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Theoretical model of TEA nitrogen laser excited by electric discharge.
Part 3. Construction and the preliminary results of the experimental setup examination

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A construction of two utilizable setups of nitrogen laser of the TEA-type produced on the basis of the experimental model described in Parts 1 and 2 [1], [2] of this work has been described. The realized models of nitrogen lasers were subjected to examinations. The preliminary results of these examinations were compared with the results of the respective theoretical calculations. High degree of consistence of the measurement results with those of the corresponding simulation calculations was achieved.

1. Introduction

Due to attractive properties of radiation emitted by nitrogen lasers, in this field research in this field is being carried out almost continuously by different centres of science and technology.

In a series of articles devoted to construction of nitrogen lasers pumped with transversal electric discharge [3]–[15], the energies and durations of pulses are reported together with some parameters of electric circuits (usually the energy accumulated in the capacitors and the supply voltage). There are very few descriptions of the scheme of electric circuit and details of the chamber structure of nitrogen laser are rarely provided.

As was mentioned in the previous parts of this work [1], [2], the constructions described in the literature are difficult to reproduce so as to obtain either optimal or required parameters (or characteristics). In practice, two regions of nitrogen laser parameters are useful, *i.e.*, those for lasers generating nano- or subnanosecond pulses of radiation of high peak power, or those for lasers of relatively high energy generated in longer pulses. As is well known, the first region of parameters may be realized in constructions working at the atmospheric pressure of nitrogen (transversally excited atmospheric lasers called TEA lasers), while constructions working at pressure below the atmospheric one (underpressure lasers of TE (transversally excited) type make it possible to cover the other region. A brief foredesign has been worked out on the basis of both the analysis of the literature data and the results of computer calculations presented in the previous parts for lasers operating at the atmospheric pressure of nitrogen and for supply voltage ranging from 15 to 20 kV.

2. Survey of constructions of TEA nitrogen lasers

In the paper of Bergmann [5], the design of a laser working at the atmospheric pressure is described. The laser generates pulses of maximal power of 0.5 MW, with supply voltage being equal to 20 kV. The pulse duration amounts to about 1 ns, while the repeatability – 10 Hz. The laser is built of plane capacitor (dielectric of 0.4 mm in thickness covered with copper foil on both sides), on which the main electrodes are located, being fastened to the elements made of plexiglass. The electrodes produced of aluminium are of 9.5 mm radius and 25 cm in length. The elements fastening the electrodes are equipped with micrometer screws, which enable the adjustment of the interelectrode distance. In Figure 1, a construction of the laser is shown. The system is released by a two-electrode spark gap (copper electrodes) working at the atmospheric pressure. The laser channel is closed by a mirror on one side, while a free outflow of nitrogen is possible on the other side of the channel. The outflow speed has been fixed at about 1 litre/min., for which the maximum power of the pulses generated by the laser is observed. The authors pay attention to the possibility of projecting a variable distance between the laser electrodes (shorter by the mirror, longer at the other end of the electrodes) in order to better synchronize the electric discharge process with the voltage wave travelling along the Blumlein line. The idea of variable distance between the electrodes has also been reported in the patent No. 2528174 (FRG) conferred on its authors Salazmann and Strohwald in 1978. The laser described in the paper is equipped with a chamber of variable resistance due to application of variable distance between the electrodes, thus eliminating the necessity of using the Blumlein line in order to create the running discharge wave.

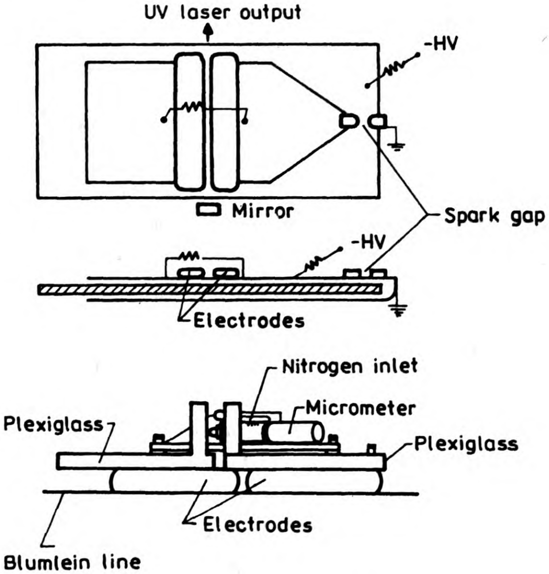

Fig. 1. Scheme of laser structure [5]

In the advertising materials of Laser Science Inc., the working parameters of mass-produced nitrogen laser are described. The laser generates pulses of maximal power 40 kW and duration 3 ns. The repeatability is adjustable within the limits of 1 – 20 Hz. The laser has a cut-off chamber which eliminates the usage of the nitrogen cylinder. After the operation life determined by the firm has expired (about 10^7 pulses), the ensemble of electrodes and mirrors, together with the chamber, are replaced by new elements available in a service workshop. The feeder and the laser are built in a common housing.

The construction of the nitrogen laser with the Blumlein line is described in the paper [7]. The line is produced of epoxide glass of dimensions 460 × 300 mm laminated with copper on both sides. The capacity of the line is about 3.5 nF. On the upper cover of the line, two aluminium electrodes of 400 mm in length and 8 mm in thickness are fastened. One of them is fastened permanently, while the other may be shifted in a way enabling both its positioning at a desired angle with respect to the resonator axis and changing the distance between the electrodes within the range of up to 10 mm. A free flow of nitrogen is made possible through the laser chamber created by the electrodes covered with plexiglass. The commutator is controlled by the spark gap working at the atmospheric pressure with preionizing surface discharge across the ceramics. The laser head was supplied by the maximal voltage of 24 kV. The laser working with the pulse repeatability of 5 – 50 Hz, generated pulses of peak power up to 200 kW, energy of about 0. 2 mJ and the duration about 0.9 ns for optimal distance between the electrodes amounting to 2.9 mm and the angle of flare between them equal to 5 mrad. For this angle between the electrodes, the ratio of the energy emitted by both sides of the resonator was 1:50. In spite of this, the application of a totally reflecting mirror from the side of shorter distance between the electrodes resulted in an increase of energy in the opposite direction by a factor of 1.5.

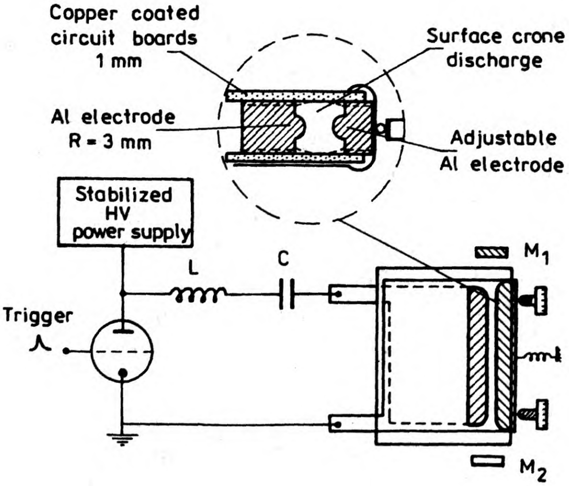

Fig. 2. Scheme of nitrogen laser of TEA type [10]

In Figure 2, a scheme of the nitrogen laser structure described by SÁNTA [10] is shown. The transmission line has been made of textolite of 1.5 mm in thickness laminated with copper on both sides. The capacitor bank was based on barium titanate dielectric ceramic capacitors. The working part of electrodes is of the radius of 3 mm and the length of about 30 cm. The travelling wave of the electric discharge has been stimulated by positioning one of the discharging electrodes at an angle with respect to the other fixed electrode. This was possible because the electrode was fastened to the working plane with the help of some copper foil. The angle of the flare of electrodes is 0.3 mrad. The resonator is created by an aluminium totally reflecting mirror and a quartz plate. As a commutator a hydrogen thyratron was used. The laser worked with normal repetition frequency of up to 50 Hz. The nitrogen flew along the resonator axis and its speed depended on the repetition frequency.

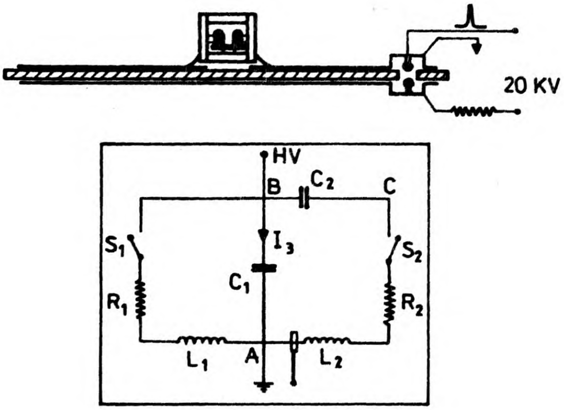

Fig. 3. Scheme of the head and a substitute electric circuit of the laser head

In the paper by PAPADOPOULOS [12], the construction of a nitrogen laser was described, the scheme of which is shown in Fig. 3. Two plate capacitors of capacity 5.6 nF each were formed of a plate of epoxide glass of sizes 107 × 58 cm and thickness 2 mm which was laminated with copper on both sides. As a commutator a three-electrode spark gap was used which was produced by using a technique assuring its minimal inductance. The resonator of length 62 cm was created by an aluminium mirror and a window produced of sapphire. The main discharging electrodes of the length 50 cm and a specially chosen shape were produced of brass. The width of the effective working surface of the electrodes was 0.75 cm. One of the electrodes was fastened firmly while the other could be shifted. In order to minimize the inductance introduced by this setup an aluminium foil was inserted between the electrode and the working plate. The laser chamber was produced of plexiglass and aluminium. The contruction enabled its demounting as one of the sub-assemblies. Nitrogen mixed with helium in 1:6 ratio was used as a mixture. The laser emitted the radiation pulses of duration 7 ns and energy 2.93 mJ for the supplying voltage 20 kV.

From the presented descriptions of construction, it follows that there is a tendency to simplify the laser structure. Four basic sub-assemblies may be distinguished.

The first one is the laser chamber. It is created by the main electrodes, with curvature radius being optimally selected in their working parts. The electrodes are made of brass or an alloy of metals resistive to pulverizing. The optical elements creating the resonator are a totally reflecting mirror and a quartz plate. The construction of the channel assures a free flow of gas. Lasers of cut-off chamber are rather rare.

The second sub-assembly consists of a plate made of epoxide glass of glassy textolite laminated with copper on both sides. The upper part of the plate formed suitably creates two plate capacitors: the one accumulating the electric energy and the other forming the travelling waves. The dimensions of the forming capacitor were calculated on the basis of fitting the velocities of the voltage wave in the line to the radiation speed in the lasing medium. Both the condensers are of the same capacity. In the central part of the plate, the laser chamber is fastened.

The third sub-assembly is the spark gap of two or three electrodes. Its reliability and permanency of parameters have a decisive influence on the stability of laser operation. The spark gap is filled with nitrogen or carbon dioxide.

In the discharging channel, the UV preionization is applied. The UV radiation is produced by creating the surface discharge across the dielectric surface.

The fourth sub-assembly of the laser is a high-voltage power supply. It renders possible the work with the repetition frequency of pulses up to about 100 Hz, for the output voltage of about 21 KV. There is a tendency to block the laser head and the power supply within one common housing.

3. Brief foredesign of laser

The maximization of efficiency, energy or radiation requires a suitable selection of the chamber sizes, capacitor capacities and other elements of the electric circuit. On the basis of analysis of the results reported in part 2 of this work [2], some simplifications of the dependences between these parameters are possible.

The brief foredesign of our experimental models have been formulated taking advantage of the works by SHIPMAN [14] and BASTING *et al.* [15]. They worked out the fundamental elements of design of nitrogen lasers which were next modified by their subsequent designers. However, the fundamental basis for us was our own complete theoretical model described in the two previous parts of this works [1], [2]. The scheme of the proposed design is shown in Fig. 4. The basic requirements determined the expected energies and the duration of pulses. In one case, a laser was desired which generated pulses of duration below 1 ns and power of about 100 kW. The other laser intended for microprocessing of thin layers should generate pulses of duration 1 ns and power 1 MW.

In order to determine the optimal length of the main discharging electrodes numerical simulation was carried out, the results of which are presented in Fig. 5.

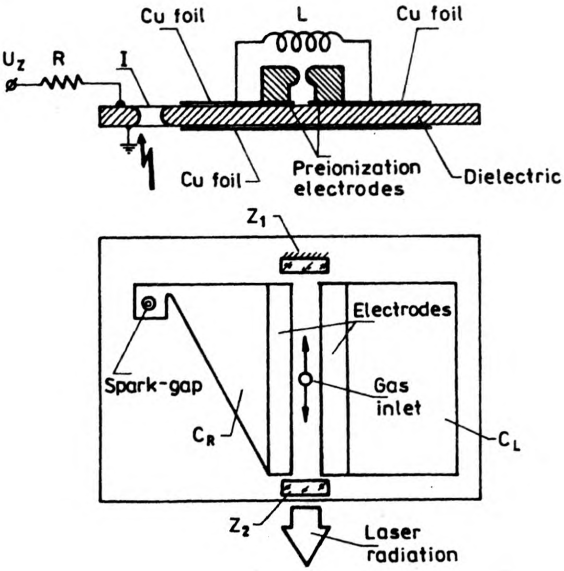

Fig. 4. Construction scheme of an atmospheric nitrogen laser of TEA type

During simulation only the length of electrodes was subject to changes, the other parameters remaining unchanged. The pulse energy grows relatively quickly with the increase of electrode length up to about 50 cm. The further increase of their length causes only negligible increase of energy value. The electrode length in an atmospheric nitrogen laser should amount to about 50 cm (for a 100 kW laser the length of electrodes will fluctuate around 100 mm). The next magnitude determining the correct work of laser is the distance between the main discharging electrodes. The dependence of radiation energy on the interelectrode distance at a constant supply voltage has been presented in Fig. 6. For each supply voltage, there exist a distance between the electrodes for which the pulses have the highest energy. For the

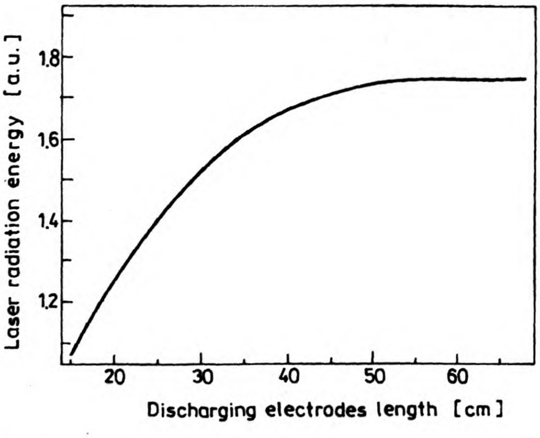

Fig. 5. Dependence of the laser radiation energy on the length of the main discharge electrodes

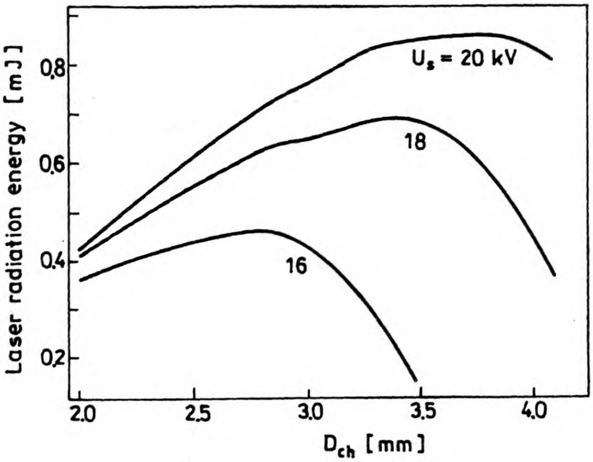

Fig. 6. Output energy of the laser radiation as a function of the interelectrode distance parameterized with respect to the supply voltage U_s

voltage of 20 kV supposed to supply our laser, the optimal interelectrode distance was between 3.6–3.8 mm (for the voltage 15 kV – about 3 mm). The electrodes must be produced of brass. Their radius of curvature, as it follows from the literature data, should amount to about 6–9 mm. Such a radius allows us to relatively well approximate the Rogowski profile. The numerical calculations of the laser efficiencies showed that their maximal values (internal, total and electric) are achievable for equal values of capacities C_R and C_L. They should be equal to about 0.5 nF (15 kV) in the first case and range between 6 and 7 nF (20 kV) in the other. This follows from the numerical calculations. The shape of the capacitor C_R should be calculated from the synchronization condition for the voltage wave with laser radiation propagating within the laser chamber. As a commutator, a two- or three-electrode spark gap of low inductance should be chosen. In order to assure uniformity of the main discharge in the laser chamber the preionization with the UV radiation should be applied. The source of the latter will be surface discharge across the dielectric surface.

4. Description of construction of the performed models of experimental nitrogen lasers

Two models have been produced: Nitro 1/110 and Nitro 1/480 MS. The most technologically advanced construction, fulfilling the requirements of a prototype is that of Nitro 1/110 laser. In the discharge channel UV preionization was applied. It consists in introducing the UV radiation in the vicinity of the main electrodes, which ionizes the medium in the discharge region. The UV radiation in the laser is created by realizing the surface discharge across the dielectric (laminate) surface [16] for the interelectrode distance of order of 6 mm. Such a preionization system is characterized by three main features, which decided about its choice: simplicity of the construction, integral connection with the supplying system and, what follows, natural easiness to synchronize the preionizing discharge with the main discharge.

The scheme of operation of the presented nitrogen laser is the following. The capacitors C_R and C_L (Fig. 4) are loaded up to the voltage U_s through the resistance R and the inductance L. After the breakdown in the spark gap the charging of capacitor C_R to the negative voltage occurs (resistor R restricts the current taken at that time from the supplying source and the choke L prevents the discharge of the capacitor C_L). A considerable difference of potentials appearing consequently between the electrodes of the laser channel, causes a development of discharge while its resistance drops down simultaneously rendering possible the mutual reloading of the capacitors C_R and C_L. The latter effect lasts very shortly of order of nanoseconds, thanks to negligible inductance of the capacitors produced as plane lines. This is accomplished by very strong currents – impedance of the line being small and contained within the limits 0.2–0.5 Ω. These parameters of discharge in the laser chamber make it possible to achieve the inversion of population of laser levels in nitrogen and in consequence the generation of the radiation pulse. This laser generates the pulses of energy up to 70 μJ and the half-width duration slightly below 1 ns. The general view of the NITRO 1/110 laser is shown in Fig. 7a.

Fig. 7. External view of the atmospheric laser. **a** – NITRO 1/110 from the left hand side, prototype functioning model, **b** – NITRO 1/480MS with power supply

The elaborated and produced second model of the nitrogen laser of TEA type has been temporarily called NITRO 1/480MS. It differs from the NITRO 1/110 mainly so far as the dimensions are concerned. The length of the electrodes has been increased up to 480 mm and the capacities C_R and C_L up to 6.3 nF. The fastening of the electrodes to the laser working plate has been improved by cementing them with an epoxide preparate conducting the electric current with the help of a specially formed copper foil. This connection is of low resistance and simultaneously renders it possible to establish the changeable distance between the laser electrodes — the latter being less close to mirror, greater at the other end of electrodes. The aim of such positioning of the electrodes is to improve the synchronization of the laser pulse generation process with the travelling wave of electric discharge appearing in the line forming the voltage pulse. Also, the construction of the spark gap was changed. A high-pressure (0.5 – 1 MPA) three-electrode spark gap was applied. This assures a more stable work of the laser. The high-voltage power supply is a self-contained device and it is possible to exploit it to feed the heads of other lasers. The view of the laser is shown in Fig. 7b.

5. Examinations of nitrogen laser of TEA type

The purpose of examining the lasers described in detail in Sect. 4 of this paper was to determine the parameters of the laser beam generated in these setups as well as the experimental selection of the working point of the head. This task is reduced to determination of the optimal voltage nitrogen pressure and the interelectrode distance. The former simulating examinations simplified, thanks to some narrowing of the region of seeking, and accelerated the performance of the experimental examinations. Another important aim of these examinations was the verification of the results of computer simulation presented in part 2 of this work [2]. For this purpose the characteristics calculated earlier by numerical methods have been determined experimentally. The comparison of the qualitative (character of changes of the examined magnitudes) and the quantitative results obtained in the way of both simulation and experiment will allow to improve the mathematical model of the laser and its wider exploitation in the works concerning the design and optimization of parameters of the nitrogen laser heads.

The measurements of characteristics of the NITRO 1/480MS laser were performed on the measurement stand the scheme of which is presented in Fig. 8. Besides the laser head and the installation of the necessary accessories (vacuum pump, pressure gauge, high-voltage power supply, laser operation, controlling devices) the stand contained the measurement devices enabling us to measure the energy and duration of the laser radiation pulse as well as the voltage in the external points of the electric circuit. The elements of the measuring system being sensitive to the electromagnetic disturbances emitted during the high-current discharge in gas were located in the Faraday cage.

The energy and duration of pulse were examined simultaneously. These magnitudes were measured as functions of the supply voltage and the pressure of the

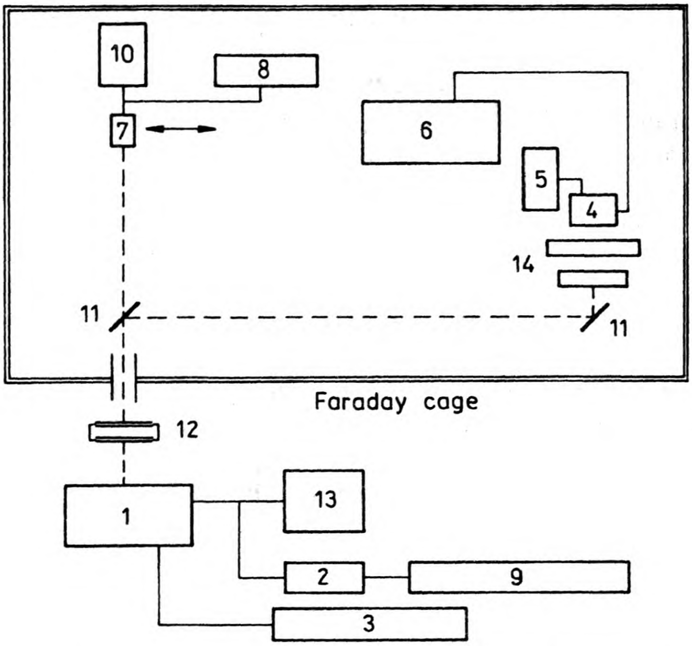

Fig. 8. Scheme of the measurement stand. 1 – Nitrogen laser head with the controlling block, 2 – high-voltage probe of Tektronix, 3 – external gas installation of the laser (gas bottle flowmeter, pump gas reduction – option), 4 – vacuum photodiode ITL (100 ps), 5 – photodiode power supply ZWN–42 (–3 kV), 6 – oscilloscope Tektronix 7844 (1.4 GHz band without amplifying insert – option), 7 – head of a RJP–734 laser radiation meter, 8 – monitor of the RJ 7620 laser radiation energy meter, 9 – oscilloscope Tesla BM 556 A, 10 – He-Ne laser (laser resonator adjustment), 11 – light dividing plate, 12 – attenuating filter for the visible range radiation, 13 – high-voltage power supply, 14 – UV radiation attenuating filter ($\lambda = 337.1$ nm)

active medium. For this purpose the beam of radiation was directed onto the half-transparent quartz plate. The part of radiation passing through was used to measure energy of the light pulse. This part was incident on a RJP-734 piroelectric probe of the laser pulse energy gauge RJ 7620 equipped with monitor of electronic readout produced by Laser Precision. The catalogue measurement accuracy within the UV spectral range is claimed to be not worse than 10%. The reflected part of radiation was used to measure the pulse duration. It was directed via the optical attenuating filters to the TFI-1859 MG-2 photodiode of Instrument Technology Limited make, which cooperated with a wideband Tektronix 7844 oscilloscope. The time resolution of the photodiode according to catalogue amounted to 0.1 ns. The response time of the oscilloscope was 0.35 ns. The resolution of the entire measurement setup was not worse than 0.7 ns. For measuring the characteristics of TEA lasers the oscilloscope worked without amplifying the inserts (response time about 0.25 ns) and the pulse from the photodiode was applied directly to the deflector plates. In this way, the transfer band of the oscilloscope amounted to 1.4 GHz and was sufficient for the measurement of pulses of duration of order of 1 ns. The value of voltage in the external points of the electric circuit of the laser head was measured with high voltage probe of P 6015 type produced by Tektronix. The attenuation of radiation introduced by the light splitter plates and the filters were corrected by an electronic system located inside the energy meter.

5.1. Measurement of the laser radiation pulse duration

The duration of laser radiation pulse was estimated on the basis of oscillograms presenting the intensity of the light flux emitted by the laser as a function of time. An example of such oscillogram is shown in Fig. 9**a**, while an example of the pulse shape calculated numerically is given in Fig. 9**b**. During the examinations the shape of the pulse did not suffer from essential changes. The pulse duration measured at half its height was contained within the 1.1 – 1.5 ns interval. Its relative error was about 10%. However, the pulse duration of the laser radiation obtained from numerical calculations ranged within 0.9 – 1.2 ns interval. This means good consistency of the two results, both in qualitative and quantitative sense.

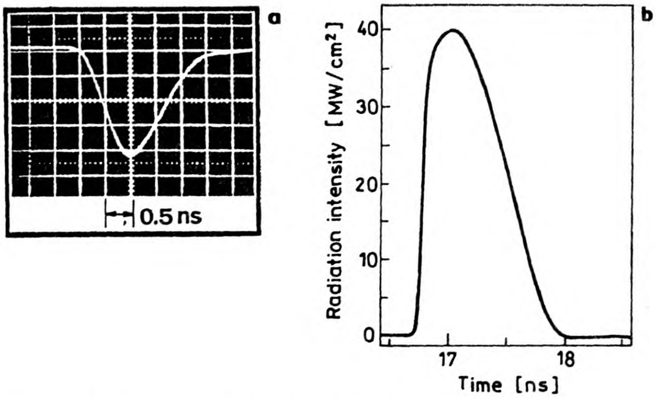

Fig. 9. Pulse shape for the NITRO 1/480MS laser radiation: **a** – experiment, **b** – theory

5.2. Energy measurement of laser radiation pulse

The measurements were made for single pulse operation of the laser. The influence of such factors as the supply voltage and the distance between the main electrodes, among others, on the pulse energy was estimated.

In Figure 10**a**, the results of radiation pulse measurement as a function of the voltage supplying the laser head are presented. The respective dependences have been obtained for a fixed distance between the main electrodes of the laser chamber. The character of changeability of the determined family of characteristics is similar. With an increase of the supply voltage the laser radiation energy increases in an almost linear way. Such a dependence has been obtained in the course of numerical simulation. Its result is shown in Fig. 10**b**.

The energy of radiation pulse as a function of interelectrode distance has been presented in Fig. 11. The characteristics have been parameterized with respect to the voltage supplying the laser head. For each supply voltage the optimal interelectrode distance may be determined. With an increase of voltage the optimal value of the

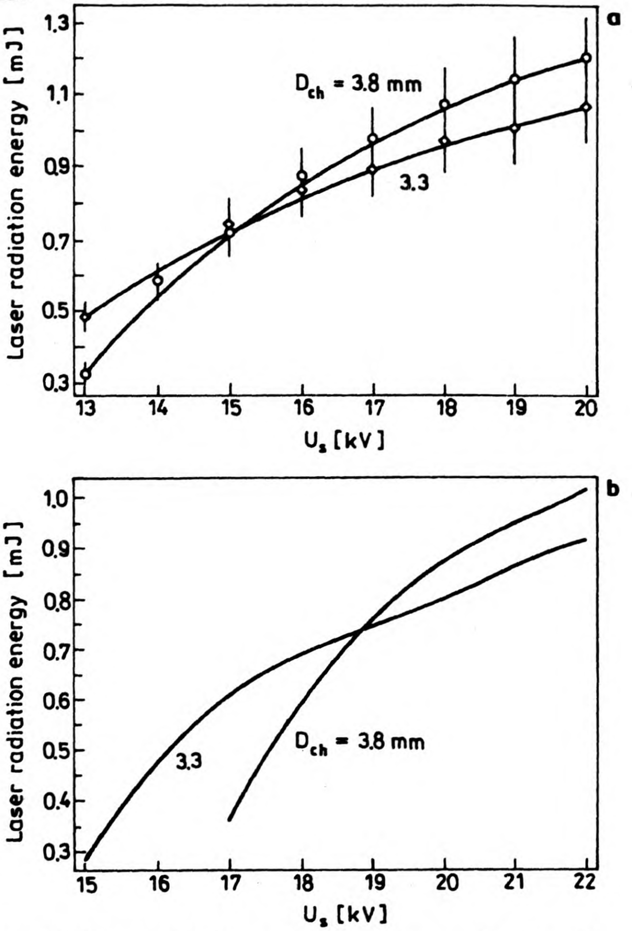

Fig. 10. Energy of the laser radiation pulses as a function of supply voltage — NITRO 1/480 MS laser: **a** — experiment, **b** — theory

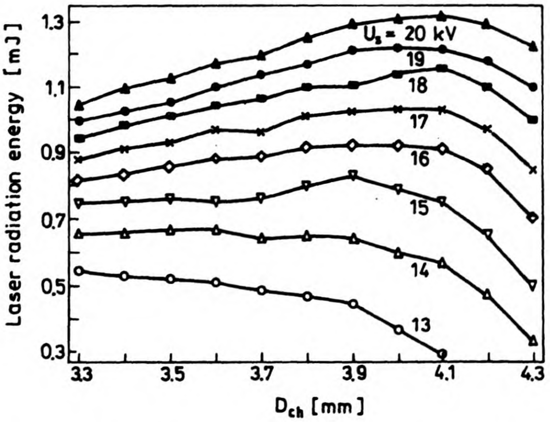

Fig. 11. Laser radiation energy as a function of interelectrode distance for fixed supply voltage U_s — NITRO 1/480 MS laser

interelectrode distance D_{ch} is shifted towards higher values. For the supply voltage $U_s = 15$ kV, the optimal value of D_{ch} amounts to about 3.9 mm. While for the voltage $U_s = 20$ kV – $D_{ch} = 4.1$ mm. For two different values of the interelectrode distance, such that $D_{ch1} < D_{ch2}$ (Fig. 10a), the higher energy corresponds to lower value of D_1 at lower voltage while the higher energy of radiation corresponds to higher value of D_2 at higher voltage. For low ranges of supply voltage, the selection of optimal E/p ratio having an essential influence on the value of the emitted energy, is made by diminishing the interelectrode distance. When preserving a constant distance D_{ch}, an increase of voltage results in an increase of E/p ratio above its optimal value. This results, in turn, in diminishing of the output energy. The situation is similar at higher voltages. The following information is essential for exploitation: for each range of voltage considered as the working voltage the value of the interelectrode distance must be optimized separately. This conclusion has been confirmed by the results of numerical calculations presented in Fig. 8.

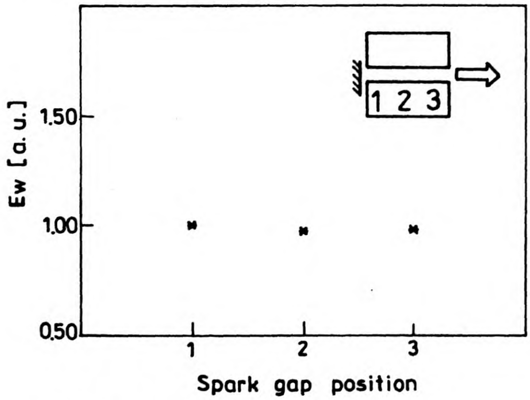

Fig. 12. Influence of the spark gap position on energy of laser radiation pulse for NITRO 1/480MS laser

In Figure 12, the influence of the spark gap position with respect to the chosen end of the discharge channel is shown for which the energy measurement was carried out. The experiment was performed for the laser model, where both the plates of the plate capacitor were rectangular. In such a system, the travelling wave of voltage may be created by locating the commutator in the corner of the condenser plate. The discharging electrodes were positioned parallelly to each other with the accuracy up to 0.01 mm. As it follows from the presented measurements, the output energy does not change in an essential way with the change of position of the installed spark gap. This is consistent with the observations made in paper [12], from which it follows that the plate capacitor does not behave like a transmission line. This is caused by the fact that current pulse duration is longer than the time necessary for propagation of radiation along the capacitor.

6. Summary

Two models of nitrogen laser have been constructed on the basis of numerical calculations obtained by taking advantage of the theoretical models especially worked out. The two lasers belong to the group of atmospheric lasers. The expected parameters of those lasers are presented in Table 1.

Table 1. Basic parameters of the performed models of nitrogen lasers

Parameters	Laser NITRO	
	1/110	1/480 MS
Electrode length [mm]	100	480
Supply voltage [kV]	15	20
Repetition frequency [Hz]	60	10
Maximal power in a pulse [kW]	~100	~1000
Pulse duration [ns]	~1	~1.5
Working capacity [nF]	0.5/0.5	6.3/6.3
Commutator inductance [nH]	14	16
Interelectrode distance [mm]	1–4	3–5

The above lasers have been exploited in design of a lathe for microprocessing thin films and as a pump for dye lasers.

The results of examinations of the NITRO 1/480 MS laser are presented in the form of characteristics obtained experimentally and simulated numerically. The comparison of the most important parameters of the laser radiation pulse obtained theoretically and experimentally is presented in Table 2.

Table 2. Comparison of the most important parameters of laser pulse obtained from experiments and computer calculations

		Nitrogen laser NITRO 1/480 MS			
		Experiment		Theory	
FWHM *	[ns]	1.2	$U_s = 20$ kV	0.9	$U_s = 20$ kV
Pulse energy	[mJ]	1.2	$U_s = 20$ kV $D_{ch} = 3.8$ mm	0.9	$U_s = 20$ kV $D_{ch} = 3.8$ mm

* Halfwidth pulse duration

Their qualitative comparison (character of changes of the examined magnitudes) showed their complete consistence. They are also consistent quantitatively up to 10–50%. The achieved consistency speaks for both correctness of the theoretical model and the proper construction of the built lasers. In this way, some useful, experimentally verified tool was obtained in the form of a theoretical model. This allows us, by taking account of many essential input data, to efficiently narrow the region of seeking of both the optimal working parameters and the design of nitrogen lasers.

References

[1] Makuchowski J., Pokora L., Opt. Appl. **23** (1993), 113.

[2] *Ibidem*, p. 131.

[3] Kunabenchi R. S., Gorbal M. R., Savadatti M. I., Prog. Quantum Electron. **9** (1984), 259.

[4] Bergmann E. E., Appl. Phys. Lett. **28** (1976), 84.

[5] Bergmann E. E., Rev. Sci. Instrum. **48** (1977), 545.

[6] Dzakowic G., Kan T., Kuenning R., Schlift L., *Design study of high average power* (20–100 *watts*) *pulsed nitrogen lasers at* $\lambda = 3371.3$ Å, Lawrence Livermore Laboratory Report UCID -16738, 1975.

[7] Sonin A. Yu., Batygov A. A., Kvantovaya Elektron. **15** (1988), 501.

[8] Taniguchi H., Saito H., SPIE **236** (1980), 294.

[9] Iwasaki Ch., Jitsuno T., IEEE J. Quantum Electron. **18** (1982), 423.

[10] Sánta I., Kozma L. Němet B., Hebling J., Gorbal M. R., IEEE J. Quantum Electron. **22** (1986), 2174.

[11] Stankov K. A., Milev I. Y., Kurtev S. Z., Opt. Commun. **62** (1987), 29.

[12] Papadopoulos A. D., Serafetinides A. A., IEEE J. Quantum Electron. **26** (1990), 177.

[13] Sánta I., Kozma L., Rac B., Kvantovaya Electron. **12** (1985), 820 (in Russian).

[14] Shipman J. D., Appl. Phys. Lett. **10** (1967), 3.

[15] Basting D., Schafer F. P., Steyer B., Optoelectronics **4** (1972), 43.

[16] Fahlen T. S., IEEE J. Quantum Electron. **14** (1979), 311.

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