DISCHARGE EXCIMER LASERS WITH AN AUTOMATED SPARK PREIONIZATION

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In this review, a possibility is shown to provide for a quasi-stationary mode of excitation and generation in excimer lasers with an automated spark preionization in a peaking or storing circuitries. Both the experimental results obtained by the author and the data reported by other researchers are analyzed. The excitation pulse duration is by n times shorter when a UV preionization is used in the peaking circuitry. This is related to duration of the preionization pulse. Quasi-stationary mode of excitation in Ne *mixtures with three-circuit pumping scheme yields a "multi-pulse" output from a* XeCl *laser. Thus, it is possible to control the duration and shape of the output pulse when using an appropriate power supply.*

INTRODUCTION

At present, discharge excimer lasers operate both in the fast and quasi-stationary modes of excitation providing short or long output pulses. Specific features of these excitation modes have been studied for the first time in our experiments[1] with XeCl molecules. It was shown that the duration of the volume discharge stage is critical for achieving a quasi-stationary excitation being dependent on the intensity, homogeneity, and position of a UV-preionization source. Quasi-stationary excitation was successfully obtained using two or three-circuit excitation scheme.[1,2] We have found that the duration of the quasi-stationary excitation depends, to a substantial degree, on where the UV source operates in the peaking or storing circuitry. Moreover, depending on the ratio of storing (C_s) and peaking (C_p) capacitance and the mode of UV sources operation fast or quasi-stationary excitation and generation can be performed.

The aim of this paper is to present our experimental results and to analyze the data obtained by other authors which demonstrate efficient quasi-stationary mode of excitation using the automated spark preionization with peaking or storing capacitors.

THE MODES OF EXCITATION WITH SPARK PREIONIZATION VIA A PEAKING CAPACITOR

We were the first who used a three-circuit scheme with a spark preionization via mesh electrode[2,3] for excitation in excimer lasers. The spark gaps were connected with a peaking capacitor. We have achieved a quasi-stationary volume discharge with the duration from 200 to 400 ns depending on buffer gas (Ar or He). In particular, the efficient lasing in the XeCl* mixture diluted with Ar with the pulse duration of 170 ns was demonstrated for the first time.

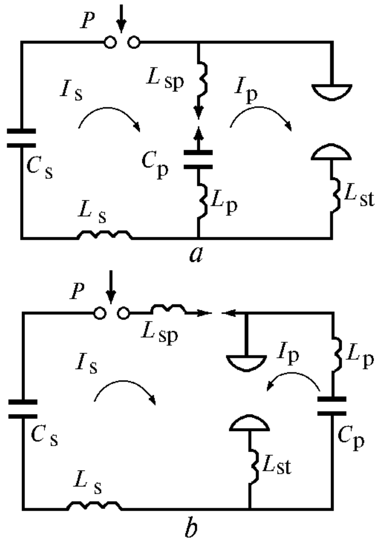

FIG. 1. Equivalent circuitry of the excitation scheme with the automated spark preionization via peaking (a) and storing (b) capacitors to obtain fast ($I_d = I_p$) and quasi-stationary ($I_d = I_p + I_s$) excitation mode.

Figure 1*a* presents an equivalent circuitry of the excitation with the spark preionization via a peaking capacitor. Two modes of excitation can be provided depending on L and C values. If $C_s = C_p$, L_p = min and $L_{st} \simeq 0$ (here L_p is the inductance of the peaking

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circuit and L_{st} is the stabilizing inductance) fast excitation mode providing maximum lasing efficiency (η) can be achieved. In this case, the discharge current is almost equal to the current in the peaking circuit ($I_d \simeq I_p$). Using this excitation mode many groups tried to obtain maximum energy and efficiency of the excimer lasers. For instance, efficiency of KrF laser was demonstrated[4] to be $\eta = 4\%$ and that of XeCl laser was 2.3%.[5]

We were interested in a quasi-stationary mode of excitation which provides for long laser pulses but at relatively lower lasing efficiency. To achieve this mode the following conditions are to be met: $C_s \gg C_p$, L_p and L_{st} values are optimal to obtain $I_d = I_p + I_s$. Our experiments on the discharge stability versus circuit parameters and mixture composition showed that in the Ar(He)–Xe–CCl_4 mixture the volume quasi-stationary discharge was mainly affected by the content of CCl_4. When p_{CCl_4} was 0.2 Torr the duration of the volume discharge reached 400 ns in He diluted mixtures.[1,2] The emission parameters obtained from a discharge occurring in a small volume (2 cm^3) in (Ne) Xe:HCl = 10:1 mixtures at a total gas pressure up to 20 atm were studied in Ref. 6 using X-ray preionization and $L_{st} = 300$ nH. Quasi-stationary lasing with the duration up to 350 ns was obtained at a total gas pressure lower than 8 atm and HCl content of 4 Torr. When the pressure increased to 11 atm and HCl content reached 5.5 Torr a multi-pulse modulation of spontaneous emission was recorded during approximately 350 ns. Using three-circuit excitation scheme and stabilizing inductance $L_{st} = 50$ nH Lisin et. al.[7] achieved about 0.15 J pulse energy at 230 ns duration. It should be noted that laser pulses were only 60 ns long without L_{st} in the excitation circuit.

For making a detailed study of the three-circuit excitation scheme we have developed a laser system with the active volume $V = D \times H \times L = 1.5 \times 0.5 \times 30$ cm^3. Here D is the electrode separation, H and L are the electrode width and length, respectively. Ar(Ne)–Xe–HCl mixtures were used. Precise measurements of the voltage at the circuit elements and discharge plasma as well as the discharge current were available. The laser cavity was composed of two dielectric mirrors with the reflection of 98% and 33%.[8] Three modes of excitation were found to be realized using this scheme. These are the fast, quasi-stationary, and "multi-pulse generation" modes. Let us now consider mechanisms of lasing modulation, mechanisms of the energy transfer from the capacitors to the discharge, distribution of energy losses in the power supply and methods to control the laser pulse shape. The task stated was achieved by the following means:

1. Sufficiently precise monitoring of the voltage and current in the circuit elements and discharge plasma. Numerical processing of the oscillograms.

2. Development of a computer code for complicated multi-circuit schemes allowing one to calculate time behavior of the voltage and current at all points of the scheme. The agreement between the data provided by this code with the measurements data was not worse than 10–15%. Current and voltage profiles were calculated using Runge–Kutt method for a system of four or more differential equations of the first order.

For the three-circuit excitation scheme with the spark preionization we have

$$\frac{dU_{C_1}}{dt} = -\frac{1}{C_1} I_1, \tag{1}$$

$$\frac{dU_{C_2}}{dt} = \frac{1}{C_2} (I_1 - I_2), \tag{2}$$

$$\frac{dI_1}{dt} = \frac{1}{L_1} (U_{C_1} - U_{C_2} - U_{sw}), \tag{3}$$

$$\frac{dU_{C_3}}{dt} = \frac{1}{C_3} (I_2 - I_3), \tag{4}$$

$$\frac{dI_2}{dt} = \frac{1}{L_2} (U_{C_2} - U_{C_3} - U_{sp}), \tag{5}$$

$$\frac{dI_3}{dt} = \frac{1}{L_3} (U_{C_3} + U_{sp} - U_{pl}) . \tag{6}$$

Here $C_1 = C_s$, $C_2 = C_p$, C_3 are the capacitance of the spark gaps, U_{sp}, U_{sw} and U_{pl} are the values of the breakdown voltage of the spark gaps, voltage across the switch and discharge plasma, respectively. The calculations first started with the first three equations, then after the breakdown of spark gaps and main discharge gap additional equations (4), (5), and (6) were subsequently involved. Verification of different versions of the simulation of the discharge gaps showed that the best agreement with experimental oscillograms was achieved when the constant voltage drop independent of current was assumed both for sparks and for the main discharge. In the model of switch operation (thyratron) an active resistance of 0.15 Ohm should be included. The breakdown voltage of the main discharge and voltage at its self-maintained stage as well as the values of inductances were taken from test experiments. The agreement between the oscillograms calculated using our code and the experimental ones was not worse than 15% with exception for the main discharge voltage which dropped smoothly during the discharge in calculations whereas it was kept nearly constant in the experiments.

The experiments showed that the mode of "multi-pulse generation" was observed only with small electrode gaps ($D \leq 1.5$ cm), enhanced inductance of the feedthrough and in mixtures with Ar(Ne) buffer gases. Analysis of the oscillograms allowed us to conclude that modulation of the laser output correlated with the modulation of the volume discharge current. The laser emission terminated when the polarity of the discharge current changed.

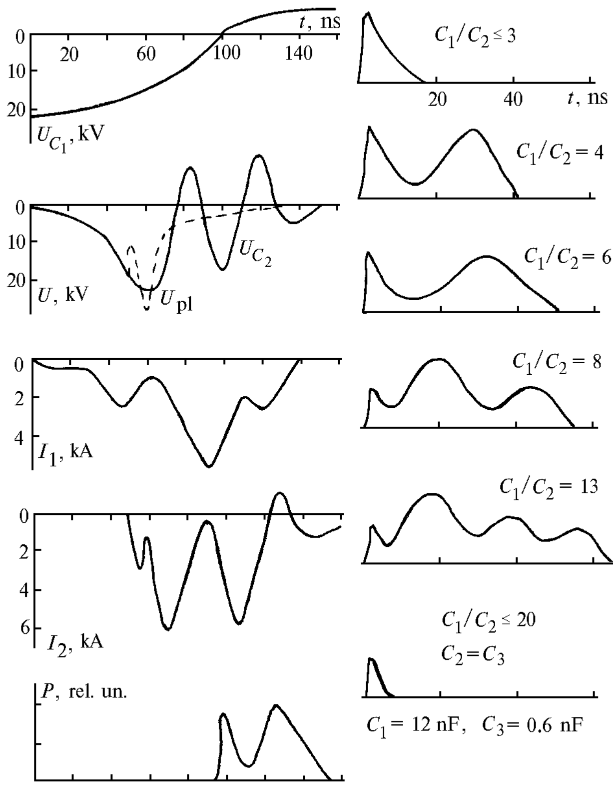

FIG. 2. Voltage (U_{C_1}, U_{C_2}, U_{pl}), *current* (I_1, I_2) *and laser waveforms obtained with* (Ne):Xe:HCl = =20:1 *gas mixture* at P = 3.5 atm *and output pulses observed at* U_0 = 25 kV *when three-circuit excitation scheme was used with a changeable* C_2 *value.*

For instance, Fig. 2*a* presents time profiles of the discharge voltage and current obtained with a version of the excitation circuitry. The circuit parameters were as follows: C_1 = 12 nF, C_2 = 2.5 nF, C_3 = 0.6 nF. The gas mixture was composed of Ne, Xe and HCl at 3.46 atm, 30 Torr and 1.5 Torr, respectively. Figure 2*b* show the laser pulses for different C_3 values. Modulation of the discharge current is attributed to the multiple energy transfer from the storing capacitor (C_1) to the discharge via the peaking capacitor C_2. Such a dosed deposition of a fraction of energy stored in C_1 is possible at certain ratios between the capacities and inductances of the circuit. This process can be described in the following way. First, the peaking capacitor is charged from the storing one and then it discharges through the gas plasma. The voltage across the peaking capacitor changes its polarity and additional charging of this capacitor starts. If the inductances L_2 and L_3 are sufficiently large the peaking capacitor begins to discharge again just after charging through the existing volume gas plasma that is still burning. The additional current pulse is observed and so on, up to the complete discharge of the storing capacitor.

Figure 2*b* shows typical laser waveforms obtained with a varying value of the peaking capacitance. At C_1/C_2 lower than 3 fast excitation mode is realized with the laser pulse duration shorter than 20 ns. When C_1/C_2 = 4 quasi-stationary excitation mode is observed and two peaks of laser emission are recorded. In this case, laser efficiency based on the energy deposited in the gas plasma is 1.7% whereas total laser efficiency is 0.9%. Energy losses in the elements of the circuit were as follows: energy stored in the peaking capacitor was 2.5 J, energy lost in the switch was 0.55 J, energy deposited in the spark gaps was 0.15 J, energy of laser emission was 0.023 J and the residual energy remaining in the storing capacitor after termination of the volume discharge was 0.45 J. Pulse duration was increased up to 60 ns with C_1/C_2 ratio and the mode of "multi-pulse generation" was observed. At $C_1/C_2 \le 20$ short laser pulses of about 10 ns were observed. In this case, the peaking capacitance was equal or lower to the spark gap capacitance ($C_2 \le C_3$) and the laser was operated as a two-circuit device with no significant influence from the storing capacitor. Hence, the mode of "multi-pulse generation" enables one to obtain laser pulse shape required and its preliminary calculation is possible. Such a regime is especially attractive for lasers operated in a pulse-periodic mode.

Table I summarizes the main publications and the highest output parameters of XeCl laser operating in different excitation modes with the spark preionization via the peaking capacitor. Here publications of the author are marked with * and parameters of KrF laser are marked with **. The maximum specific output energy achieved up to now with the KrF laser Q_S = 2.8 J/l atm,[10] the highest efficiency of the KrF laser was reported in Ref. 4 to be η = 4%. The parameters obtained with XeCl lasers are Q_S = 1.6 J/l atm[12] and η = 2.3%.[5] The maximum pulse duration observed in the quasi-stationary excitation mode was 230 ns.[7] The limitation on pulse duration in lasers with the preionization via the peaking capacitor results from a limited time of existence of the preionization. The duration of volume discharge stage is tightly related to the length of the preionization pulse. To confirm this conclusion we have performed experiments with similar excitation schemes but with the preionization performed via the storing capacitor. In this case, only the value of the storing capacitance determines the duration of the preionization pulse.

TABLE I. Main publications and the highest output parameters of XeCl *lasers obtained in different modes of excitation and spark preionization via the peaking capacitor.*

No.	Pumping scheme	Buffer gas	ρ, %	V, l	Q_{las}, J	Q, J/(l·atm)	$\tau_{h/2}$, ns	τ_{base}, ns	η, %	Year	Refs.
1	$C_1/C_2/C_3$ + UV	Ar, He	10	0.3	0.02	0.06	40	170	–	1977	3*
2	$C_1/C_2/C_3$ + UV	Ar, He	10	0.3	τ_p = 200 ns (Ar)				–	1978	2*
					τ_p = 400 ns (He)						
3	C_s/C_p + UV	–	–	1	0.5	–	30	–	0.27	1979	9
4**	C_s/C_p + UV	KrF	–	0.2	1	2.8	–	–	0.50	1979	10
5	Bl(C)/C_p + UV/R_{st}	He	90	0.06	0.015	–	80	120	–	1980	11
6	$C_1/C_2/C_3$ + UV	Ar He									
	C_s/C_p + UV	Ne	10–40	0.1–0.3	0.3	0.4	40	170	0.7	1982	1*
7**	C_s/C_p + UV	KrF	–	–	–	–	–	–	4	1986	4
8	C_s/C_p + UV	Ne	10	0.08	0.34	1.6	80	120	2	1987	12
9	C_s/C_p + UV/L_{st}	Ne	40	0.08	0.09	0.4	80	160	0.85	1987	13
10	C_s/C_p + UV/L_{st}	Ne	–	–	0.3	–	23	60	2.3	1988	5
11	C_1/C_2 + L_{st}/C_3 + UV	Ne	10	–	0.2	–	150	230	0.7	1989	7
12	$C_1/C_2/C_3$ + UV	Ne	33	0.015	0.02	0.4	15	60	0.9	1990	8*
13	$C_1/C_2/C_3$ + UV	Ne	20–50	0.04	0.09	0.6	5	100	–	1990	14

EXCITATION MODES WITH THE SPARK PREIONIZATION VIA STORING CAPACITOR

Figure 1*b* presents an equivalent circuitry of the excitation scheme with the automatic preionization via the storing capacitor. This scheme provides both the fast and quasi-stationary excitation modes depending on the discharge circuit parameters. This excitation scheme is most favorable for the quasi-stationary operation of the discharge excimer lasers ($I_d = I_s + I_p$). This operation mode was proposed in our paper[15] for the first time. Our basic idea was that the peaking capacitor forms a volume discharge in the laser gap providing preliminary high-voltage excitation pulse. Long maintenance of the volume discharge is kept due to low voltage storing circuit providing the discharge current I_s. The storing circuit includes UV a preionization source. In this case, the duration of the preionization pulse is determined by the duration of discharge current in the storing circuit.

Such a scheme was used for the first time in the fast excitation mode by McKee et al[16] in their experiments with KrF, XeF and ArF lasers. In these experiments, the pulse duration reached 20 ns. The preionization sparks were located behind a mesh electrode. We have developed similar excitation scheme in a laser with the active volume $V = 2.4\times0.5\times80$ cm^3 but with the spark gaps were closed to one of the electrodes.[17] First experiments were performed with a Marx generator whose effective operating capacitance of 10 nF was equal to the capacitance of the peaking capacitor. This scheme operated in the fast excitation mode. The inductance of the storing circuit was 50 nH whereas that of the peaking circuit was no larger than 2 nH. In He–Xe–HCl mixtures we have obtained pulse energy of 127 mJ, laser efficiency of 0.5%, and pulse duration of 20 ns.

When the Marx generator was replaced by a storing bank with the total capacitance C_s = 60 nF[15] a 200 ns-long quasi-stationary mode of the discharge was observed for the first time. However, duration of the laser pulse increased only by a factor of 2 reaching 40 ns. We supposed that the quasi-stationary excitation mode was affected by the discharge current density and the buffer gas. For instance, authors of Ref. 18 and 19 reported on an increase in the lasing energy by a factor ranging from 1.5 and 2 using Ne as a buffer gas instead of He in XeCl lasers operated in the fast excitation mode. It was supposed in Ref. 18 that Penning ionization of Xe in Ne based mixtures is efficient. As a result, XeCl number density formed in the ion-to-ion recombination process is increased. We have the following reactions in the discharge plasma:

$$\mathrm{Ne} + \bar{e} \rightarrow \mathrm{Ne}^* + \bar{e}, \tag{7}$$

$$\mathrm{Ne}^* + 2\mathrm{Ne} \rightarrow \mathrm{Ne}_2^* + \mathrm{Ne}, \tag{8}$$

$$\mathrm{Ne}^* + \mathrm{Xe} \rightarrow \mathrm{Xe}^+ + \mathrm{Ne} + \bar{e}, \tag{9}$$

$$\mathrm{Ne}_2^* + \mathrm{Xe} \rightarrow \mathrm{Xe}^+ + 2\mathrm{Ne} + \bar{e}, \tag{10}$$

$$\mathrm{Xe}^+ + \mathrm{Cl}^- + \mathrm{Ne} \rightarrow \mathrm{XeCl}^* + \mathrm{Ne}. \tag{11}$$

In our opinion, this is the most convincing explanation of the kinetics of XeCl formation in the Ne-based mixtures, especially in the quasi-stationary mode of excitation and generation. It is confirmed by the experimental data. Similar situation is observed in the Ar-based mixtures. If in our laser He was replaced by Ne the output energy increased by a factor of 2 though the pulse duration was the same. The discharge current density was observed to be as high as 0.8 and 1 kA/cm^2, respectively. The absence of quasi-stationary generation was attributed only to a high discharge current density.

In a novel laser device with the discharge electrode width W from 0.5 to 2 cm (active volume configuration was $2.4\times W\times 80$ cm^3), the storing capacitance of 60 nF and the peaking capacitance of 10 nF we used additional stabilizing inductances connected to the storing capacitor. In that device, the laser gap was preionized either from one side or from two sides of one of the electrodes.[20,21] We have obtained quasi-stationary mode of excitation and generation in a Ne-based mixtures with the duration longer than 170 ns, energy of 0.5 J and the efficiency of 1.6% at HCl partial pressure of 3 Torr. The electrode width was found to be optimal at 1 cm providing the discharge current density $J = 200$ A/cm^2 in the Ne-based mixtures and 350 A/cm^2 in the He-based mixtures. Quasi-stationary generation was obtained only with Ne diluent whereas with He short laser pulses with the duration no longer than 50 ns were observed.[21] When the peaking capacitance was increased to 20 nF the discharge current and energy deposition in the fast discharge increased too. Hence, only short pulses with the duration no longer than 70 ns were observed with all buffer gases.

To improve the preionization of the laser gap we designed a similar two-circuit excitation scheme with a symmetric surface spark preionization via the mesh electrode. The active volume of that laser was $V = 3\times 1.5\times 35$ cm^3, $C_s = 75$ nF, $C_p = 10$ nF. This scheme was used to obtain quasi-stationary excitation mode in gas mixtures with Ar, He and Ne.

Figure 3 presents the output energy as a function of pressure of Xe:HCl = 10:1 (3 Torr) at a charging voltage of 38 kV. Maximum output was demonstrated with He-based mixtures. This is apparently connected with the specific features of the preionization (additional high energy electron beam is formed between the spark gaps and the mesh electrode[22]) as well as with a high discharge current density. Metal anode was illuminated uniformly across its entire width of 1.5 cm whereas the discharge width near the mesh electrode was only 0.8 cm. However, the width of the laser beam was 1 cm with all buffer gases. Figure 4 shows typical oscillograms of the discharge voltage, current in the storing circuit and lasing in Ar-, He-, and Ne-based mixtures at $p = 1$ atm and $U_0 = 30$ kV. The lowest breakdown voltage and the shortest delay of the discharge formation was observed in Ne-based mixtures. Duration of the quasi-stationary stage of the discharge in these mixtures achieved 200 ns. A linear increase in the output energy with the gas pressure increase was found (see Fig. 3). The duration of laser pulses was up to 100 ns that is related to the quasi-stationary excitation mode. The highest discharge current was observed in Ne-based mixtures. The peak discharge current density in mixtures with all buffer gases ranged from 1 to 2 kA/cm^2. Thus, the laser pulse duration and the output energy were limited. For instance, laser pulse duration was only 50 ns in Ar-based mixtures and no longer than 35 ns in He-based mixtures. Therefore, using two-circuit excitation scheme with $C_s >> C_p$ and spark preionization it is possible to obtain a quasi-stationary mode of excitation and generation in Ne-based mixtures at the discharge current density $J \leq 200$ A/cm^2.

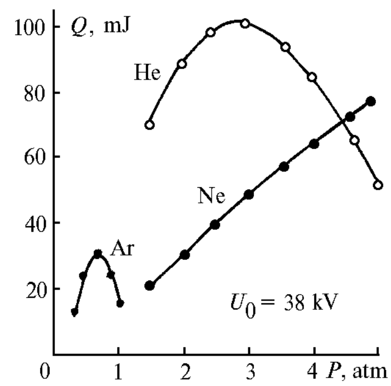

FIG. 3. Output energy versus total gas pressure in Xe:HCl = 10:1 (3 Torr) Ar-, He-, *and* Ne-*based mixtures. Spark preionization via a mesh electrode was used.*

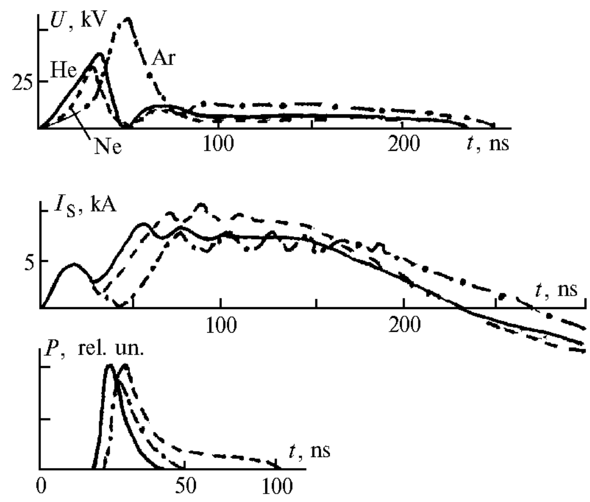

FIG. 4. Typical waveforms of the discharge voltage, current in the storing circuit, and lasing observed at $p = 1$ atm, $U_0 = 30$ kV *with the spark preionization via a mesh electrode in* Ar-, He- *or* Ne-*based gas mixtures.*

Based on analysis of the main publications on XeCl lasers with the fast and quasi-stationary excitation modes we present data on the highest output parameters of lasers with the spark preionization via the storing capacitor in Table II. In this table, the publications of the author are marked by *, data on ArF and KrF lasers with the highest parameters are marked by **; 2IC means two independent excitation circuits with the separate power supplies; MSC denotes the magnetic switch. The most optimal parameters of XeCl laser were reported in Ref. 23. These are Q_{out} = 1 J, τ = 275 ns and η = 2.2%. The highest specific output energy was obtained in Refs. 20 and 24 they are ~1 J/l atm and the highest lasing efficiency was demonstrated in Ref. 24. It was found to be 2.9%. In Ref. 25 pulse duration achieved was 600 ns at Q_{out} = 0.1 J and η = 0.02%. The theoretical paper[26] should be especially mentioned here as its authors have declared a possibility to obtain Q_{spec} = 11 J/l atm and η = 5.5%. It seems to be of practical interest since the values of the lasing efficiency of 3.9% in KrF laser and 2.1% in ArF laser have already been demonstrated.[27]

In conclusion, we summarize the main results described in this paper which were obtained with the spark preionization via the peaking or storing capacitors.

TABLE II. Main publications and the highest output parameters of XeCl *lasers with fast and quasi-stationary excitation mode and spark preionization via a storing capacitor.*

No.	Pumping scheme	Buffer gas	ρ, %	V, l	Q_{las}, J	Q, J/(l·atm)	$\tau_{h/2}$, ns	τ_{base}, ns	η, %	Year	Ref.
1**	C_s + UV/C_p	KrF	5	0.125	0.11	0.7	7	20	1	1978	16
2	C_g + UV/C_p	He	10	0.1	0.13	0.4	10	15	0.5	1980	17*
3	C_s + UV/C_p	He	10–40	0.1	0.127	0.5	15	40	0.5	1981	15*
				Quasi-stationary mode of the discharge							
4	C_s + UV + L_{st}/C_p	He	10–40	0.2	0.127	0.5	15	40	0.5	1982	1*
		Ne		Quasi-stationary mode of the pumping							
5	C_s + UV/C_p	Ne	10	0.12	0.28	0.6	20	80	2.9	1984	24
					0.68	1	20	40	1.8		
6	C_s + UV + L_{st}/C_p	Ne	10	0.18	0.5	0.75	15	170	1.6	1986	20*
7	C_s + UV/C_p theory	Ne	–	0.12	5.5	11.6	75	100	5.5	1986	26
8	C_s + UV + L_{st}/C_p + L_{st}	Ne He	7	0.18	0.5	0.75	15	170	1.6	1989	21*
9	C_s + UV/C_p	Ne	40	1.3	0.1	–	500	600	0.02	1989	25
					0.6	–	300	400	0.25		
10	2IC/MSC	–	–	0.54	1	–	200	275	2.2	1989	23
11**	C_s + UV/C_p	KrF	–	0.12	0.5	–	15	30	3.9	1994	27
		ArF			0.27	–			2.1		

CONCLUSION

The following conclusions can be formulated based on the results of investigations of the volume discharge and XeCl laser output parameters when using multi-circuit excitation schemes, automated preionization sources via the storing or peaking capacitors in Ar (He, Ne)–Xe–CCl_4 (HCl) mixtures:

1. The volume quasi-stationary discharge in He-based mixtures with the duration up to 400 ns and in Ar-based mixtures with the duration up to 200 ns was obtained in our experiments for the first time.

2. Higher efficiency of XeCl laser in Ar-based mixtures as compared to that in He-based mixtures at the output pulse duration of 170 ns was demonstrated in our experiments for the first time.

3. Quasi-stationary mode of excitation and generation in Ne-based mixtures with Q_{out} = 0.5 J, τ = 170 ns and η = 1.6% was realized in our experiments for the first time. Using the three-circuit excitation scheme the "multi-pulse generation" was observed.

4. The discharge current density is one of the main parameters which affect the duration of output pulses under quasi-stationary pumping.

5. Ion recombination dominates in the formation of XeCl molecules in Ar and Ne-based mixtures only in a quasi-stationary excitation mode.

6. It is shown that any location of the preionization sources in the electric circuit (in its peaking or storing part) leads to both fast and quasi-stationary excitation modes. However, duration of the quasi-stationary excitation mode is shorter by a factor of n if UV preionization is performed via the peaking capacitor as compared to that performed via the storing capacitor. This is related to the duration of the preionization pulse.

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