Discharge technology for excimer lasers of high average power

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ABSTRACT

The self-sustained discharge of excimers is analyzed. Several excitation schemes that have been successfully applied are compared. For high repetition rate operation not only the discharge stability and its efficiency are important selection criteria but more important is the potential of fast discharge switching with minimum pulse energy. Pulse compression plays a key role in the laser performance. A technology for low energy compression is described.

INTRODUCTION

The development of a one kilowatt excimer laser may to some extent be considered as a study of several separated technological problems. It concerns the discharge, the preionization, the gas flow, the optical system, materials that are compatible with the laser gas mixture, the purifying system and life time studies. At a certain stage of this research the mutual dependence of these subjects has to be investigated and full scale experiments have to be carried out on a complete system with the versatility of parametric studies. In a previous contribution¹ we reported on preliminary design studies of our 1 kWatt Eureka excimer laser project.

In the present paper we restrict ourselves to some problems of high repetition rate discharges. This study is very important because the stability of the discharge and especially the efficiency of the production of the upper laser level density have a strong bearing on the shock strength, the size of the heat exchanger and the power of the fan in the circulating system.

Although the development of a high repetition rate excimer discharge is a logical extension of successful research on single shot experiments the discharge technique and circuit components used in single shot experiments are not simply adequate for high repetition rate. Short rise time and high current pulses needed for high power stable excimer discharges can be easily obtained with low inductance spark or rail gaps. These switching components are not suitable for high repetition rate and long life time. Well known reliable high voltage switching tubes like thyratrons with limited current and current rise times can not be used directly in discharge circuits. Even without these limitations the inherent relatively high inductance together with the capacitance of the stored discharge energy do not allow of short time duration.

Compression technology is necessary. Applying the well known pulse compression technology for the required discharge energy, say 50 joule at 1 kHz, the heat dissipation of the used saturable inductors causes serious problems. The larger the energy to be compressed the more core material and consequently the more lost energy must be released from the components.

For that reason the discharge technology has to be critically evaluated. It turns out that the prepulse-main pulse technology is very attractive. This is not only because of its efficiency but also because the fast switching with circuit components is restricted to the prepulse only. The smaller the prepulse energy the less complicated the pulse compression technique. Therefore a study of discharge quality at low prepulse energy is very relevant. In the present contribution we shall evaluate the condition of stable discharges and the technology that is most appropriate to obtain the best performance. In the second part the reached conclusions are incorporated into the design of a high repetition circuit using a compression technology for minimum pulse energy.

1. SELF-SUSTAINED DISCHARGE TECHNOLOGY OF EXCIMER LASERS

A self-sustained discharge of a laser gas can be obtained by a homogeneous electron avalanche of an initial low density plasma. The low electron density of the initial plasma may be obtained by photo-ionization of the discharge volume with UV light or X-rays. The discharge implies the sudden application of a strong electric field that causes the electron multiplication in the laser gas. In order to avoid the formations of filamentary arcs i.e. an unstable irregular discharge, it is necessary to start with an initial homogeneous electron density in the order of 10^8 electron $[\text{cm}^{-3}]$ and a very fast rise time in the order of 10 nsec of the applied electric field. With the formation of the discharge by the applied field the plasma resistivity decreases rapidly with the increasing plasma density. In this way the discharge will reach the so called quasi steady state conditions for which the voltage U_B across the discharge gap is more or less constant. However the impedance across the discharge gap will then become lower than the driving circuit output impedance. When this occurs the discharge will go into an oscillatory discharge which is unfavourable for the laser process. With special precautions this can be avoided. To utilize the self-sustained discharge for laser action of rare gas halide several excitation schemes have been successfully studied. We shall discuss and compare in sequence the single pulse discharge, the double pulse discharge and the resonant overshoot double pulse discharge.

1.1. Single pulse discharge

Fig. 1. Scheme of a single discharge.

The direct approach to discharge the laser gas is shown schematically in fig. 1. The energy storage capacitor C_1 is connected to the laser head in series with a switch²⁻¹¹. To increase the initial electric field of the discharge a small peaking capacitor is used in parallel with the discharge. The voltage across the electrodes can then be twice the charging voltage. After preionizing the laser gas with an external source, e.g. X-rays, or UV radiation from a corona discharge or sparks in series with the main discharge the strong electric field is applied. This LC-circuit is relatively simple. However, the voltage required for a rapid breakdown of the laser gas is not consistent with efficient impedance circuit coupling. In fact during the electron multiplication in this avalanche discharge, the impedance decreases very rapidly. The voltage across the discharge gap reaches a more or less constant quasi steady state value with practically no dependence on the current. This phase of the discharge is most effective for the

excitation mechanism of the laser process. It is straightforward to show that for efficient energy transfer from the capacitor into the discharge the charging voltage of the capacitor should be twice this steady state discharge voltage. The latter condition is not consistent with the required high voltage of a rapid breakdown of the discharge. Hence in an optimized system the current and voltage plots show the ringing of the circuit and only during a short period of the first oscillation laser power is generated. This is shown in fig. 2. Mainly for this reason the efficiency is low and not more than one percent. Another drawback of this scheme is the fast switching of the total discharge current.

Fig. 2. The discharge voltage, discharge current and output of a single discharge excimer laser.

In stead of using a circuit switch like a spark gap the system can be improved by using the laser itself as the switch^{9,11,12}. The triggering occurs during the preionization by UV or X-rays. In this case the applied voltage is limited because of spontaneous breakdown. Also the time delay between the charging of the main capacitor and the preionization is critical. Since the applied voltage will not be as high as in the case of an additional switch the avalanche and the output depends strongly on the preionization¹².

1.2. Prepulse-main pulse operation

Since the voltage required for rapid breakdown is not consistent with efficient impedance matching of the electric circuit to the laser head it has been proposed^{13,14} to use an electric circuit in which the avalanche breakdown (prepulse) and the quasi steady state discharge (sustainer) are provided by separate circuits. The sustainer capacitor will then be charged to twice the steady state voltage (U_B) for optimum impedance matching. There are in principle two modes of operation: the switch mode and the diode mode. The first one turns out to be the more attractive one because in the diode mode the polarities of the two pulses are equal and consequently there will be a time delay between the two discharge pulses due to the inductance of the sustainer circuit. Since there is always a tendency to form streamers or filamentary arcs any delay for the main pulse should be avoided.

It has been shown that a very attractive technology to separate the prepulse from the main pulse (sustainer) is the use of a simple and reliable magnetic isolator^{13,14}. The high voltage breakdown pulse, supplied by a low-energy circuit, is isolated from the low-impedance sustainer circuit by means of a saturable magnetic inductor. The principle is shown in fig. 3. The

low-impedance sustainer with a relatively large capacitor C_1 is connected to the laser head by a metal plate surrounded by a race track from low-loss ferrite bricks. This capacitor is charged to $2U_B$ shortly before firing the prepulse circuit. This prepulse circuit consists of a small peaking capacitor C_2 in series with a capacitor C_3 of equal size and a spark gap. The capacitor C_3 can be positively charged (switch mode) or negatively charged (diode mode) with respect to the main capacitor C_1 . In the case of the switch mode one side of C_3 is connected to C_1 with the voltage $2U_B$ whereas the other side has a voltage of at least $6U_B$. Once the preionization pulse for X-rays is fired the spark gap in the prepulse circuit is switched and the voltage across the peaking capacitor becomes $-4U_B$ during a few tens of nanoseconds causing the breakdown of the discharge. In the meantime this prepulse saturates the magnetic switch so that after the avalanche process of the prepulse the main pulse will automatically maintain the discharge. An efficiency of 4% has been reported¹⁴.

Fig. 3. Operation scheme of a prepulse - main pulse discharge.

Since the polarity of the prepulse and the main pulse are opposite there is a current reversal in the discharge. The voltage drop across the magnetic switch is $6U_B$. It may happen that in order to obtain a faster avalanche and a more stable discharge the prepulse voltage over the laser head must be higher than $4U_B$ and consequently the voltage over the switch is higher than $6U_B$. The fast switching now occurs in the low energy circuit with the total voltage of $6U_B$.

1.3. Resonant overshoot

Fig. 4. Resonant overshoot circuit scheme.

This technique¹⁵ is at first glance very similar to the above switch mode operation. The difference, however, is the operation principle as determined by the specific values of the chosen passive components. Looking at fig. 4 and comparing with fig. 3 we have the additional condition that the resonance time τ_1 between C_1 and C_2 in the case of the saturated magnetic switch is shorter than the resonance time τ_2 between C_2 and C_3 . The principle of operation is follows. The capacitors C_1 and C_2 are charged again to $2U_B$ and the connected voltage to C_3 is now only $4U_B$ in stead of $6U_B$ of the previous case. After preionization the prepulse is again fired within a few microseconds after charging C_1 , C_2 and C_3 . Because the voltage drop over C_3

is now only $2U_B$ the voltage over C_2 now changes from $2U_B$ to $-2U_B$ which is still too low to start the avalanche. In the meantime the magnetic switch saturates by the maximum voltage drop of $4U_B$ and it allows a current flow from the main capacitor C_1 . Since τ_1 is now smaller than τ_2 the voltage across C_2 changes from $-2U_B$ to $6U_B$ by which a fast avalanche breakdown takes place immediately followed by the main discharge. A typical example is shown in fig. 5. An efficiency of 5% has been reported¹⁵.

TYPICAL WAVEFORMS

V-PFN = 5.4 kV

Fig. 5. Typical waveforms of a resonant voltage overshoot system obtained for a XeCl laser having a mixture of 2 mbar HCl, 20 mbar Xe and 4 bar Ne. The discharge length and electrode separation are 60 and 1,5 cm, respectively. The output energy is 0.3 J. The solid and dotted lines in the upper figure are the discharge voltage and the X-ray acceleration voltage, respectively. For the lower figure the solid and dotted lines are the main pulse current and the laser output, respectively.

We note that because of a voltage drop of only $4U_B$ over the main magnetic switch, in this case less ferrite is needed and further that the energy for fast switching is now only $2/3$ of that described in the previous case. The inductor L_2 is also saturable and smaller than L_1 .

It is important that the resonance charging of C_2 from $2U_B$ to $-2U_B$, which happens after L_2 is saturated, occurs very fast during the time τ_2' because the size of the magnetic core material in L_1 is proportional to τ_2' . After this resonance charging the inductor L_2 will have a high impedance for a current flow from C_3 to C_2 and thus a large τ_2 value so that the design condition that τ_1 is smaller than τ_2 can be easily fulfilled.

2. HIGH REPETITION RATE OPERATION

For high repetition rate switching the thyatron is probably the best candidate. The disadvantage is its limitation with respect to current and current change. Hence the thyatron is not suitable for fast switching of the discharge circuit. A solution to this problem is magnetic pulse compression of a thyatron pulse so that a much shorter pulse with higher current can be applied to the discharge. For obtaining pulses shorter than 100 nsec. saturable ferrites may have much less dissipation losses than amorphous metals¹⁶. For high repetition rate it is very important to use as little saturable ferrite as possible because of reduction of material cost, saturation losses and cooling provisions. Moreover, since less ferrite will also decrease the saturated inductance and thus shorten the pulse duration, the stability of the discharge will benefit from it.

Fortunately the scheme of resonant overshoot, as we discussed above, allows the minimum energy to be switched for fast pulsing. For example, in the case of 4 bar XeCl laser mixture used in an electrode separation distance of 2 cm one finds U_B about 5 kV. The charge voltage of C_3 is $4U_B$ or 20 kV. Using a prepulse energy of 2 joule for a main pulse energy of 20 to 30 joules we obtain from $E = \frac{1}{2} C_2 U_p^2$, where U_p in the case of resonant overshoot is equal to $6U_B$, so that $C_2 = 4.5$ nF. For a pulse duration of 100 nsec the average current is about 1.5 kA and $\frac{dI}{dt}$ is in the order of 10^{10} A/sec. These values are within the specifications of commercial long life thyatrons.

The prepulse must be as short as possible in order to minimize the amount of saturable ferrite and also for obtaining a rapid rise of the electric field in the discharge. Due to practical limitations as given by the inductance of the laser head and the minimum formation time of the discharge an optimized prepulse will be about 25 nsec.

Although standard magnetic pulse compression technology can be used to reduce the pulse time the problem is that for low current short pulses a relatively large fraction of the pulse current will pass the saturable absorber before saturation. This means that the effect of pulse compression is considerably reduced. Since fast switching of the excimer laser by resonant overshoot can be performed with minimum energy and a minimum amount of saturable ferrite material in the main circuit, pulse compression technology has to be adequate for low current short pulses. For this reason we introduce a different method.

2.1. Pulse line compression

To compress the 100 nsec thyatron pulse to 25 nsec we use a pulse line compression technique as shown in fig. 6. It consists of coaxial pulse forming lines. A two stage coaxial waterline is separated by a coaxial ferrite line in such a way that for the saturated ferrite the impedance is as good as possible. Further, the second stage ends with a small ferrite line for pulse sharpening. A good choice¹⁷ for a high-frequency saturable ferrite is CMD 5005 from Ceramic Magnetics. The flux swing is about 0.5T, the magnetic field intensity to reach saturation, H_s , is 2 kA/m and the field intensity to achieve $\mu \sim 5\mu_0$ is about 5 kA/m whereas the dissipation losses were reported as only 100 J/m³.

Following the above example of 4.5 nF and a pulse duration of 25 nsec the dimensions of the waterline are determined. We use ferrite rings of 2 cm thickness and inner and outer diameter of respectively 4.4 and 8 cm. Using the scheme of resonant overshoot the pulse compression deals with $4U_B$ or 20 kV. To hold off this voltage one needs 6 rings of total flux area of 21.6 cm².

During saturation before switching the first stage of the waterline there is a "current leakage". The saturation current during this 100 nsec pulse may result to a leakage pulse with an energy of about 10% of that of the switched pulse. For that reason the second waterline having the same dimensions as the first has at its current exit two ferrite rings. Further because of some impedance mismatch the front edge of the switched pulse shows one or two period reflections of the boundaries of the central ferrite line. The pulse sharpening rings at the exit of the second waterline will hold off the leakage pulse and also the leading edge of the switched pulse.

Fig. 6. Pulse line compression scheme for low energy pulses.

This is demonstrated in fig. 6 where it is assumed that initially the coaxial lines are not charged. Fig. 6a shows the pulse compression line with the thyatron circuit. After switching the thyatron at $t = 0$ we plot in fig. 6b the time history of the voltage in the waterline near

A. The voltage hold-off time of L_3 is equal to τ_2 . At saturation, switching the pulse, the voltage drops to $2U_B$ and remains constant during $2\tau_1$ seconds where τ_1 is the transient time for the current pulse to pass the waterline. At the point B near L_2 the voltage increases initially relatively slowly by the saturation current through L_3 , followed by the switched pulse with some mismatch structure in the leading edge. This is shown in fig. 6c. Finally after passing L_1 the unwanted structures are filtered and a short pulse of duration $2\tau_1$ is obtained as shown in fig. 6d.

2.2. Fast switching of the discharge at high repetition rate

By means of pulse line compression a 25 nsec pulse of -10 kV is finally switched to the peaking capacitor C_2 which is constructed along the laser head. This is shown schematically in fig. 7. With multi-cable connections to fit impedance matching the charging time of C_2 will be about $\tau_2 = 25$ nsec. The advantage of this short charging time is that, because the voltage hold-off i.e. core area of L_1 is proportional to this charging time, less energy will be dissipated. Further there is a lower inductance after saturation so that the main pulse is shorter. Although one might argue that the reduction of the voltage hold-off of L_1 by the pulse sharpening of L_2 is just equal to that of L_2 , the difference is however the core volume of L_1 and L_2 .

Fig. 7. Fast switching circuit for high repetition rate.

During τ_2 the voltage drop across the main switch is 20 kV. The used ferrite race track must have a flux swing of 20 kV times 25 nsec (5×10^{-4} Vsec). After the voltage across C_2 has reached $-2U_B$ there will be resonant energy transfer from C_1 to C_2 with the result that the voltage across C_2 reaches $6U_B$. In the period that the voltage of C_2 changes from $-2U_B$ to $2U_B$ the two ferrite rings near B reset to have now low impedance for current flow from the coaxial capacitor to C_2 . Near the time the voltage of C_2 passes $2U_B$ to reach its maximum of $6U_B$ the ferrite inductor L_2 then opposes current flow from C_1 and C_2 . The voltage across the electrodes increases far above $2U_B$ and before reaching the maximum value of $6U_B$ the gas breaks down. It should be noted that the current from C_1 flows continuously by first charging C_2 and then after breakdown through the laser gas so that there is no delay between prepulse and main pulse.

3. REFERENCES

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