A Giant Pulse Laser with a Triggerable Passive Q-Switch Performance

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Abstract:

A method of Ruby Laser operation is described which produces fast, intense and triggerable giant laser pulses by Q-switching with a selective saturable organic dye. The Ruby rod 5/8 inch in diameter and 7 inches long is used in an ellipsoid pump configuration. The passive Q-switch element is placed between the 90-deg rod with a TIR chisel and a separate end mirror. A double-pulse circuit energizes a linear flash tube. A pre-ionizing pulse fires the main capacitor bank. After a suitable delay a second trigger signal switches the energy of a 8-μF capacitor (E_{max} = 450 Joules) to the flash tube load. This short high-power pulse, now not current limited, will start laser action corresponding to the second trigger signal on conditions which will be discussed in this paper. The jitter relative to the second trigger signal, the energy and power output of the resulting giant pulses will be reported.

Introduction

In the last few years the importance of the ruby laser in plasma physics has been growing steadily. Besides the use of ruby lasers as a diagnostic aid, there has recently been an increasing trend towards producing plasma with powerful pulse lasers. Mostly of interest are laser devices which generate a very short, powerful pulse which has to be applied at a moment of time within the jitter called for by the experiment. In this paper a method of ruby laser operation is described which produces triggerable giant laser pulses by means of a passive Q-switch device. The jitter of the conventional passive Q-switching technique (typically 50 µsec) is reduced by utilizing a "double pulse" excited flash tube performance. By this method giant pulses with a jitter of approx. 1 µsec can be generated with relatively small technical resources.

1. Giant Pulse Generation by Q-Switching

1.1 Survey

In 1962 it was shown by McClung and Hellwarth[1] that a single pulse of very high intensity may be obtained from a laser if the onset of stimulated emission is delayed by means of a shutter until excitation reaches a level far above the threshold with the shutter open. To distinguish such pulses from the commonly observed laser radiation they were called "giant" pulses. In the last few years several experimental methods of laser giant pulsing have been demonstrated using rotating prisms, electro-optical or passive Q-switch devices.

The most common methods and their characteristic data for a given laser system are set out in a table (Fig. 1).

The Pockels cell, a solid state analogon of the Kerr cell, offers the advantages of smaller size, longer life, less power consumption and operation at lower voltages compared with the Kerr cell.

A succesful technique using a passive device is a saturable absorber inside the laser cavity as a fast optical switch [2] [3] [4]. Apart from the high jitter, a passive cell is every bit as good as the Kerr or Pockels cell and, in addition, has the advantage of being easier to handle. The principle of the passive switch is described briefly in the following section.

1.2 Q-switching with a saturable organic dye as absorber

With suitable organic dye solutions the transmission T is varied by optical pumping of the absorption transition. It holds that

$$T = e^{-\sigma(\nu) \cdot (n_1 - n_2) \cdot l}$$

where n_1 is the number of molecules in the ground state E_1, n_2 the number of molecules assuming the state E_2 on absorption, $\sigma(\nu)$ the absorption cross section at the laser frequency ν, and l the absorption length. With high luminous flux the transition is saturated and the transmission $T \rightarrow 1$ ($n_1 = n_2$).

If such a saturable absorber is placed in a laser resonator, oscillation is prevented until the ruby is pumped to an inversion level determined by the initial transmission T_o with

$$T_0 = e^{-\sigma(\nu) \cdot n_1 \cdot \ell}$$

Initial laser action causes the absorber to become nearly transparent (T = 1) in a very short time and a giant pulse is delivered. For a resonator system with saturable absorber the following relations are valid:

$A(t) \cdot R \cdot T_o < 1$ no laser radiation

$A(t) \cdot R \cdot T_o \sim 1$ threshold condition

$A \cdot R \cdot 1 \gg 1$ giant pulse

A(t) is the amplification per transit and R is the mean reflectivity of the end mirrors. Passive Q-switching is a threshold phenomenon, i.e. an uncertainty in the amplification curve A(t) produces a much greater jitter of the giant pulse compared with externally triggered devices. This uncertainty is caused mainly by the pump source and the ruby temperature. In the following chapter the influence of the pump source on the time at which the giant pulse occurs is investigated, a constant ruby temperature being assumed.

2. Time Fluctuation of the Giant Pulse for a Laser System with a Passive Q-switch

A laser oscillation occurs when the ruby is pumped to the inversion level at which the amplification is greater than the losses in the resonator. This condition can be formulated as follows:

$$N_2(P,t) \geq N_{2S}$$

where $N_2(P,t)$ is the number of ions at the level 2 that are excited by the pump source P, N_{2s} the number of ions at the moment the pulse occurs (threshold).

The function $N_2(P,t)$ is derived using the ansatz:

$$dN_2 = a N_0 P(t)\, dt - \frac{N_2}{\tau_2}\, dt \qquad (1)$$

where the first term stands for the number of ions excited by the pump source and the second term stands for the loss due to spontaneous emission; a is the ion cross section at the pump frequency, N_o the total number of ions, on the assumption that $N_o \gg N_2$, and τ_2 the life time of the level 2 (for ruby τ_2 = 3 msec). The solution of the differential equation (1) will now be treated separately for the case of a rectangular and a sinusoidal pump pulse shape.

2.1 Rectangular pump pulse shape

For P(t) = P = const equation (1) has a simple solution

$$N_2 = a N_0 P \tau_2 \left(1 - e^{-t/\tau_2}\right) \qquad (2)$$

which is represented graphically in Fig. 2a. Let $N_2 = N_{2s}$ at the moment $t = t_s$ when the pulse occurs. By rearranging (2) we obtain t_s as a function of the pump intensity P (Fig. 2b):

$$t_s = \tau_2 \cdot \ln \frac{P}{P - \frac{N_{2s}}{a N_0 \tau_2}} \qquad (3)$$

For small deviations of the pump intensity ΔP the fluctuation of the time at which the pulse occurs is obtained by differentiating (3):

$$\Delta t_s = \tau_2 \cdot \frac{\Delta P}{P} \left(1 - e^{t_s/\tau_2}\right) \qquad (4)$$

In Fig. 2c this jitter Δt_s is plotted as a function of the ratio t_s/τ_2 for a fluctuation of the pump intensity $\Delta P/P$ = 2% occurring in practice. As expected, the jitter increases with the threshold time because the population curve becomes flatter.

2.2 Sinusoidal pump pulse shape

The pump source is normally supplied by a capacitor via a current-limiting choke, giving the intensity distribution shown in Fig. 3a. Equation (2) becomes invalid because P(t) is no longer constant. If the intensity distribution is replaced by a sinusoidal function this gives a useful approximation for the pumping process in the ruby and a solution of the differential equation (1) with $P(t) = P \sin (2\pi \frac{t}{T})$:

$$N_2 = a N_0 P \frac{T}{2\pi} \left\{ e^{-t/\tau_2} + \sin(2\pi \frac{t}{T} - \frac{\pi}{2}) \right\} \qquad (5)$$

This solution is represented in a simplified version and can only be used if the period T of the sinusoidal function is smaller than $2\pi \cdot \tau_2$. Fig. 3b shows the population N_2 versus time for the values T = 3 msec and τ_2 = 3 msec.

In order to obtain the optimum output power of the laser pulse the threshold value N_{2s} has to be in the region of the curve maximum. This maximum is represented on an enlarged scale in Fig. 3c. In addition, a pair of curves are drawn which represent the pump intensity $P + \frac{\Delta P}{2}$ and $P - \frac{\Delta P}{2}$ respectively. The jitter Δt_s is obtained from the intersections of the threshold value line N_{2s} = const as $\Delta t_s \sim 100$ µsec for a 2 % deviation of the pump source. It can be seen from this graph that the jitter only becomes a little smaller ($\Delta t_s \rightarrow \Delta t_s'$) when the threshold is lowered.

Δt_s can be substantially reduced by forcing a rapid increase of the population N_2 by means of a superimposed, fast and very intense pump pulse (Fig. 3d). In the case of pump pulses of short duration ($t \ll \tau_2$) the second term of equation (1) can be neglected and the increase of the population ΔN_2 becomes

$$\Delta N_2 = a N_0 \hat{P} \Delta t \qquad (6)$$

where $\hat{P}$ is the amplitude of the superimposed pump pulse and Δt the duration. The moment t_P at which the superimposed pulse is applied should preferably be chosen such that $t_P \sim t_s - \frac{1}{2}\Delta t_s$. The reduced jitter Δt_s is calculated from an approximate formula, the derivation of which will not be described here. This gives

$$\Delta t_s = \frac{\Delta P}{P} \cdot \frac{P}{\hat{P}} \cdot \frac{T}{2\pi} \left(e^{-t_s/\tau_2} + 1\right) \qquad (7)$$

On substitution of the values $\frac{\Delta P}{P} = 2\ \%$ and $T = \tau_2 = 3$ msec already used above we obtain a $\Delta t_s = P/\hat{P} \cdot 15\ \mu$sec, valid for a threshold time $1.2 < t_s < 1.5$ msec. If the amplitude of the superimposed pulse is taken as $\hat{P} = 10\ P$ the jitter becomes $\Delta t_s = 1.5\ \mu$sec; this is a considerable improvement on the original value of $\Delta t_s \sim 100\ \mu$sec.

The next section deals with the practical aspects involved in producing a fast, high-current superimposed pulse of the pump source.

3. Double-Pulse Excited Flash Tube Circuit

Fig. 4 shows the principal circuit diagram. The main pump energy is stored in the capacitor bank C1 and is discharged to the flash tube by firing ignitron 1. Current is limited by the choke L1 for the purpose of prolonging the tube life. Ignitron 2 switches a short high-power pulse from the capacitor C2. This pulse need not be current-limited when the flash tube is filled uniformly with plasma. Consequently, the tube is conditioned to accept a current density that would otherwise be destructive[5]. Without the current-limited main pulse the short high-power pulse would fracture the tube wall by generating a shock wave.

Triggering is realized by injecting a narrow high-voltage pulse to the flash tube. The starting pulse drives the thyratron pulser 3 delivering a 3.2 kV pulse to transformer 3 which applies a 25 kV preionizing pulse to the anode of the flash tube. The main pulse is fired by pulser 1 whose pulse is applied to ignitron 1 by a decoupling transformer. To ensure optimum operation of the flash tube there is a delay of 40 μsec between the preionizing and main pulses (timer 1). After a suitable delay - regulated by timer 2 -

pulser 2 fires the high-power pulse from capacitor C2 to the flash tube load with a 10 µs rise time and a peak current of several 10,000 amperes. The delay of the timer 2 is found from the threshold value condition treated in section 2.2 to be $t_P \sim t_s - \frac{1}{2}\Delta t_s$, where t_s and Δt_s have to be determined experimentally.

4. Experimental Arrangement and Measurements

4.1 Pumping Device and Optical Cavity

The ruby rod 5/8 inches in diameter and 7 inches long is exfocally pumped in an elliptical cylinder [6] by a linear flash tube (EGG, FX 47 B). Air cooling of the tube gives a maximum repetition rate of 1 ppm. The ruby rod is water-cooled to obtain a consistent laser performance.

The passive cell, methylene blue in water, is placed between the 90-deg rod with a TIR chisel (the flat end with anti-reflection coatings) and a separate end mirror. The end mirror is a high-quality plane quartz-plate with dielectric coatings of about 50 % reflectivity.

4.2 Measurements

If the laser system described in section 4.1 is operated without a Q-switch an input energy of 4500 Ws (equivalent to a voltage U_1 = 2.25 kV) gives an output energy of approx. 10 Ws, the laser pulses having a mean power of approx. 600 kW. In Q-switch operation an output energy of 0.6 Ws is measured for the same input energy and a transmission of the dye $T_0 \approx 0.2$. This is equivalent to an output power of the giant pulse of approx. 30 MW. At the maximum of the inversion curve the jitter is $\Delta t_s \approx 60$ µsec with a threshold time t_s = 1.25 msec and a repetition rate of 1 ppm.

In double-pulse operation it was possible to reduce the jitter to 1 µsec by choosing, for instance, the following parameters: voltage U_1 = 2.20 kV, voltage U_2 = 14 kV, delay Δt_2 = 1.2 msec.

The ratio $P/\hat{P}$ corresponding to the ratio $I/\hat{I}$ of the light intensities at 5660 Å was 0.7. The delay of the giant pulse relative to the trigger signal of the high-current pulse was 15 μsec.

If the voltage U_1 is lowered to 2.18 kV, corresponding to a decrease of the pump intensity P of 2 %, the delay increases to 20 μsec with a jitter of 2 μsec.

Conclusion

As can be seen from eq. (7), the jitter Δt_s at a given fluctuation of the pump intensity $\frac{\Delta P}{P}$ is proportional to the ratio $P/\hat{P}$ or to the ratio of the light intensities $I/\hat{I}$. A further reduction of the jitter can only be achieved either by decreasing the intensity I of the main pulse or increasing the intensity $\hat{I}$ of the superposed pulse. The latter is limited, on the one hand, by the lifetime of the flash tube and, on the other, by the luminous efficiency of the lamp at a pump frequency of 5660 Å. In the case of Type FX 47 B the maximum luminous efficiency occurs at a tube current of 15,000 A/cm^2. Reducing the intensity I, of course, decreases the output power of the laser pulse. If the efficiency of the pumping device is then improved a more favourable value of the ratio $I/\hat{I}$ can be obtained and thus the jitter reduced even more.

It is known that symmetrical pumping in a rotational ellipsoid has the optimum efficiency and, in addition, the Q of the resonator is more constant during the pumping pulse [6]. The measurements are to be repeated with a configuration of this kind, and it is expected that this will give better results.

It is clear that the double-pulse method is not capable of reducing the jitter to a level comparable with that of the jitter of electro-optical devices. At any rate, this method allows more universal application of the passive Q-switching technique and can be used when a jitter of about 1 μsec is required.

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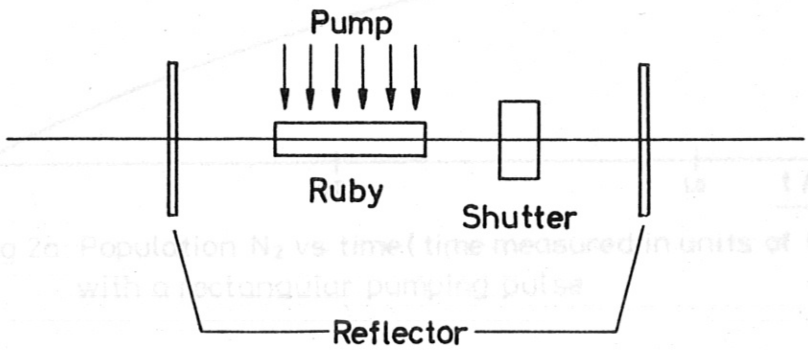

Fig 1a: Schematic of Apparatus for Q-Switching

	Peak Power [MW]	Line Width [Å]	Rise Time (nsec]	Pulse Width [nsec]	Jitter [nsec]
Kerr Cell	50	0,5	3-4	10	10
Pockels Cell	50	0,03	10	15	50
Passive Cell	125	0,02	3-7	10	50.000

Fig 1b: Characteristic data in a Lasersystem (Korad, K-1 Series) using different Q-Switching Techniques

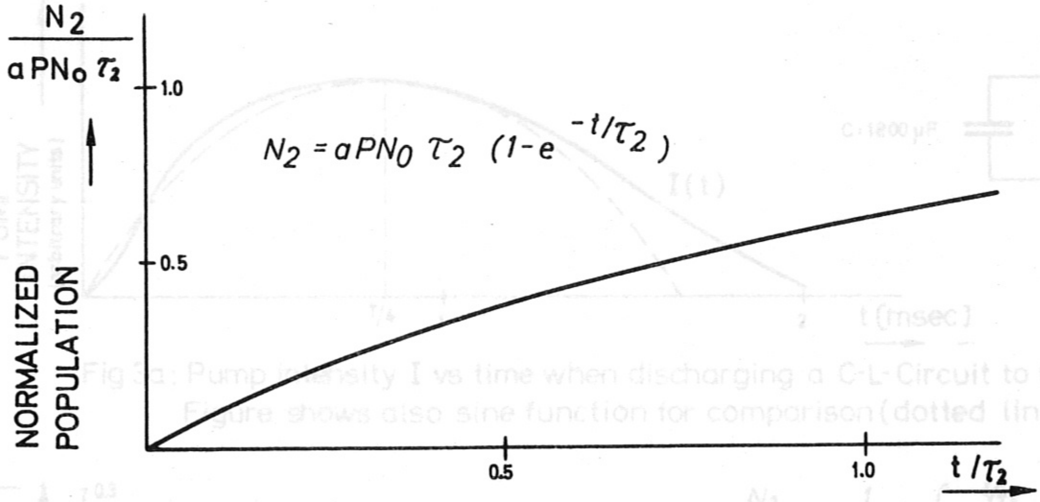

Fig 2a: Population N_2 vs time (time measured in units of lifetime τ_2) with a rectangular pumping pulse

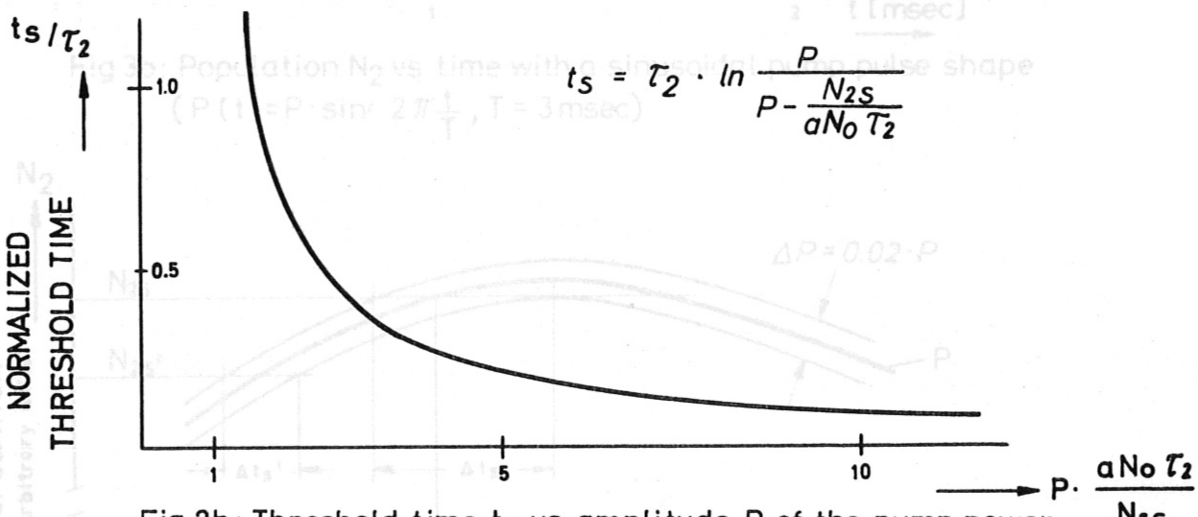

Fig 2b: Threshold time t_s vs amplitude P of the pump power (P measured in units of $\frac{N_{2s}}{aN_0\tau_2}$) with a rectangular pumping pulse

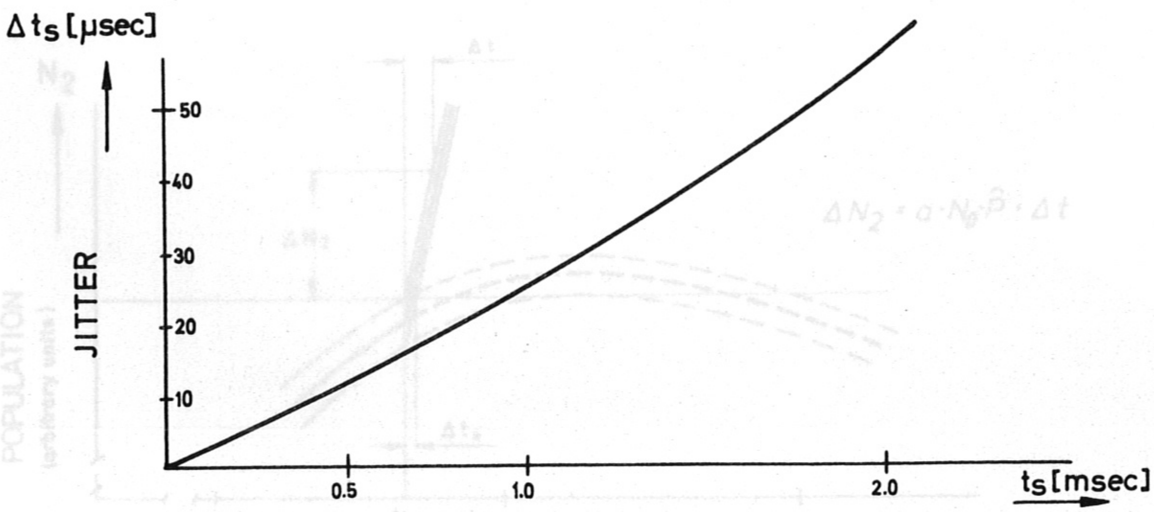

Fig 2c: Jitter Δt_s vs threshold time t_s with a rectangular pumping pulse using an uncertainty of the pump power $\frac{\Delta P}{P} = 2\%$

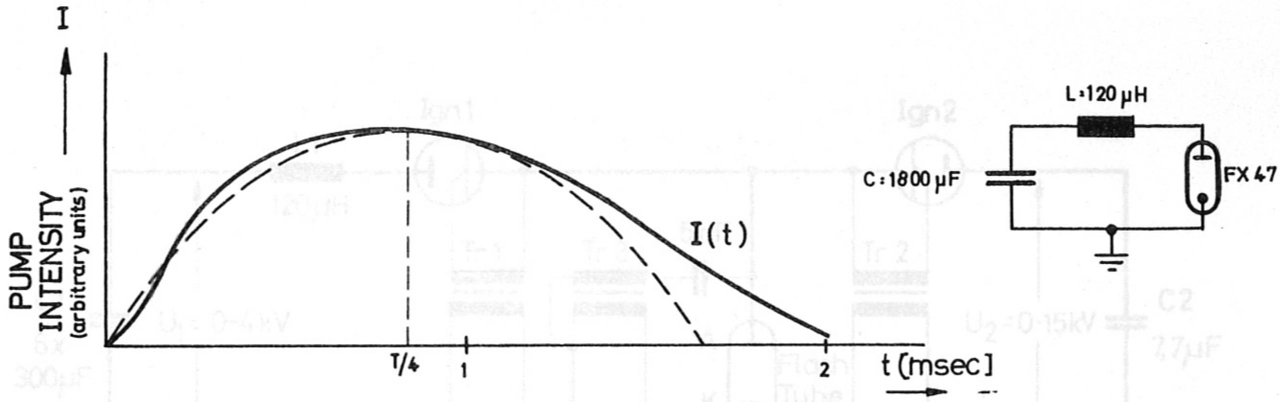

Fig 3a: Pump intensity I vs time when discharging a C-L-Circuit to the Flash Tube
Figure shows also sine function for comparison (dotted lines)

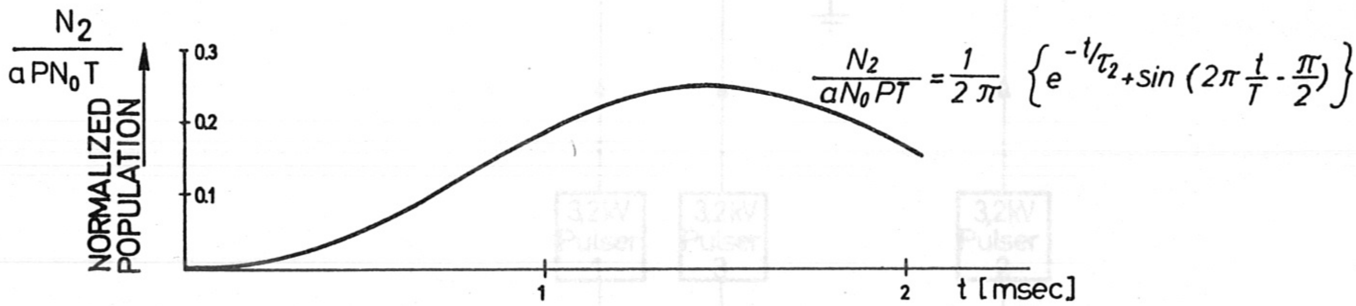

Fig 3b: Population N_2 vs time with a sinusoidal pump pulse shape
$(P(t) = P \cdot \sin 2\pi \frac{t}{T}, T = 3\,\text{msec})$

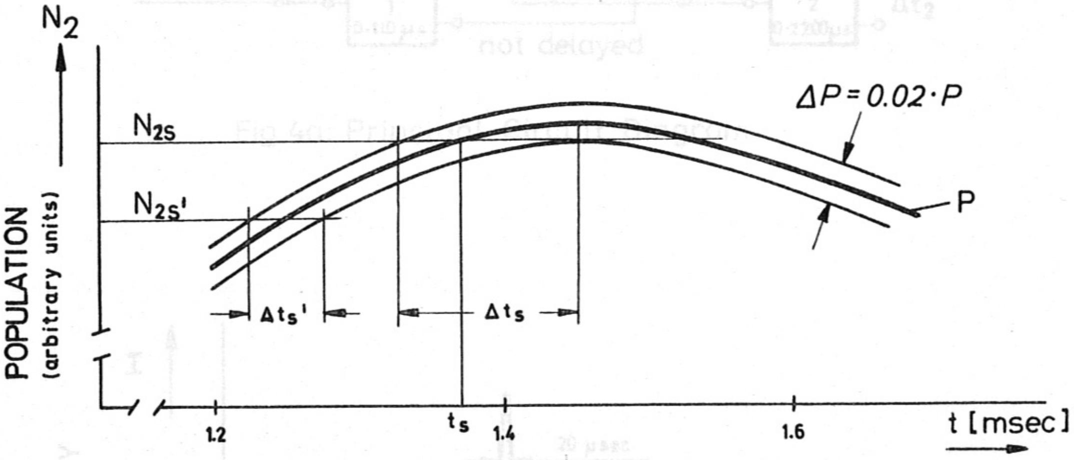

Fig 3c: Population N_2 vs time like fig 3b, but with expanded scale

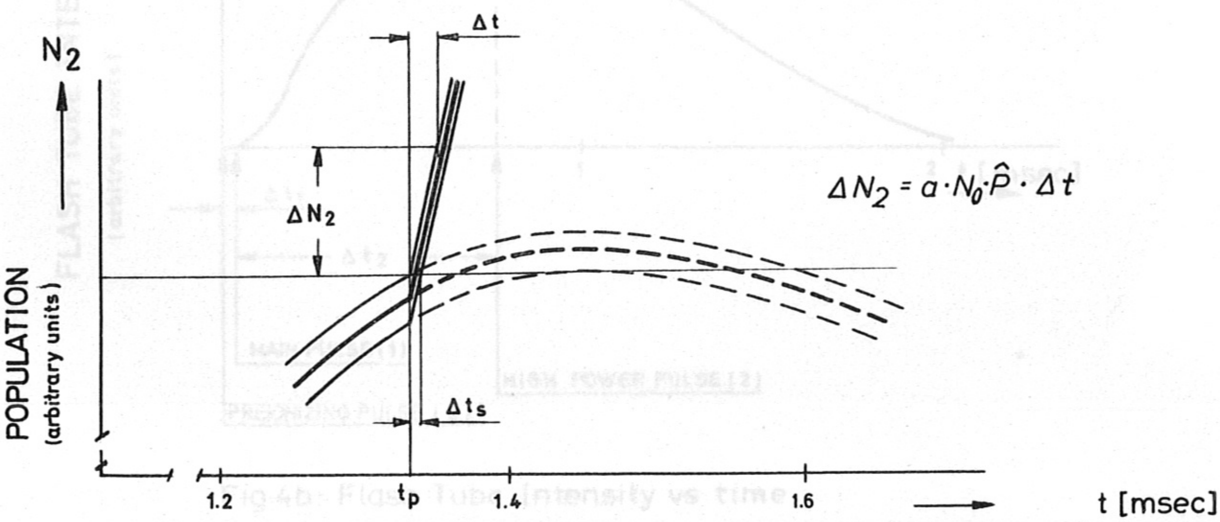

Fig 3d: Population N_2 vs time like fig 3c with super imposed pumping pulse $\hat{P}$

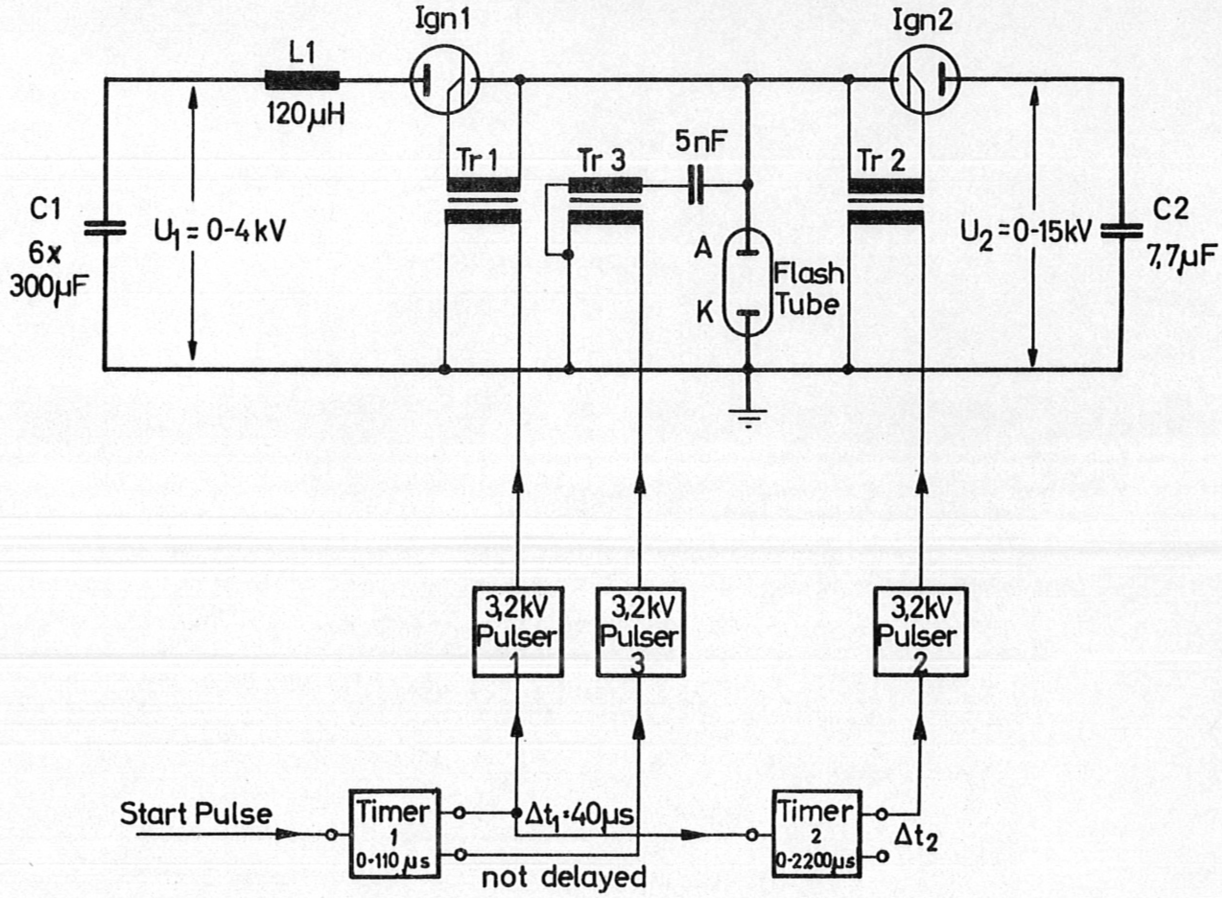

Fig 4a: Principal Circuit Diagram

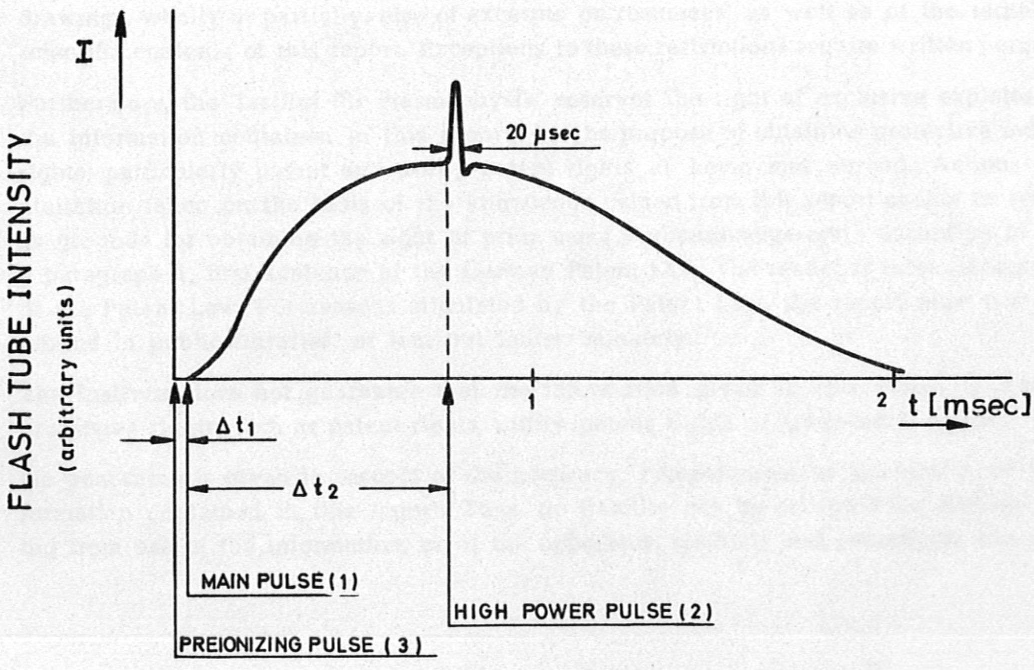

Fig 4b: Flash Tube Intensity vs time