fused glass or silica quartz. The term quartz, although incorrect, has become synonymous with flashlamps and for ease of reference will be used in this brochure.

There are three major groups of quartz used in flashlamp construction - clear fused quartz, doped quartz and synthetic quartz. Although temperature and strength, each of group has similar properties regarding they differ in their respective transmittance at the UV end of the spectrum, from 200 to 400 nm.

QUARTZ TYPES

Clear Fused Quartz

Clear fused quartz is the basic building block for the majority of flashlamps. It has an upper operational limit of approximately 600°C and is readily available in a wide range of sizes. The UV cut off commences at approximately 220 nm. The only major disadvantage of clear fused quartz is the problem of solarization or the appearance of a purplish discoloration due to color centres forming within the quartz. The color centers are localities of ion impurities. These are thought to include ion, aluminum, germanium and some rare earths. Solarization results in a broad band reduction in the transmittance of the quartz. The color sites generally form during the high energy operation of flashlamps. It does not appear to occur under low power conditions.

Many flashlamp pumped laser systems use lamps made from clear fused quartz. It is not generally possible to predict whether a particular mode of operation will make a lamp more susceptible to solarization. If problems are experienced with solarization there are alternative types of quartz available to alleviate the problem.

Doped Quartz

The UV transmission properties of quartz can be modified by the incorporation of a dopant in the material. This dopant usually takes the form of cerium or titanium oxides. The quartz still appears clear but as Figure A shows, the UV transmission has been modified. This modification is desirable when potentially damaging UV from the flashlamp must be eliminated. This includes, in the case of a lamp operating in free air, the elimination of ozone or the prevention of UV damage to Nd:YAG rods, reflectors, plastics and 'O' rings.

Cerium Doped Quartz

Clear fused quartz doped with cerium oxide is finding increasing applications in flashlamps for laser pumping. The UV cut off at approximately 380 nm ensures that harmful UV is eliminated from the pump chamber. The UV absorption is accompanied by fluorescence in the visible spectrum. As some of this falls in the absorption bands of Nd:YAG an increase in laser efficiency can be expected. Significantly as cerium doped silica does not solarise it has very stable characteristics throughout lamp life making it a very desirable envelope material for flashlamps when laser pumping.

Titanium Doped Quartz

Clear fused quartz doped with titanium oxide is available in many different grades, each one having a different UV cut off profile. It has similar characteristics to cerium doped quartz but suffers badly from solarization and does not have the fluorescence characteristic. Once used extensively when UV filtering was required for flashlamps, it has all but been superseded by a cerium doped quartz. It is however frequently encountered in medical and sun ray type lamps and non-laser flashlamps when ozone must be prevented.

Optical Transmission of Envelope Materials

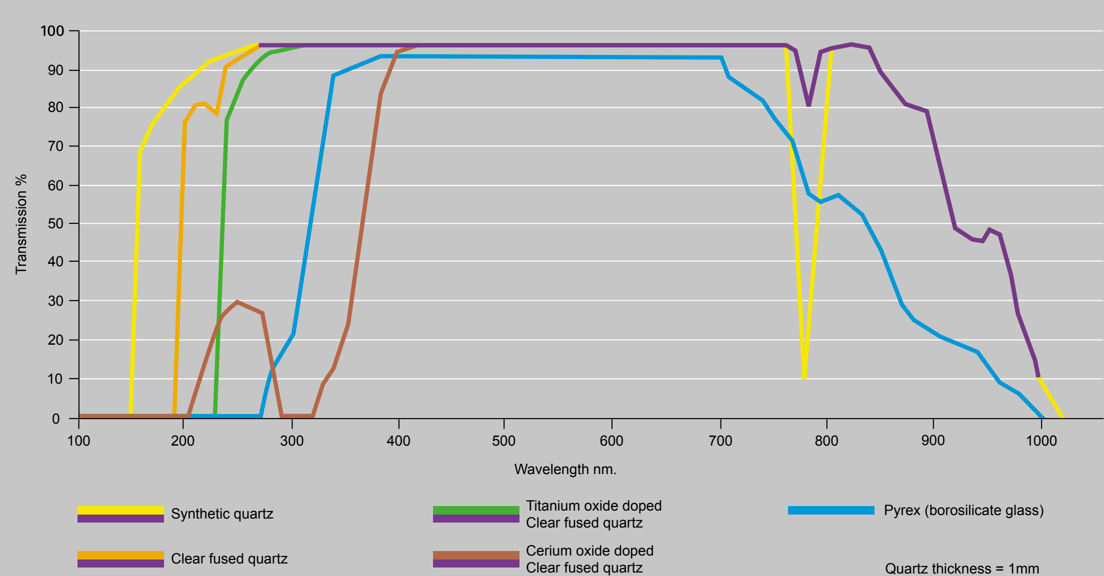


Figure A

Synthetic Quartz

In addition to doped and undoped quartz tubing there is another type of quartz material available. This is high purity, man-made, synthetic quartz. It is widely specified when transmission down to 160 nm is required. It generally has superb optical qualities and complete freedom from solarization. It is the most expensive of all the quartz materials and the least readily available.

General Considerations

Quartz tubing with 1 mm wall thickness is the most frequently specified for flashlamps. This, over a wide range of sizes, gives a good compromise between mechanical strength, availability, ease of lamp manufacture and lamp thermal properties. At internal diameters greater than 12 mm the wall thickness should be increased to 1.25 to 1.5 mm. Quartz thickness above 2.5 to 3 mm is not desirable as high thermal gradients can be formed in the quartz during lamp operation, possibly leading to the formation of stress cracks. Under conditions of high average power and low peak power, e.g. krypton arc lamps, 0.5 mm wall thickness quartz is specified for maximum heat transfer from the lamp and to minimize the thermal gradient. The internal diameter of quartz tubing is normally available in whole mm increments. Intermediate sizes can be obtained if required. A general purpose tolerance for flashlamp tubing is ± 0.3 mm for the outside and inside diameters. For small lamps of 2 to 4 mm bore and up to 75 mm arc, precision bore tubing is available, giving good repeatability of lamp performance, especially lamp impedance. Generally the tolerance of quartz tubing becomes greater as the sizes increase.

SEALS

Regardless of type, when constructing a flashlamp or arc lamp it is important that the final product shall be a hermetic structure, that is to say the quartz envelope and the electrode assembly must make a gas and vacuum tight seal. The seals commonly used in flashlamp construction fall into three categories: ribbon seal, solder (end cap) seal, and rod (graded) seal.

Ribbon Seal

With this seal the quartz is bonded directly to a thin strip of molybdenum foil. This thin strip is necessary to prevent cracking of the seal due to the unequal expansion and contraction rates between quartz and molybdenum. As there are no intermediate sealing glasses used, the full thermal potential of quartz can be realized. It is also a very robust and strong seal. One advantage of the ribbon seal is that lamps constructed using this technique have minimal dead volume. The importance of this will be discussed later.

Ribbon seals have been extensively employed in the manufacturing of high pressure mercury/xenon compact arc lamps. At least one manufacturer uses them for a series of krypton arc lamps. The limitation and disadvantage of lamps using ribbon seals is the low peak and RMS currents that can be passed through the thin molybdenum ribbons used in the seals, effectively precluding them from being used in pulsed flashlamps.

Solder (End Cap) Seal

These seals use a technique that allows a bond to be made between a circular band of invar and the quartz tube that is the lamp envelope. The seal is made using a lead indium solder with a melting point of 350°C. Like the ribbon seal, lamps can be constructed with very small dead volumes. Other advantages include high mechanical strength over other seals and very high peak current capability, potentially the highest of all the seal types.

The disadvantage of the solder seal is its low service temperature, typically 100°C, this not only affects lamp operating conditions but also prevents any high temperature vacuum processing during manufacturing. Also, long term shelf life is questionable due to the possible porosity of the solder seal. Ribbon or rod seals have a virtually unlimited shelf life.

Rod (Graded) Seal

Among the group of seals that physically bond quartz/glass to metal is one universally known as the rod seal. This bonding is accomplished by a transition glass that is wetted to the un-oxidized surface of the tungsten, giving rise to its other name, the bright seal. This design is extensively used in flashlamps for solid state laser pumping because of its high reliability, high peak and RMS current capability.

This seal technology allows high temperature, high vacuum processing to be carried out during the evacuation and gas fill stages of lamp manufacturing, ensuring a reliable product where batch to batch variation is kept to a minimum. Like the ribbon seal, virtually the full thermal potential of silica tubing can be realized.

Although short-term operation of the seal area at 600 °C is possible, for long-term service temperatures must not exceed 300 °C. At temperatures greater than 300 °C oxidization of the tungsten lead-in wire will cause the seal to fail. When high peak currents and fast rise times are encountered, or large bore lamps are to be constructed, a useful and elegant variant of the rod seal called the reentrant seal is used.

Examples of this seal are to be found in the QDX, QDF and the large bore QXA lamp series which appear in the second section of this brochure. Here the seal is effectively under compression during the shock wave created by lamp operation.

ELECTRODES

The most important component in a flashlamp is the cathode. The anode is of minor importance, providing the necessary design criteria are adhered to. The choice of materials used in the construction of electrodes for flashlamps and arc lamps has to be made very carefully. At the anode the main concern is power loading due to electron bombardment from the arc, while the cathode must be able to supply an adequate amount of electrons (low work function) without damage to its surface (sputtering).

Cathodes

Cathodes are commonly constructed using some type of dispenser method. This typically takes the form of a porous tungsten matrix filled with a barium based compound to give a low work function. Most manufacturers have their own proprietary methods for producing cathodes although the ancestry of most can be traced back the original Philips' cathode.

There are many cathode variations available from which the lamp designer may choose, each having a particular merit making it appropriate for a particular application. For example the designer may specify a cathode having an abundant availability of emissive compounds for use in a DC arc lamp, but when specifying a cathode for a high peak power application, a cathode with a limited amount of emissive compound would be chosen. Cathodes need to be chosen with extreme care for operation in the millisecond regime as the arc can strip off large amounts of cathode material, drastically shortening lifetime.

Excelitas developed a number of proprietary cathodes that offer outstanding lifetimes under these harsh conditions.

Anodes

The main criteria the designer has to consider when specifying the anode design for a flashlamp or arc lamp is that it has a sufficient mass or surface area to cope with the given power level. Anodes are made from either pure tungsten or lanthanated tungsten, the latter being frequently chosen as the lanthanum content improves its machinability.

Other Considerations

The shape of a flashlamp electrode is generally determined by the service conditions it will encounter. The most striking example being the difference between a DC krypton arc lamp and a pulsed xenon flashlamp. In the case of the arc lamp, the cathode is pointed, not only to ensure arc attachment well away from the walls of the lamp, but also to create the correct temperature necessary for true thermionic emission. On the other hand the pulsed xenon flashlamp generally employs a cathode with a flattened radius.

Every attempt is made to prevent the formation of hot spots that could give rise to the sputtering of cathode material during operation. These considerations are necessary given that a pulsed device could possibly be handling peak currents in excess of 1,000 amps, whereas the DC arc lamp is operating under steady state conditions of 15 to 40 amps.

Another difference encountered in electrode design is dictated by low and high average power operating conditions. In the case of low average power operation there will be very little heating effect at the electrodes, although peak powers can be extremely high. Consequently the electrode structures can be quite small. Examples of these electrode styles can be found in the QXA range of flashlamps in the second section of this brochure. For high average power operation provision has to be made to extract as much heat as possible from the electrode. This is generally achieved by shrinking a portion of the lamp envelope on to the electrode surface. Examples of this type of construction can be found in the QXF range of flashlamps in the second section of this brochure. To cool the electrodes under these high average power conditions demineralized water is channelled over the lamp's surface, thus removing heat not only from the electrodes but also from the envelope itself.

Providing adequate vacuum degassing has been carried out during lamp manufacturing it is relatively unimportant how hot the anode runs during operation. On the other hand it is of paramount importance that the cathode is not allowed to overheat as this will seriously reduce lamp lifetime.

COOLING CONSIDERATIONS

Lamps operated at low input energies and at low flash rates seldom require special cooling considerations. Heat from the lamp envelope and electrodes is lost by natural radiation. However, as the input power and the flash rate is increased there will come a point where some method of accelerating heat removal from the lamp must be considered. Most commercial pulsed Nd:YAG lasers and all DC arc lamp pumped Nd:YAG lasers require liquid cooling. Liquid cooling is normally achieved by flowing demineralized water over the lamp at approximately 4-10 liter per minute. The water is channelled over the lamp by use of a ‘flow tube’.

All envelope materials have a maximum power loading that is expressed in W/cm^2. This maximum not only depends on whether it is convection, forced air or liquid cooled but also on the type of quartz used. When liquid cooling is specified, deionized water has been found the most suitable. Ordinary tap water is not usable as it is highly conductive and will short out the trigger pulse causing unreliable lamp operation. In addition it will cause severe electrolysis when lamp connectors are totally immersed in the coolant, e.g. DC krypton arc lamps. The water must have a resistivity of 200 kOhms or greater. Only stainless steel and plastic components can be used in the water circuit.

When forced air-cooling flashlamps, the air blast must extend to the ends of the lamp and include the seals and connectors. Preferably the air should be filtered. Forced air cooling is not often encountered in Nd:YAG laser pumping applications.

Power Loadings

The cooling requirement for flashlamps and DC arc lamps used for laser applications are well defined. To determine the method necessary for correct lamp cooling, divide the average input power in watts into the internal wall area (cm^2) bounded by the arc length. The resulting quotient is in watts per cm^2.

Loadings assume xenon gas fill. Due to higher internal temperatures derate by 10% for krypton. In fluid cooled applications with adequate cooling of electrodes the quoted permissible wall loadings are often exceeded by large margins. Conversely, as these loadings are for new lamps, they will require derating as they age, or a safety margin built in to allow for absorption due to sputtered deposits from electrodes or solarization.

Failure to adequately cool flashlamps will result in unreliable operation and shortened lifetimes.

If between:

0-15 watts/cm^2 convection cooling is sufficient

15-30 watts/cm^2 forced air cooling is recommended. Liquid cooling should be considered at 15 watts/cm^2 if lamp is operated in a confined environment i.e. laser pump cavity

30-320 watts/cm^2 liquid cooling must be used

The approximate upper limits for various envelope materials are:

Doped quartz (UV absorbing) 1 mm wall thickness, 160 watts/cm^2

Clear fused quartz 1 mm wall thickness, 200 watts/cm^2

Synthetic quartz 1 mm wall thickness, 240 watts/cm^2

Clear fused quartz 0.5 mm wall thickness, 320 watts/cm^2

FILLING GAS AND PRESSURE

Xenon and krypton are normally chosen as the filling gases for DC and pulsed flashlamps. Xenon is more commonly encountered because of its higher overall conversion efficiency, especially when used in lamps for pulsed solid state laser systems. However at low power densities, krypton provides a better match to Nd:YAG than xenon. This is due to the excellent overlap between the absorption bands of YAG and the strong line radiation from low power density krypton, even though the overall efficiency is poorer than xenon. Examples of lamps that exploit this effect are the QCW krypton arc lamps and the QJK pulsed krypton flashlamps.

Fill Pressure

Generally the higher the fill pressure the higher the efficiency for laser pumping. For pulsed lamps the highest practical pressure is approximately 3000 torr. Above this, triggering can be a major problem. Usually pressures greater than 760 torr are only found in small lamps (3-5 mm bore) operating at moderate power densities. Efficiency considerations aside, fill pressure can be altered to modify the lamp's electrical parameters, for example lower pressures allow for lower trigger and bank voltages, although at low pressures below 100 torr, cathode sputter can become a major problem.

The lamp's impedance characteristic is also affected by fill pressure. Typical fill pressures encountered in flash and arc lamps are as follows:

- General purpose flashlamps 450 torr xenon
- Krypton DC arc lamps 4 atmospheres
- Pulsed krypton flashlamps 700 torr
- Xenon compact arc flashlamps 1-3 atmospheres

Dead Volume

Earlier in the text, mention was made of the dead volume in a lamps construction. This is defined as the non-active internal area of the lamp, i.e. the internal volume from the electrode tip to the seal.

Although a lamp is manufactured with a given cold fill pressure in operation this pressure will rise as current density is increased. It follows that a lamp having a large dead volume will attain a lower pressure during operation than a lamp with a small dead volume and that the efficiency of the latter will be greater.

Dead volume effects are very important on high average power lamps, e.g. DC krypton arc lamps, high average power pulsed lamps and especially lamps where pulse durations exceed several milliseconds. In the case of a DC krypton arc lamp, consider two lamps, both having the same arc length and internal diameter, but differing on the mount of dead volume. Note that dead volume includes not only the area behind the electrode but also the length of the electrode. Both lamps can be made to operate with near identical volt ampere curves but the fill pressures can show as much as 2 atmospheres difference.

Lamp Impedance – K_o

There are a number of ways to express lamp impedance. Perhaps the most common is the parameter K_o, shown as ohms (amps$^{0.5}$). K_o is dependant upon lamp geometry (arc length and internal diameter), gas fill, and gas type. It is also influenced by lamp dead volume.

During lamp operation K_o will, given equal arc length, internal diameter and cold fill pressure. It will also be lower in a lamp with a large dead volume than one with a smaller dead volume due to the difference in the fill pressures of the lamps during operation.

It is important to realise that the values of K_o calculated from equation 2-3 are only a notional indication of the lamp's impedance as the calculation is performed only for the arc length and does not take into account any dead volume into which the fill gas can expand during lamp operation, effectively preventing K_o from obtaining its calculated value. However, although this deviation is dependent on pulse duration, energy and arc diameter, in real terms only occasional problems are encountered between calculated and actual component values and operating voltages for correct lamp operation.

Figures B to D show how K_o scales against gas type, pressure, internal diameter (bore) and arc length.

It can be seen that K_o is inversely proportional to the lamp internal diameter (d) not to d^2 and that it is proportional to arc length. K_o is also a fairly weak function of pressure. For example, if in a given flashlamp it is necessary to change the fill gas from xenon to krypton, and maintain the same lamp impedance, then an approximate 70% pressure increase will be necessary for krypton, although there is only a 12% relative difference in the lamp impedance between xenon and krypton at the same pressure.

The K_o parameter is discussed further later in the text.

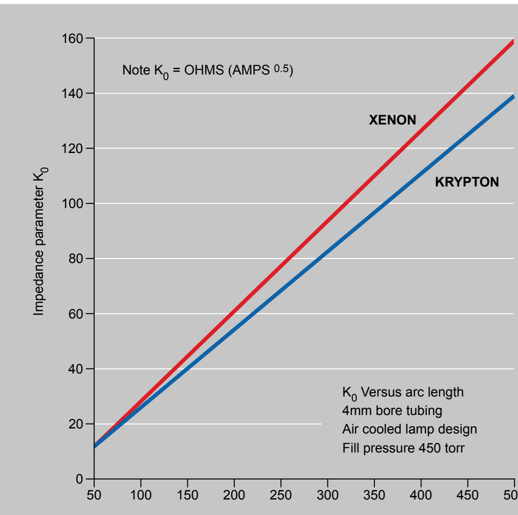


Figure B

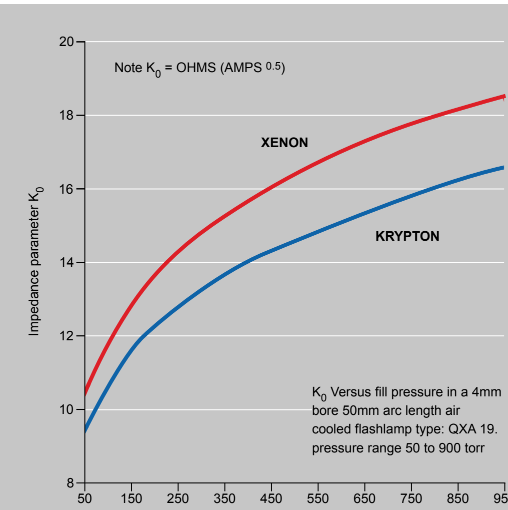


Figure C

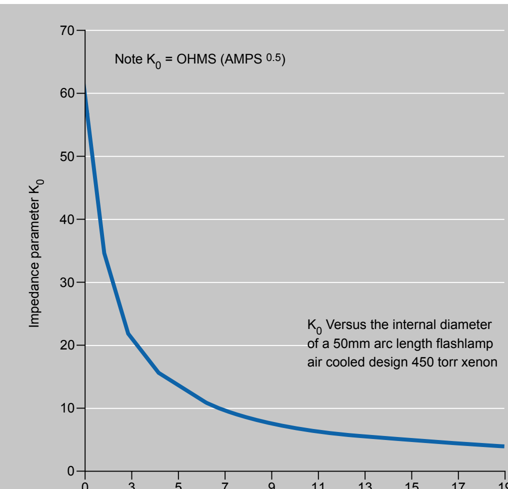


Figure D

PLASMA PHYSICS

Although the physics of an arc plasma is complex, a basic model is presented in order to explain several dynamic properties of pulsed and DC lamps. Please refer to Figure E: "Cathode Sheath and Plasma Dynamics".

Of the four states of matter, (solid, liquid, gas and plasma), plasmas operate at the highest observable temperatures. At the centre of the lamp axis, xenon and krypton temperatures may reach 10,000 Kelvin. This temperature falls rapidly in the radial direction where it may reach 1200 to 1500 Kelvin very near the surface of the quartz, which is below the softening point of 1940 Kelvin for SiO_2.

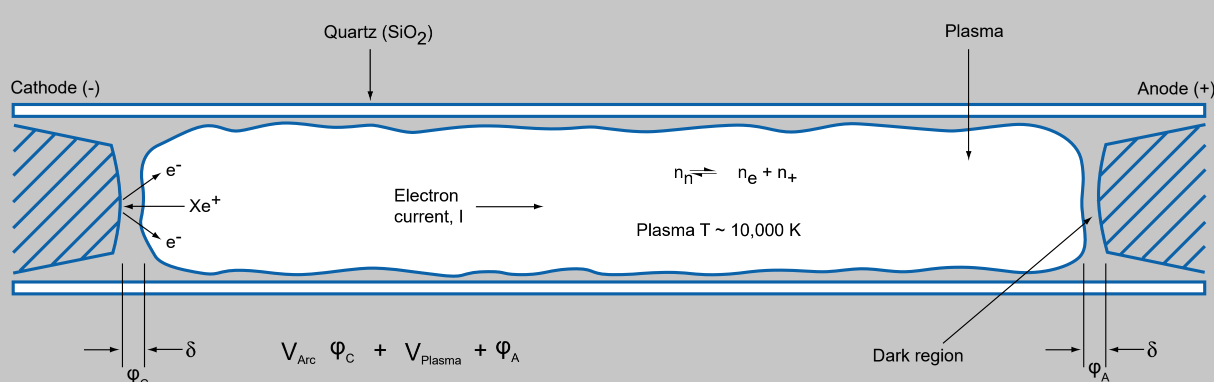
Because electrons are much more mobile than the positively charged Xe^+ or Kr^+ ions, they are found in large concentrations near the inside surface of the quartz, making the inner wall electronegative. The electronegative attraction causes a migration of ions to the inner surface where electronion recombination occurs. The high electronion recombination at the inner wall results in a large population of neutral Xe or Kr atoms, which have a much lower temperature than ionized particles, and therefore acts as a thermal buffer between the arc plasma and the inner wall of the quartz.

Inside the arc plasma, three species of particles exist at any given time: electrons, positively charged ions and neutral atoms. The concentration of ionized atoms is less than 1% and accounts for all the emitted light energy. Ions travel from the anode to the cathode, while electrons travel from the cathode to the anode.

The damage observed at the cathode and anode are produced by different mechanisms. We will discuss only the effect upon the cathode. Very near the cathode surface, there exists a thin region, d, of ion current whose distance from the cathode surface to the light emitting region of the plasma is on the order of tens of microns. We call this the dark region. It is preoccupied with an abundance of ionized atoms which experience a voltage, called the sheath voltage, j_c. The sheath voltage may be five to fifteen volts and accelerates the ions into the cathode surface. The heavy ionized particles strike the cathode surface with enough energy to cause physical damage and are the primary limitation of cathode lifetime.

Finally, full voltage measured across a lamp while it is operating is the sum of the voltage drops across the anode and cathode electrodes, the anode and cathode sheath voltages and the plasma voltage.

Cathode Sheath and Plasma Dynamics



Notes:

1 Electrons have higher mobility that ions
2 Electron oscillations > 1GHz
3 Ion oscillations ~ Mhz
4 φ_C = Cathode sheath voltage (~5-15 Volts)
5 φ_A = Anode sheath voltage
6 Electron emisson at cathode surface: = Thermionic + Field Emission + Photoelectric
7 Cathode surface damage is induced by ion bombardment. Acceleration of ions applied by Cathode sheath voltage
8 Ionization of neutral xenon or krypton atoms <1%
9 δ = tens of microns: increases as mean free path increrases; mean free path increases as pressure decreases
10 Lamp current, 1, is maintained by power supply
11 Lamp current and ion current are balanced in the arc
12 n_n = number of neutral atoms, n_e = number of electrons and n_+ = number of ionized xenon or krypton atoms

Power balance at the cathode surface:

Qnet = (heat of condensation) - (heat of evaporation)
Qnet = (Qc + Qe) - (Qt + Qn + Qm)
Qnet = net equilibrium heat flux into the cathode surface
Qc = heat added to the surface by ion bombardment
Qe = heat added from plasma electrons
Qt = heat removed by evaporation of thermionic and field electrons
Qn = heat removal by neutral ions in recombination with electrons
Qm = heat removed by evaporation of Barium atoms

Net cathode surface temperature is approximately 2000K

Figure E

SPECTRAL OUTPUT

Flashlamps and arc lamps emit an optical spectrum that covers a wide range of wavelengths. These extend from the UV cut off of the envelope material 160-381 nm, to the gradual IR cut off at approximately 2.5mm although the energy contained at these extremes is small.

The radiation produced by flash and arc lamps is primarily dependent on current density and to a lesser extent on the gas type and pressure (mercury and halide lamps excepted). At low current densities there is atomic line radiation corresponding to bound-bound energy state transitions. At higher current densities continuum radiation predominates resulting from free-bound and free-free transitions with the line structure now observed as small deviations in the spectrum dominated by continuum radiation. At high current densities the output approximates to a black body radiator of 9500°C.

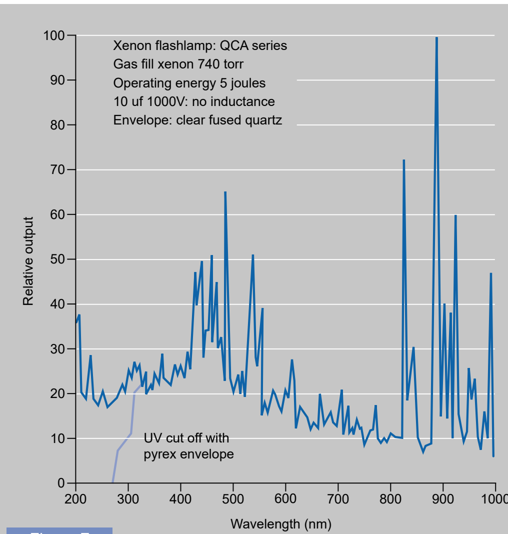


Figure F

Efficiency

The conversion of electrical input power into radiated optical power for xenon flashlamps between 200 nm -1100 nm is approximately 50%. Generally the efficiency improves with increasing current density and gas fill pressure providing the lamps are operated from high efficiency impedance matched circuits. Xenon converts approximately 10% more electrical input power into radiated optical power than krypton.

Spectral Output Graphs

Figures F to K show nominal spectral 'footprints' for xenon and krypton flashlamps and arc lamps under various conditions.

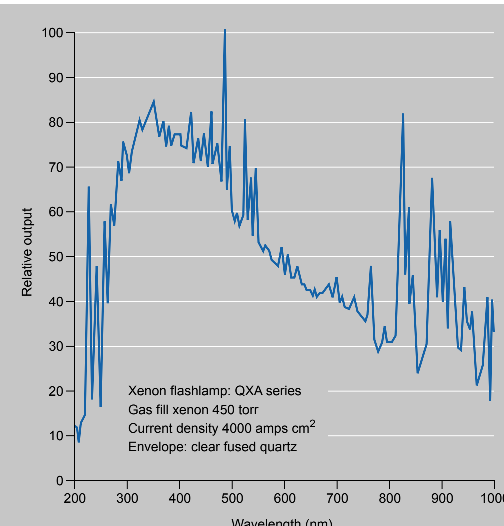


Figure G

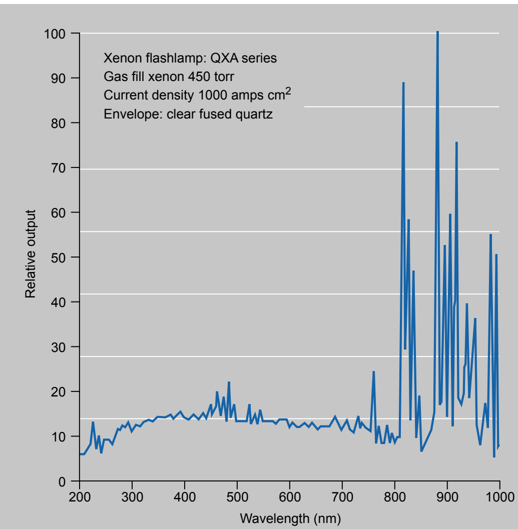


Figure H

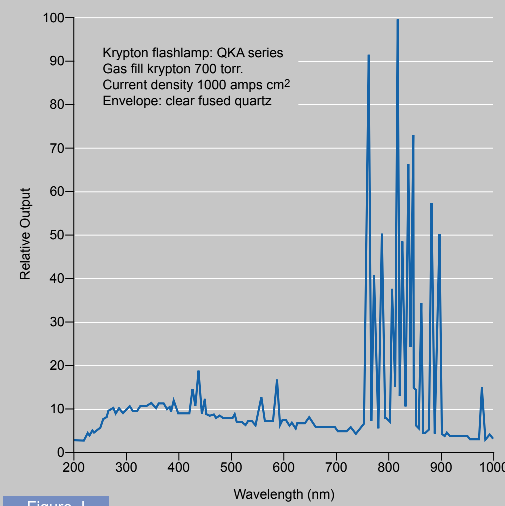


Figure J

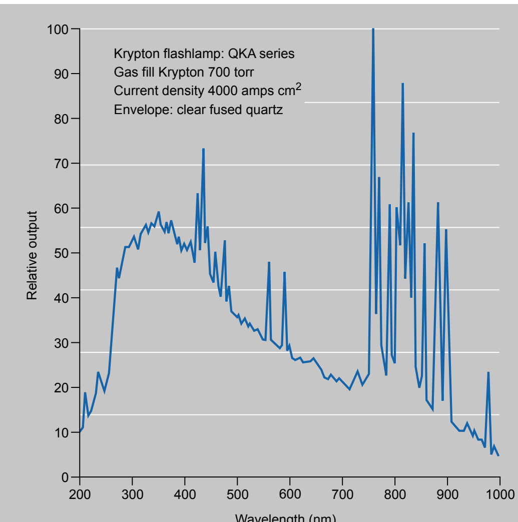


Figure I

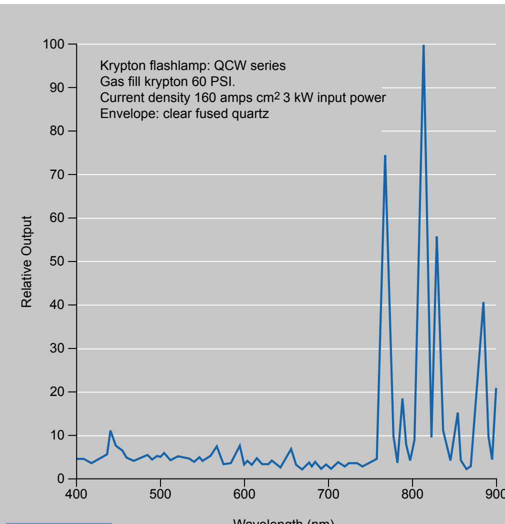


Figure K

TRIGGERING

In most flashlamp circuits the voltage on the energy storage capacitor is lower than the lamp self-flash threshold. In common with other gas discharge devices, flash and arc lamps exhibit extremely high resistance in their non-conducting state. In order for the lamp to conduct, a spark streamer is formed between the electrodes. This is accomplished by the application of a high-voltage trigger pulse.

A number of trigger techniques in current use are shown in Figures M to T (pages 15-17).

The trigger process occurs in several stages. Initially a spark streamer is formed between one or both electrodes and the inside wall of the lamp. This spark then propagates by capacitive effects along the inside wall of the lamp to the other electrode. If the voltage drop between the electrodes formed by this trigger streamer is lower than the capacitor voltage then the lamp will conduct.

Regardless of the trigger method used the process depends on the presence of a voltage gradient or reference plane on or near the lamp's surface. Without it, reliable triggering cannot be guaranteed. This reference plane can take the form of a nickel wire wrapped round the outside of the lamp (external trigger) or the metallic structure of the laser cavity and cooling water (series trigger).

It is difficult to accurately define trigger pulse requirements. Not only must the trigger voltage be correct but also the length of time required for the trigger streamer to form has to be taken into account. This is generally 60 ns per cm of arc length. If the trigger pulse is not present for long enough, triggering will be erratic, even at high trigger voltages.

Each lamp type will have a different trigger curve similar to the one shown in Figure L. However, even with careful quality control during lamp manufacture, lamps of the same type, even from the same batch, will show some variation from the expected curve. The scatter will be greatest at the extremes of lamp V_{min} and V_{max}. Generally the trigger voltage should be at least 60% above that required to start most lamps of a given type.

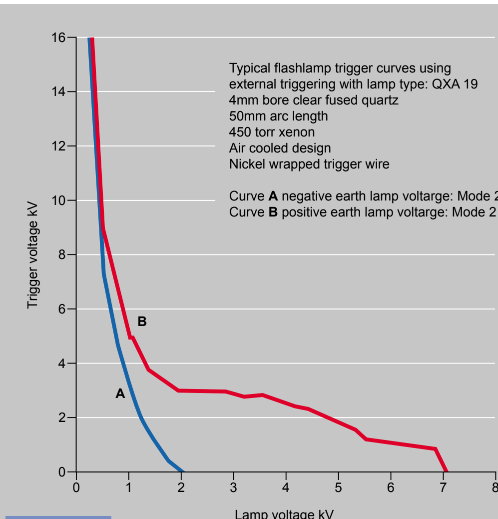


Figure L

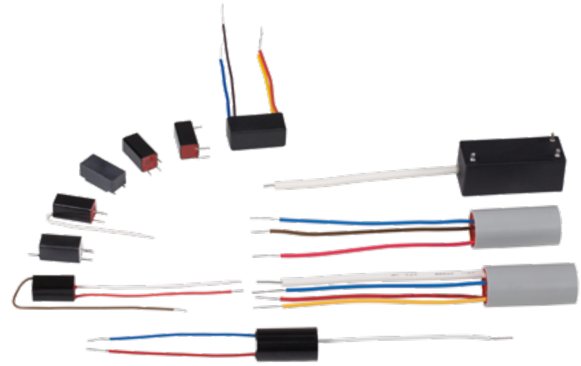
In addition to having the correct trigger voltage, the relative polarity of the trigger and capacitor voltages should be observed as shown in Table 1.

Trigger Mode	Common Electrode	Power Supply Polarity	Trigger Polarity External	Trigger Polarity Series
1	Cathode	Positive	Positive	Negative
2	Cathode	Positive	Negative	Positive
3	Anode	Negative	Positive	Negative
4	Anode	Negative	Negative	Positive

Table 1

Common Used Trigger Coils For External Parallel Triggering

Type	Sec. Voltage max. (kV) unloaded
ZS1052-1(H)	12
ZS1052-4 UL(H)	12
ZS1052-11(H)	12
ZS1624-1(H)	22
ZS1324-20V-LUL(H)	20
ZS1324-24V-LUL-4(H)	24
ZS1031(H)	26
ZS1032 UL(H)	26



For detailed product information regarding **High-Power Water-Cooled Flashlamps** please click or scan:

MODULATED CW AND QUASI-CW

External Trigger

Applicable to air cooled lamps only, a high voltage trigger pulse from a step up trigger transformer is applied to nickel wire wrapped around the outside of the lamp, it is the simplest, cheapest and least difficult of all trigger methods to implement. The external trigger transformer is a small, lightweight component. External trigger permits greater circuit design flexibility as the transformer is outside the main discharge loop. External trigger is not often encountered in industrial solid state lasers, although it is used extensively for flashlamps used for photographic applications, stroboscopes, high speed fast rise time flashlamps and single shot low average power laser systems, i.e laser range finders. It's main disadvantage is that a high voltage is present on the outside of the lamp, making insulation difficult if, for example, the lamp is used in a metal laser cavity.

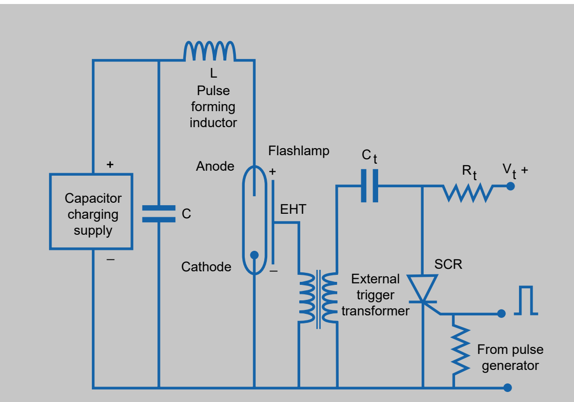


Figure M

Series Triggering

The high voltage end of the series trigger transformer secondary is connected directly to one of the lamp electrodes. After triggering lamp current flows through the trigger transformer secondary, this acting as part or all of the pulse forming inductor. Consequently the series trigger transformer is a larger, heavier and expensive item compared to an external trigger transformer. Series triggering is used extensively in industrial high average power solid state laser systems. It offers better long term reliability compared to external triggering and has the advantage that no high voltages are present on the outside of the lamp. Triggering also takes place at lower capacitor charging voltages. As the trigger transformer primary has a very low impedance the trigger SCR must be able to handle high peak currents (greater than 1500 amps). Snubber components are usually incorporated to protect the SCR.

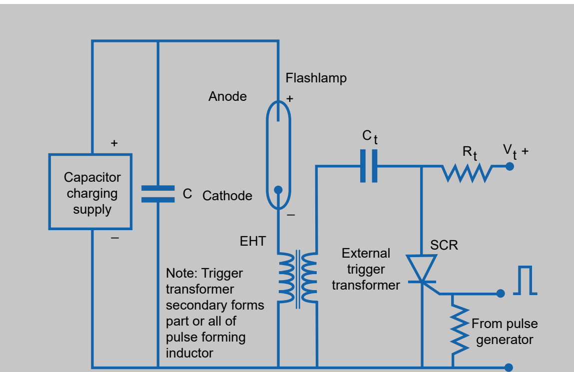


Figure N

Simmer Operation

After triggering a low current DC discharge is maintained through the lamp (simmer). Typically this is 50-500 milliamps. Lamp pulsing is controlled by an SCR in the main discharge loop. Trigger methods (simmer strike) can be series or external. Simmer mode operation generally extends lamp lifetimes and is often used in high power, high repetition rate applications including most industrial solid state laser systems. Delay circuitry is normally needed in the capacitor charging supply in order to allow the SCR to fully turn off following lamp pulsing. Snubber components are normally required to protect the SCR peak. As the control SCR handles high peak and RMS currents it must be selected with care. Simmer current and voltage must be in the correct region of the lamp's VI curve if stable simmer is to be achieved. Simmer also offers higher laser pumping efficiency of up to 20% at low current densities. This advantage disappears at high current densities. Another benefit is improved pulse to pulse optical output stability.

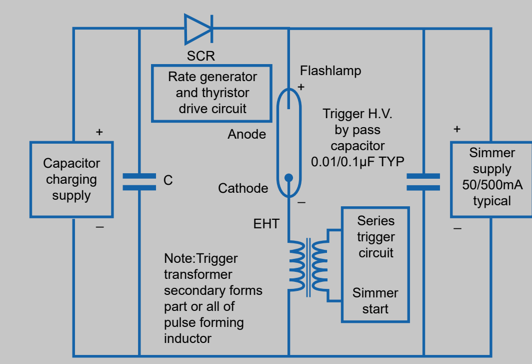


Figure O

Pseudo Simmer

In portable equipment, or situations where the maintenance of a low current DC discharge through the lamp would be power prohibitive, many of the advantages of simmer operation can be obtained by using a technique known as pseudo simmer. The lamp is triggered conventionally using external or series triggering. Current from the energy storage capacitor is initially limited to approximately 50 milliamps by resistor Rs. After a delay of approximately 100-200ms Rs is shorted out by the SCR and the main discharge occurs. As lamp current flows through the SCR it must be selected with care. Snubber components are normally required to protect the SCR. Pseudo simmer is often used in laser range finders and other applications where improved pulse to pulse repeatability of light output is required. It also prevents the overheating of the relatively small cathodes used in convection cooled flashlamps that can occur when using normal simmer operation.

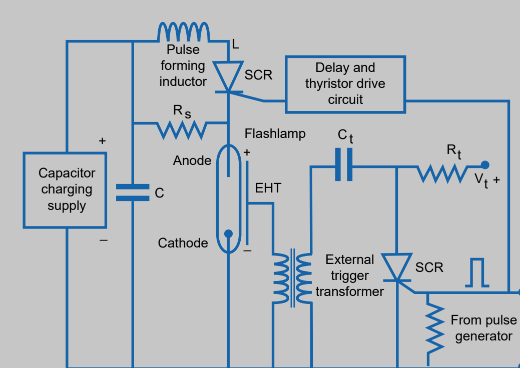


Figure P

Shunt Diode

It is desirable to choose capacitance, inductance and voltage to give a critically damped pulse at a given pulse duration. Generally with high impedance lamps normally used for YAG laser pumping this is never a problem. When it is not possible to design for critical damping and lamp current is oscillatory, a shunt diode across the energy storage capacity ensures that energy stored in the inductor (trigger transformer) is transferred through the lamp rather than back through the capacitor as negative voltage. The diode must be able to handle high peak and RMS currents. It should be connected directly across the energy storage capacitor and a 0.1 mf snubber capacitor connected across the diode to bypass high transient voltages. Typical lamp circuits requiring this kind of treatment are those operating compact arc flashlamps such as the QCA series.

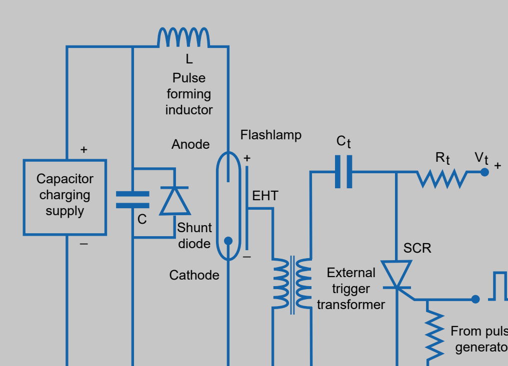


Figure Q

Fast Rise Time Operation

When high-energy short pulse durations are required (less than 10 microseconds), calculations normally indicate small values for the energy storage capacitor (typically 0.5-10 mf). Consequently capacitor voltage is frequently well above the lamp's self flash voltage threshold. The lamp must therefore be isolated from the storage capacitor until lamp pulsing is required. This is normally achieved by using a triggered spark gap ignatron or hydrogen thyratron (spark gap operation shown). Due to the high voltages and currents associated with high-energy short pulse duration operation, solid state switches (SCR) cannot normally be used. In order to obtain the fastest lifetimes all circuit inductance must be minimised. Longest lamp lifetimes under these harsh conditions are realised using simmer operations.

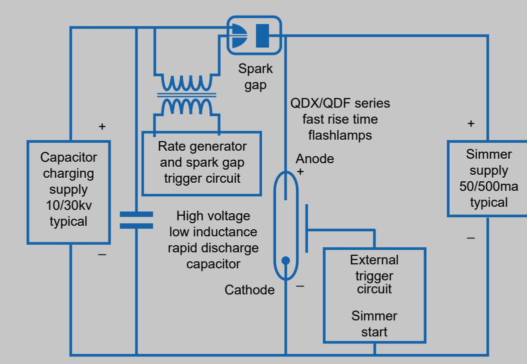


Figure R

Variable Pulse Width Control

Stepless control over pulse duration is possible by running the lamp under simmer and using a high power, high current, high voltage NPN transistor to control lamp pulsing over a wide range of pulse durations; from 500 microseconds to over 20 milliseconds. The lamp is triggered using conventional series or external trigger techniques. Simmer current is normally in the range 0.5-3 amps. Snubber components will normally be needed across switching transistor and blocking guide. Care must be taken to prevent turn of transience associated with inductance in the trigger transformer. As control of pulse duration does not require inductance, external trigger can be used possibly by applying the high voltage trigger pulse directly to the cavity which is suitably insulated from ground. Note the use of floating simmer supply. Energy storage capacitors are electrolytic. Bank voltages are typically 300-600 volts. This lamp control technique is frequently used in high average power solid state laser systems.

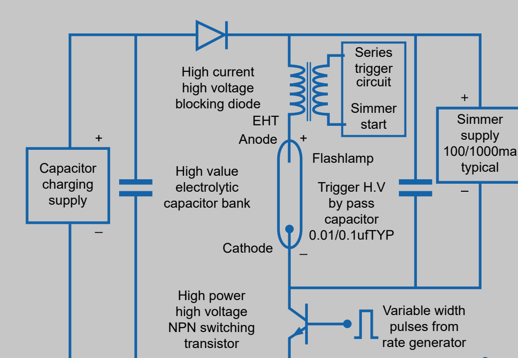


Figure S

DC Krypton Arc Lamp Circuits

DC krypton arc lamps need special circuit design considerations for satisfactory lamp operation. These lamps undergo three distinct phases during start up, namely trigger, boost and current control. Initially a trigger streamer is formed between the lamp electrodes using series triggering. Lamp impedance at this point is very high and the voltage drop across the lamp electrodes is not low enough to allow current to flow from the constant current supply with its relatively low open circuit voltage (say, 200 volts). The boost phase provides the bridge between the high impedance trigger streamer and the low impedance running condition. In the boost phase a small capacitor (47-100 mf charged to approximately 1000 volts) is discharged through the lamp via a current limiting resistor. The trigger streamer now grows in diameter and current and lamp voltage drops to a point where the constant current supply is able to take over and control the lamp.

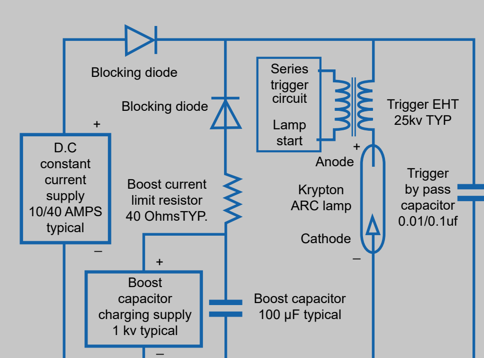


Figure T

OPERATION

CW lamps have recently proven to be effective for laser pumping and other applications when operated by the following two methods: Modulated CW and Quasi-CW. Therefore, there are now alternatives to the standard DC krypton arc lamps commonly operated at a fixed current.

Modulated CW

With this method of operation, a lamp is rapidly switched between a "simmer" current and a peak current; peak current is chosen for a particular application. When the lamp is not operational, a standby current is recommended. Peak current pulse durations are typically of the order of a few milliseconds, whereas the standby current may remain for several minutes. Duty cycles are commonly 50%. We recommend the following maximum and minimum values for the various currents given in Table 2. Figure U gives a typical pulse waveform for Modulated CW operation.

Bore (mm)	Recommended Maximum Peak Current (A)	Recommended Maximum Peak Current (A)	Minimum "Simmer" Current (A)	Minimum Standby Current (A)	Recommended Maximum Wall Loading (W/cm²)
3	12	10	1	5	320
4	24	20	2	10	320
5	33	30	3	15	320
6	45	40	5	20	320
7	56	50	10	28	320
8	73	65	20	33	320

Table 2

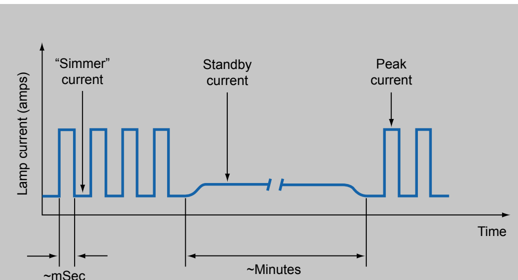


Figure U

Quasi-CW

Quasi-CW is a term given to the mode of operation whereby the driving current is sinusoidal. The most cost effective means of operating a CW lamp in Quasi-CW mode is to use the line (mains) frequency or a multiple thereof. A typical Quasi-CW waveform is given in Figure V. The "Depth of Modulation" is the deviation in current from the nominal value and the peak current. Depth of Modulation should not exceed 50% of the nominal. For best performance, lamps should not be operated above their recommended average power requirements.

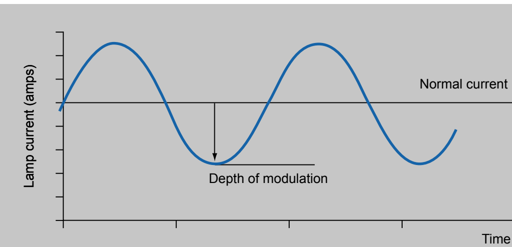


Figure V

PULSED FLASHLAMP CIRCUIT CALCULATIONS

Many pulsed flashlamps are operated from inductor/capacitor single mesh pulsed forming networks (PFN's) or electronic switching. For PFN operation, the values of inductance (L), capacitance (C), and capacitor charging voltage (V_o) are chosen to give a critically damped pulse of the desired duration and energy with a given lamp impedance (K_o). The pulse shape under conditions of critical damping will have a near gaussian profile. It is generally desirable to operate lamp/PFN's under conditions of critical damping. This will ensure the maximum energy transfer between lamp and PFN, also maximising lifetime.

For a given pulse width, energy and lamp impedance there is only one value of C, L and V that result in critical damping. The term a is conventionally taken to describe the pulse shape and is normally chosen to be 0.8 for critical damping.

If the lamp is to operate over a wide range of input energies, with C and L fixed (V_o varied to alter E_o), the circuit should be designed for critical damping at the maximum energy; the circuit will then become overdamped as V_o is reduced.

DESIGN PROCEDURE

The standard design procedure for flashlamp single mesh L/C drive networks was originated by J.P. Markiewicz and J.L. Emmett (reference 1).

The starting point for this design procedure is the volt ampere characteristic of a flashlamp that can be described as:

(1) $V = \pm K_o(i)^{0.5}$

Where
- V = voltage across flashlamp (volts)
- i = discharge current (amps)
- K_o = impedance parameter
- = ohms $(\text{amps})^{0.5}$

This equation is approximately true for current densities above 500 amps per cm^2. K_o is the impedance parameter and is determined primarily by lamp arc length, internal diameter, gas type and fill pressure.

(2) $K_o = 1.28\ (P/450)0.2\ l\,/\,d$ (xenon)

(3) $K_o = 1.28\ (P/450)0.2\ l\,/\,d$ (xenon)

Where
- P = fill pressure (torr)
- l = arc length (mm)
- d = bore diameter (mm)

For low loss circuit conditions C, L and V_o are calculated from the following equations:

(4) $$C = \frac{[2E_o\, a^4\, T^2]^{\ 0.33}}{K_o^{\,4}}$$

(5) $L = T^2 / C$

(6) $V_0 = (2E_o / C)^{0.5}$

Where
- C = storage capacitor (farads)
- L = total circuit inductance (henries)
- E_o = stored energy (joules)
- a = damping parameter 0.8 for critical damping (reference 1)
- V_o = voltage on storage capacitor (volts)
- T = 1/3 of pulse width (seconds)

(7) $= (LC)^{0.5}$

(8) total pulse duration = $3(LC)^{0.5}$ at 10% current points

Although equations (4), (5) and (6) make no allowance for arc dynamics (see reference 2) they are quite accurate for first order approximations, and are effective in predicting the shapes of current pulses.

The design steps are:

(a) With energy input, pulse duration and lamp K_o known C is found from equation (4).

(b) L is then calculated from equation (5)

(c) Finally V_o is calculated from equation (6)

Damping parameter a is given by:

(9) $K_o / (V_o Z_o)^{0.5}$

For critical damping in a low loss circuit the value assigned to a is normally 0.8. Practical limits are 0.7 – 1.1. Lower than 0.7 and current reversal is possible (circuit oscillatory, possible lamp damage). When using low impedance lamps and/or current reversal cannot be avoided use a shunt diode across the energy storage capacitor. See Figure Q (page 17).

Other relationships are:

(10) Peak current = $(V_o Z_o) / 2$ (amps)

(11) Circuit impedance $Z_o = (L/C)^{0.5}$ (ohms)

(12) Stored energy = $C(V^2) / 2$ (joules)

(13) Peak current density = ipk/A (amps/cm^2)

Where
- ipk = peak current (amps)
- A = lamp across sectional area (cm^2)

The calculation of peak current from (10) frequently results in an over estimation of peak current. This is because no allowance has been made for flashlamp resistance. This can be calculated from:

(14) $R_t = pl / A$

Where
- R_t = Flashlamp resistance (ohms)
- p = plasma resistivity
- = 0.015 for T x 100 ms
- = 0.02 for 100 ms > T x 1000 ms
- = 0.025 for T > 1000 ms
- A = cross sectional area of lamp (cm^2)
- l = arc length in cm
- T = 1/3 of pulse width (ms)

Equation (10) can then be rewritten to include (14) giving a more accurate estimation of peak current, especially when lamp current is not critically damped.

(15) Peak current $= V_o / (Z_o + R_t)$ (amps)

RC CALCULATIONS

A number of non critical lamp applications do not use LC PFN's (i.e.) photographic flash, stroboscopes, etc.). Such configurations are referred to as resistance capacitance (RC) lamp circuits. It is often necessary to calculate pulse duration and peak current of RC lamp circuits. The general arrangement is:

(16) $T = R_t C$

(17) Peak current = V_o/R_t (amps)

Where T = pulse duration at full width 1/3 height (seconds)
R_t = Lamp resistance (ohms)
C = capacitance (farads)
V_o = voltage on storage capacitor (volts)

Although results from (16) and (17) cannot be regarded as accurate, they will provide "ball park" figures.

CALCULATIONS AT SHORT PULSE DURATIONS

For the calculation of circuit conditions with lamps operating at short pulse durations use equations (4), (5) and (6) with the following notes:

(a) The calculated capacitor values will generally be larger than required for the chosen pulse duration. For total pulse duration in the range 1-10 ms reduce the calculated capacitance by 4. In the ranges of 11-20 ms, reduce it by 2. These corrections appear to be on a sliding scale with large corrections below 1 ms. Recalculate for V_o with the new capacitor value.

(b) Assume total circuit inductance of approximately 1 mH. All unintentional inductance must be carefully controlled. QDX/QDF lamps can be supplied terminated with special coaxial cable.

(c) At short pulse durations the arc may never completely fill the lamp bore. The estimated diameter is approximately 50%-70% of bore diameter. This gives an apparent increase in the value for K_o accounting for the errors noted in (a).

SIMMER VOLTAGE CALCULATIONS

It is very difficult to simply quantify simmer voltages. The standard equation $V = \pm K_o (i)^{0.5}$ will not work under simmer conditions as the arc diameter does not fill the bore. The standard equation will predict simmer voltages far lower than test measurements would indicate. In order to make an approximation of simmer voltage we need to know the diameter of the arc for a given simmer current. We can then use this to modify impedance parameter K_o (it will become a much higher value) and thus predict a more accurate simmer voltage. The equations are simplifications of those given by Dishington (reference 2).

(18) $V_s = K_o(d/d_a)\,(i_s)^{0.5}$

Where V_s = Lamp simmer voltage
K_o = Lamp impedance constant
d = Lamp bore (ID)mm
d_a = Arc diameter mm
i_s = Simmer current amps

(19) Arc diameter d_a is given empirically by: $d_a = (i_s)^{0.8}\,1.8$

The arrangement holds only while d_a is in the free arc regime. The transition point is approximately d x 0.7.

It should be stressed that the answers obtained from this simple approach will be an approximation only. There are many factors that will affect any measured simmer voltage. These would include gas pressure increase due to temperature rise within lamp and cathode condition. It is not uncommon to find simmer voltages varying by as much as 150 volts due to the arc attachment point moving around the cathode surface. This is most noticeable when relatively low simmer currents are being used (around 50 milliamps).

KRYPTON ARC LAMP VOLTAGE CALCULATIONS

It is often necessary to predict lamp voltage or lamp input power as a function of varying lamp current. Figures W and X show measured and calculated voltage/current characteristics for two commonly used 4 and 6mm bore krypton arc lamps. In the range of normal operation the lamp is functioning in the region of positive resistance on its voltage/current characteristic. Under these conditions the discharge is wall stabilised and can be predicted by the following equation:

(20) $V = V_t - ((A_t - A) \times R_d)$

Where R_d = Dynamic impedance and is given empirically by

(21) $(V_t / A_t)\,/3.25 - b$

Other terms are:

V = lamp voltage
V_t = lamp voltage at test current
A_t = test current
A = desired lamp current
R_d = dynamic impedance (slope)
b = lamp bore in centimetres
R_s = static impedance normally specified at full power and is V_t / A_t

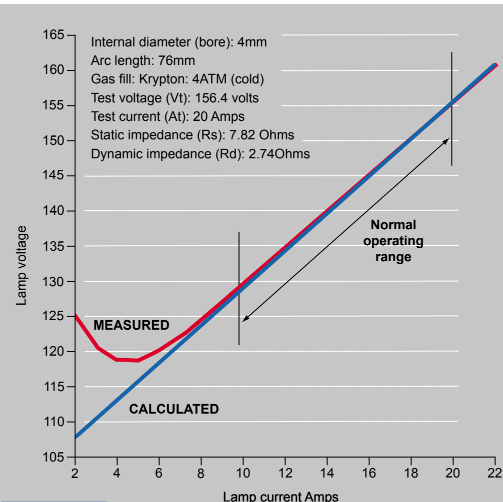


Figure W

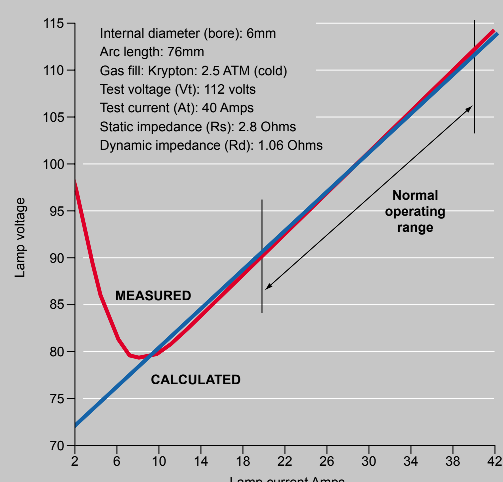


Figure X

V_t and A_t are the only parameters needed to describe the volt/ampere characteristics of krypton arc lamps operating in the normal positive slope of their specifications. These measurements are normally taken at full power by the lamp manufacturer as part of the lamp test programme and are be supplied with every lamp.

It will be noted that the equation is in error at the point where the arc diameter is contracting and the discharge is no longer wall stabilised. This occurs at approximately:

4 mm bore = 6 amps
5 mm bore = 8 amps
6 mm bore = 10 amps

Generally at these current levels the lamp will be operating well outside of its normal operating range. These errors are consequently of no significance.

FLASHLAMP LIFETIME

There is no general method available for the reliable estimation of flashlamp lifetimes. In the high energy regime, see Figure Y it is possible to predict with reasonable accuracy the expected lifetime using equation (22). In this high energy regime lifetime is primarily determined by the mechanical strength of the quartz tubing and the amount of degradation caused within the lamp by ablation of the quartz material.

In the low energy regime of Figure Y lifetime is primarily determined by electrode effects, principally that of sputtered material from the cathode. The sputtered deposits will slowly build up on the inside wall of the lamp, reducing output. Here lifetime prediction using equation (22) would result in greatly over estimating lamp lifetime. The curves of Figure Y give a general expectation of lifetimes in the low energy regime. Note the improvement with simmer operation.

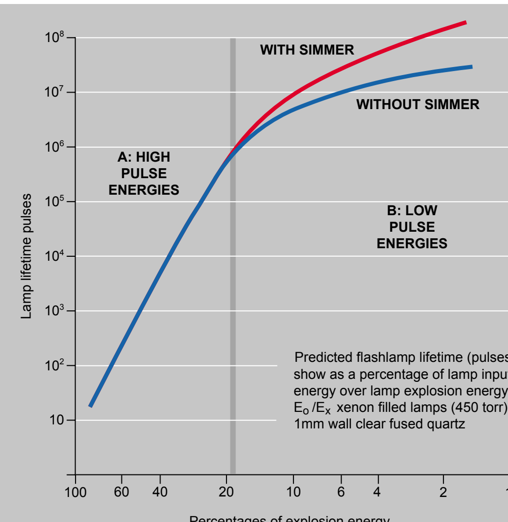


Figure Y

LIFETIME EXPECTATIONS AT SHORT PULSE DURATIONS

The driving circuitry for fast rise time, short pulse durations must be designed very carefully in order to get the maximum lifetime from the lamp.

Fast rise time, short pulse duration lamps such as the QDX and QDF series are normally operated beyond their self flash voltage and use either a spark gap, thyratron or ignatron to control lamp pulsing. These lamps are operated by over volting, frequently coupled with simmer and prepulse techniques. Conventional external triggering is not normally possible or recommended for long lifetime applications.

Regardless of the method of circuitry chosen to operate fast rise time lamps the prime consideration is to ensure that arc growth starts from a centrally located position relative to the wall of the lamp. Simmer or prepulse techniques will generally ensure a central arc placement prior to the main pulse. External triggering, although the most simple and cost effective, guides the arc to the lamp wall. If the arc growth starts on or near the lamp wall, given time and with sufficient energy serious ablation or erosion of the silica will take place. This not only weakens the lamp but also results in considerable deposits forming on the inside wall of the lamp substantially reducing light output. In addition large amounts of oxygen are released by the decomposition of the silica affecting lamp triggering and jitter times.

LIFETIME CALCULATIONS

High Energy Regime

The standard method used to determine flashlamp lifetimes in the high energy regime is to show operating energy (E_o) as a percentage of lamp single pulse explosion energy (E_x).

(22) Life pulses = $(E_o / E_x)^{-8.5}$

Where E_o = operating energy (joules)
E_x = lamps explosion energy (joules)

For example:

Life Pulses	% E_o / E_x
10^2	0.58
10^3	0.44
10^4	0.33
10^5	0.26
10^6	0.197

For a given lamp with a given set of operating conditions (E_x) can be calculated by using the single pulse explosion constant (K_e).

(23) $E_x = K_e\ (T)^{0.5}$ (joules)

Where K_e = lamp single pulse explosion constant
T=1 /3 pulse width in seconds

K_e can taken from data sheets or from the following:

(24) K_e = Q x *l* x d

Where Q = quartz tubing coefficient
24600 for d x 8 mm
21000 for d = 10-12 mm
20000 for d x 13 mm

l = arc length (cms)
d = bore diameter (cms)

Note: For QDX/QDF series lamps Q is doubled
For QHX series lamps Q is halved

Low Energy Regime

At percentages of (E_o/E_x) less than 0.197% or lifetimes greater than 10^6 we enter a region where lifetime is determined by electrode effects and long term erosion of the quartz wall. Here any calculation made by (18) must be considered suspect at anything greater than $3x10^6$ pulses. Reliable estimations of lamp lifetime are difficult and are often based on a rule of thumb approach or situ testing under the given conditions. An example of the rule of thumb approach is the graph of Figure Y.

It is important to keep lamp peak currents at or below 4000 amps per cm^2 for long lifetime applications if the long term erosion of quartz is to be avoided. See Figure Z.

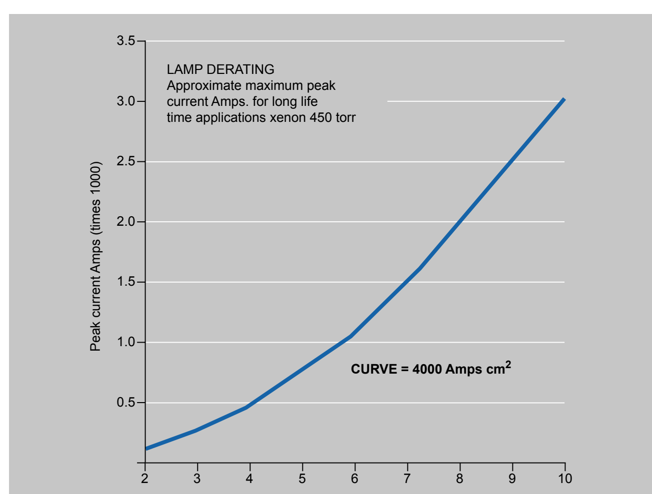


Figure Z

LAMP SELECTION

Assuming that the correct choice of lamp type has been made based on service requirements and assuming that pulse energy, pulse duration, arc length and lifetime have been set by system constraints, the dependant variable will be lamp bore. This may be determined from the following equations:

(25) $E_x = E_o / (l/Lp)^{1/8.5}$

(26) $K_e = E_x / T^{0.5}$

(27) $d = 4.06\ K_e^{10-3} / l$

Where:
E_x = Lamp explosion energy (joules)
E_o = Operating energy (joules)
L_p = Required lifetime pulses
K_e = Single pulse explosion constant
d = Lamp bore (mm)
d = Lamp bore (mm)
l = Arc length (mm)

The procedure is:

(a) Determine lamp explosion energy from equation (25).

(b) Calculate single pulse explosion constant from equation (26).

(c) Calculate lamp bore from equation (27). If an intermediate size is calculated, e.g. 6.5 mm, select next whole number bore size – e.g. 7 mm. Quartz tubing is generally only available with whole number bore sizes in mm.

The procedure is useful for lifetimes in the high-energy regime i.e. to approximately 3 x 106 (see Figure Y).

POWER LOADING AND COOLING

To determine the cooling method necessary for correct lamp operation, lamp average power and wall loading must be determined.

(28) $P_{ave} = E_o\ f$ (watts)

(29) $V_{ave} = P_{ave} / p/d$ (watts/cm^2)

Where:
P_{ave} = average power (watts)
V_{ave} = average wall loading (watts/cm2)
E_o = energy input to flashlamp (joules)
f = pulse repetition rate (pulses per second)
l = arc length (cm)
d = lamp internal diameter (cm)

The maximum permissible loadings for flashlamps and DC arc lamps can be summarised as follows:

Wall loadings between:

0-15 watts/cm^2 convection cooling can be used

15-30 watts/cm^2 forced air-cooling is recommended. Liquid cooling should be considered at 15 watts/cm^2 if lamp is operated in a confined environment i.e. laser cavity

30-320 watts/cm^2 liquid cooling must be used

Upper limits for silica envelope materials:

Doped quartz (UV absorbing) 1 mm wall thickness 160 watts/cm^2

Clear fused quartz 1 mm wall thickness 200 watts/cm^2

Synthetic quartz 1 mm wall thickness 240 watts/cm^2

Clear fused quartz 0.5 mm wall thickness 320 watts/cm^2

SQUARE PULSE OPERATION

The method of operating krypton and xenon large bore flashlamps for many milliseconds per pulse has become commonplace in the industrial laser industry. The technique is recognized by several names and is used in many non-laser industries as well. As these names may suggest, Square Pulse, Long Pulse and High Charge-Transfer operation offer a means of delivering high peak and mean powers from krypton and xenon flashlamps.

Charge transfer may exceed several Coulombs per pulse and high repetition rates (exceeding 300 Hz in some applications) are easily achievable. Pulse durations range from one to ten milliseconds, depending on the application. Under such operating conditions, many kilowatts may be generated in a single water-cooled flashlamp.

Figure P shows a typical circuit configuration where energy storage is maintained in the capacitor, C. A small percentage of the stored energy is released during each pulse, (usually less than 10%) and the voltage is maintained by the capacitor charging supply between pulses. Current and voltage waveforms of a typical 1.5 millisecond Square Pulse appear in Figure AA.

Excelitas engineers and scientists have developed a class of advanced cathodes for Square Pulse lamp operation in recent years. These advancements are identified by our Series 2000 cathode technology. Lamp lifetimes have been increased by a factor of three to five in many instances due to our advanced state-of-the-art cathodes.

K_O DISSUSSION

Many electrical engineers have attempted to model the impedance of a lamp, called K_o, using standard circuit simulation packages such as PSpice™. Unfortunately, one cannot accurately model the impedance of an arc plasma using a series or parallel combination of passive elements. This is because the plasma impedance is non-linear and changes with time for the case of a flashlamp.

Non-linear Plasma Resistivity

What then is meant by the term K_o? All plasmas exhibit a resistivity. Goncz[1] was the first to provide an accurate model for plasma resistivity in flashlamps in 1965. He showed that plasma resistivity is inversely proportional to the square root of current density. The non-linearity between lamp voltage and current, therefore, can be given by the empirical relationship, $V=K_oI^{1/2}$. However, this equation incorrectly implies that K_o is a constant, much like resistance in conductors. Unlike metals, xenon and krypton atoms do not have conduction, or valence, electrons. The "resistance" to the flow of electrons in a gaseous plasma involves a very different collision mechanism than with conductors. Therefore, we look for a region in the V-I curve of a lamp's plasma to approximate its impedance. From such observations, the expression for K_o is well known and appears in the Pulsed Flashlamp Circuit Calculations section.

Time-Dependence of Arc Growth

Figure AA shows voltage and current measurements for a single 1.5ms square pulse in an 8mm bore, 152mm arc length, krypton flashlamp at 440 Torr. By using the relation $K_o=V/I^{1/2}$, we produce the graph in Figure BB. One can readily see the linear region near 20 on the vertical scale. This region of constant lamp impedance is what we mean by K_o. In fact, the graph produces a meaningless result at 1.5ms where K_o nearly drops to zero. This is impossible and the dashed line provides the real result. K_o begins at a very high value just prior to a pulse, then drops rapidly as the plasma freely expands, then finds a linear region as the plasma encounters the inner wall of the tube. Near the end of the pulse, as the plasma column begins to collapse, K_o returns to a very high value at the end of the pulse indicated by the dashed line.

Therefore, lamp impedance is neither linear nor constant during a pulse. In the case of a wall-stabilized plasma, as described in the previous paragraph, there is a region of linearity which we refer to as K_o.

There is no table here, Figure AA relates to the graph headed 'Voltage/Current Waveforms' and Figure BB relates to the graph headed 'Lamp impedance'

Figure AA is also referred to under Square Pulse Technology.

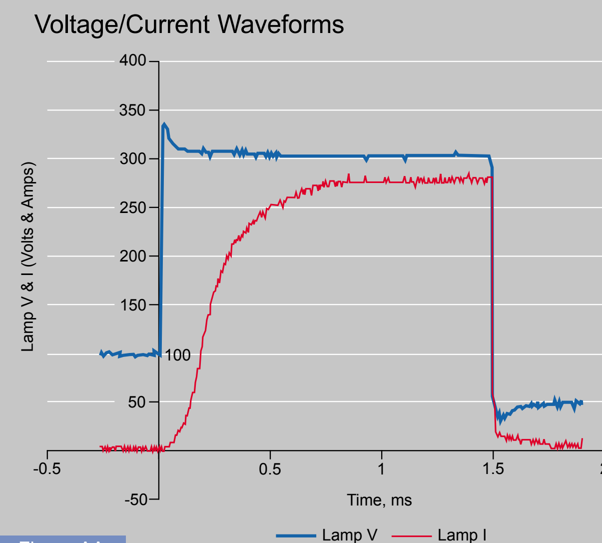


Figure AA

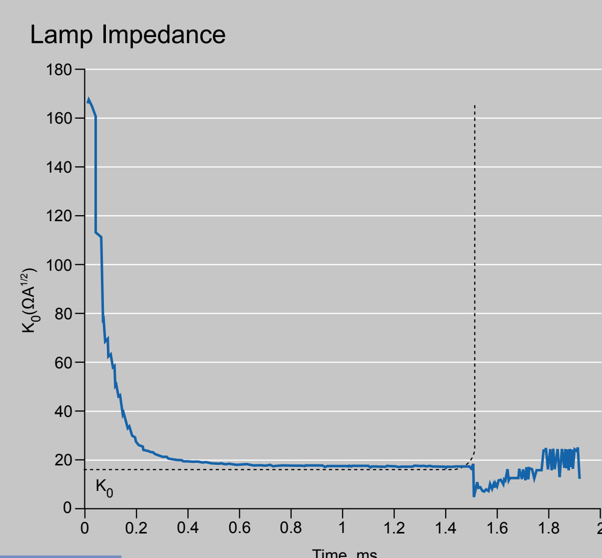


Figure BB

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2 Electronic Flash Strobe – Harold E. Edgerton. Published by MIT Press.

3 Solid State Laser Engineering – Waiter Koechner. Published by Springer-Verlag.

4 Pulsed Light Sources – I. S. Marshak. Published by Plenum Publishing Corporation New York.

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