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Industrial repetitive-pulse CO_2 laser

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ABSTRACT

The parameters of a repetitive-pulse CO_2 laser are given and its construction described. The energy characteristics of the radiation and the shape of the laser pulse have been investigated as a function of the composition and pressure of the mixture. Aspects of the design approaches are considered: implementation of rotation in vacuum by means of magnetic clutches, the presence of two discharge chambers, and the automatic control elements. The functional capabilities eligibility, and lifetime of individual elements and assemblies are evaluated.

Keywords: CO_2-laser, pulse periodic laser, industrial laser

1. INTRODUCTION

The prospects of laser technology have been substantially enhanced with the appearance of CO_2 lasers with repetitive-pulse action (CO_2-RPL). In a CO_2 repetitive-pulse laser, in contrast to CW lasers, the radiation is characterized by three independent parameters: the energy, duration, and repetition frequency of the pulses; this makes it possible to obtain a broad spectrum of technical regimes. The presence of three parameters and the possibility of attaining high peak powers in the pulses, ensuring evaporation of the materials being processed, in conjunction with the simplicity and reliability of the design,, make it possible for these lasers to find extensive application in industry [1-3].

The first investigations into the technical of CO_2-RPL have shown that in some cases they may prove more effective and more economical than CW lasers, and that several operations, such as piercing of holes, can only be implemented with such a laser operating mode. When the radiation of repetitive-pulse lasers is used for cutting and welding, the cuts and seams are narrower and the ratio of the depth of fusion to the width is greater [4]. The repetitive-pulse mode of processing with high peak power also offers advantages in cutting of dielectric, composites, extra-hard, and high-melting materials.

It it possible to employ CO_2-RPL with short pulse duration and sufficient energy for successful laser ultrasound inspection of materials, selective excitation of chemical reactions, separation of isotopes, and optical pumping of the active media of lasers in the far infrared range. Thus the development of industrial repetitive-pulse CO_2 lasers capable of operating reliably and efficiently in industry with average power of 1 kW and above is now an urgent task.

Here we report research and development results for a repetitive-pulse industrial laser (RPIL) with an average power of 2 kW, an energy of 1-4 J in a pulse, a pulse duration of 10-50 μsec, and a pulse repetition frequency of up to 1200 Hz.

2. DESCRIPTION OF LASER STRUCTURE

From a structural viewpoint the industrial repetitive-pulse CO_2 laser developed consists of a gas-discharge loop with volume of about 1 m^3 and means of pumping, two discharge chambers loop with volume of about 1 m^3 and means of pumping, two discharge chambers, a resonator, a heat exchanger, and a base with auxiliary systems: evacuation, gas admission, etc. (Fig. 1). Since the laser is oriented toward commercial production, extensive use is made in its design of series-produced components and assemblies. Such am approach simplifies the fabrication and equipping of the laser and improves its reliability. The laser has two gasdynamic channels and two discharge chambers. The two-chamber design, with a common resonator or two independent resonators, makes it possible to produce one or two beams, respectively, which broadens the technical capabilities of the laser.

The working mixture is pumped by two centrifugal fans. The average rate of flow of the mixture through the discharge gap is 21 m/sec, with no more than a 10% deviation from this value for fan speeds of 1500 rpm. Rotation is imparted by means of magnetic clutches through an impermeable partition. Despite a certain amount of complexity in manufacture, this way of realizing rotation offers such positive qualities as not subjecting the gas loop to the organic materials used in motors, lack of any need for introducing power into the vacuum. In order to establish slipping of the clutch halves during starting the motors are provided with a smooth starting circuit. .

As we have noted, two discharge chambers are used for pumping of the laser mixture. The principal structure of a discharge chamber is the duralumin anode plate with flat working surface. Two profiled copper cathodes are suspended from the anode plate through dielectric spacers. 34 motors-vehicle sparkplugs, attached to the anode, are used to produce ultraviolet preionization. The series of sparkplugs is downstream by 40 mm away from the discharge axis. The sparkplug electrodes project 2 mm above the working surface of the anode. Utilization of sparkplugs substantially simplifies the structure of the discharge chambers. The auxiliary-discharge capacitors (type KVIZ, 470 pF, 16 kV), connected into stacks as shown in the high-voltage pulse circuit of Fig. 2, are mounted above the anode directly in the neighborhood of the sparkplugs. Two such discharge chambers make it possible to excite the laser mixture in a volume of $2\times(1\times0.02\times0.025)$ $m^3$and provide a specifi energy contribution of up to 2 J/(m^3Pa) at a pulse repetition frequency of 250 Hz. The two discharge chambers are joined by a U-shaped stable resonator consisting of their output in it, a spherical mirror with 15 m radius of curvature, and two rotating mirrors. The mirrors are located on two plates coupled together by three Invar rods. The spherical and rotating mirror are copper and are cooled by running water.

The output assembly consists of a located output window (coated plate of KCl or ZnSe) and a semitransparent mirror, a planet-parallel GaAs plate. A diaphragm located near the output mirror is used to extract the fundamental transverse mode. The combination of a two-chamber structure and a resonator of this type makes it possible to obtain three laser operating regimes. In the first, with simultaneous operation of the discharge chambers, the energy in a pulse reaches 2-4 J at a pulse repetition frequency of 1-600 Hz. Alternate operation of the discharge chambers constitutes the second regime; here the pulse repetition frequency is doubled, with a corresponding reduction of the energy in a pulse. In the third regime one discharge chambers operates with a certain delay with respect to the other, which lengthens the radiation pulse.

Specialized power supplies have been developed for charging of the storage capacitors [5].The capacitors are charged in the course of a single pulse lasting about 150 μsec; 200 μsec later a trigger pulse is applied to the thyratron grid, a pulse discharge takes place, and the radiation pulse is formed. Fig.3 shows the graphic representations and oscillograms of characteristics pulses, from the starting pulse to the radiation. The discharge-current oscillogram was measured by means of a Gorowski loop, and the voltage over dc sources: even at the maximum pulse repetition frequency (600 Hz) the capacitors and thyratron cutoff, reduces energy losses due to leakage currents, and makes the laser safer. What is more, such sources are significantly smaller in size and lighter in weight than dc sources.

Owing to the breakdown of CO_2 in an electric discharge the average power and stability of the discharge in CO_2-RPL decrease with time. Thus to stabilize the laser radiation parameters it is necessary to have constant partial renewal of the mixture. An automatic gas-supply system was developed for this purpose that makes it possible to prepare the required mixture, implement makeup at a rate that depends on laser operation, and stabilize the pressure in the gas loop with an accuracy of ±133 Pa.

The system comprises two tanks, pressure sensors, electromagnetic valves, and a control unit. The mixture prepared in the mixing tank is delivered to the storage tank, and then into the gas loop. At the instant at which the pressure in the tanks drops below a particular value, the mixing tank is disconnected and preparation of working mixture in accordance with partial pressures commences in this tank; during this time gas-circuit makeup is carried out from the storage tank. When the working pressure is reached in the mixing tank the bypass valve joining the mixer and storage tanks is opened and the cycle is repeated.

It should be noted that in a repetitive-pulse industrial laser a high degree of gasloop tightness is attained for such a class of lasers. The amount of leakage into the loop is $\leq 3.5*10^{-3}$ Pa/sec, which has made it possible to reduce the rate of flow of gases for renewal of the mixture.

3. OPTICAL-PHYSICAL PARAMETERS OF LASER.

The most important characteristics of a repetitive-pulse industrial laser are the energy parameters of the radiation pulses: waveform, duration, and stability in the course of operation. In addition we also have the maximum average radiation power, the divergence, the efficiency, and the lifetime of the laser and its individual assemblies.

A type TPI-2M calorimeter was employed to measure the energy of the radiation pulses. The energy of one pulse was determined by averaging ever a series of 200 pulses, the repetition frequency being high. This method was used to measure the dependencies of the laser-pulse energy on the contribution to the discharge for various relationships of the concentrations of N_2 and CO_2 and various values of pressure of the molecular components (Fig.4).

The average radiation power was measured by means of a type M3-48 wattmeter with modified receiving head. The dependence of average power on pulse repetition frequency, $P_{av}(f_{rp})$, was measured. The measurements were carried out for a CO_2:N_2:Ne=1:4:10 mixture with a pressure in the gas loop of 32 kPa, and contributions to the discharge of 22.5 and 40 J/pls. $P_{av}(f_{rp})$ is linear up to frequencies of 360 Hz and 440 Hz, respectively. A further increase in frequency led to concentration in the discharge. Statistical processing of the dependencies of average power on pulse repetition frequency yields an estimate for the stability of the average radiation power of ±3% over the time during which the measurements were made. The question of the stability of the laser radiation parameters is being investigated in detail.

In addition to measuring pulse energy we investigated pulse shape and measured the duration. The waveform of the laser pulses was observed by means of a special type FIPCh photodetector and a type C9-4A oscillograph. The time resolution of the measurement system was $1*10^{-9}$ s. The oscillogram shows the single pulse produced with alternate operation of the discharge chambers and doubled pulse at the shifted-pulse regime. A shift by 2.5 μsec leads to the formation of a «two-hump» laser pulse with corresponding elongation. This pulse has the same peak power as an individual pulse, but it has twice the energy.

Fig.5 shows the way in which laser-pulse duration depends on the composition of the mixture and the pressure of the molecular components (here we have in mind the duration with respect to the zero level).

A year of operation of the laser makes it possible to draw conclusions as to the lifetime and reliability of the basic elements and assemblies of the unit. The lifetime of the pumping system, operating for more than 1000 hr, is basically associated with the «aging» of the magnets in the clutch halves and the stability of the lubricant used for the bearings located in vacuum; according to our estimates this lifetime is at least 5000 hr.

The accrued operating time of a discharge chamber depends on the reliability of the preionization system and the electrodes themselves. As operation as show, the most critical elements, determining the accrued operating time of a discharge chamber are the cathodes, which require preventive maintenance every 200 hr, since the oxide film that appears over course of time impairs the stability of the discharge. The preionization sparkplugs withstand $5 \cdot 10^8$ pulses with no change in their characteristics. An expert estimate of the time of operation to sparkplug replacement comes to 10^9-10^{10} pulses.

The good radiation resistance of the GaAs plate used as the output mirror and of the coated ZnSe used as the output window provide an output-assembly lifetime of 500 hr, while the copper mirrors require preventive maintenance after more than 1000 hr of operation. After this time chemical cleaning of the elements is required to remove the «scale» caused by the presence of residual mechanical and organic impurities in the laser loop; repolishing is employed if cleaning does not yield the desired results/ The operating time schedule may be increased by improving the cleanliness of the loop/ Attempts to use dielectric mirrors on substrates of KCl and ZnSe have not met with success owing to low radiation resistance.

The average power level reached of 1 kW does not represent the limit for a laser of such design. As an example, by shifting to a fan speed of 3000rpm it is possible to double the average radiation power by doubling the pulse repetition frequency, but this shift encounters difficulties associated with the need for careful dynamic balancing of the fans with the magnetic half clutches. These difficulties are not fundamental in nature and can be fully overcome.

A program has now commenced to work out laser lasing regimes for piercing of holes in metals, dielectric, and composite materials. Preliminary experiments have shown that the repetitive-pulse industrial laser will find extensive applications in laser technology.

The model described above is used as the basis for a double-beam variant of the laser. This variant differs from the basic model in that it employs two resonators in combination with two discharge chambers. The beams are extracted on one side and at the same level in height. The transition to the double-beam variant allowed nearly two-fold reduction of beam load upon the optical components, which is useful in increasing their service life. Besides, on drilling thick materials with laser, processing on both the sides may prove to be preferable, as there exist the effects of saturation and quasi-saturation with the depth of beam penetration into the material [139]. The effect of quasi-saturation manifests itself in retardation of growth rate of the hole depth, and the saturation effect shows up in full termination of the hole deepening. On punching thin (foil) materials the use of two beams permits the process efficiency to be almost doubled, as the time needed for punching a hole (usually less than 0.5 s) is substantially below the time required for the machine working head movement from hole to hole.

The physical and technical characteristics of both the variants of IPTL-2 laser are presented in Table 1. It is evident from the table that the mean power in the single-beam variant is below the total mean power in the double-beam model. The chambers in the single-beam model are combined by a common □-shaped resonator. It is difficult to achieve the regime of time coincidence of discharge pulses in both the chambers provided with self-contained power supply.

Table 1

Parameter	**Unit**	**Single-beam variant**	**Double-beam variant**
Max. mean beam power	kW	1.5	1.0
Rated mean beam power	kW	1.0	0.75
Max. pulse energy	J	4.0	2.0
Max. pulse repetition rate	Hz	1400	700
Beam wavelength	μm	10.6	
Beam divergence	mrad	3	
Aperture	mm	20	
Required electric power	kW	40	
Gas consumption: CO_2	m^3/h	0.01	
N_2	m^3/h	0.06	
He	m^3/h	0.06	
Gas mixture working pressures	Torr	100-220	

The case in point is discharge synchronization with < 0.1 μs accuracy (with regard for duration of generation peak) under repetitive-pulse mode.

The reliability of such synchronization in long-term service is not high. The operation of two chambers with the time shift of the order of pulse duration objectively involves beam power losses, primarily at the cost of radiation absorption in the second operating chamber by the hot, but inactive gas arriving from the first chamber. Under alternate operation of the chambers radiation losses are also high owing to long extension of the resonator passive region (about 2 m) as against the active region (1 m); radiation losses turn out to be considerable.

The studies were conducted on energy characteristics of the double-beam variant of the laser, offering the greatest advantages for many industrial applications. The double-beam variant of IPTL-2 laser uses two stable resonators of the same type. Each of the resonators is formed by a non-transmitting concave mirror having radius of curvature 16 m, and the output mirror presents a plane-parallel plate of GaAs with anti-reflected outer side. The radiation is extracted through the window of anti-reflected ZnSe. Measurements were made of some characteristics of the beam shaped by this resonator.

The measurements were performed with the use of calorimeter TPI-2M. Fig.6 illustrates the dependence of average power in a single beam on pulse repetition rate with maximally possible energy input at the frequency under consideration. In the measurements, the mixtures were used which are most applicable to technical experiments. It is clear from the graphs that critical pulse repetition rate, that requires a reduction of energy input into discharge with the aim of diffuse discharge retention, lies in the range from 500 Hz for the mixture CO_2:N_2:He=1:6:6 to 700 Hz for the mixture CO_2:N_2:He =1:3:6. The mixture pressure is equal for both the cases and makes 210 Torr, and the maximum specific input is 160 J/l atm. Thus, the laser can operate with the maximum pulse repetition rate from 500 to 700 Hz.

Fig.7 illustrates the character of radiation energy dependence on energy input into the discharge, and on pressure of the mixture. In these experiments the mixture CO_2:N_2:He =1:3:6 was used. The graphs show that at a fixed value of energy input radiation energy increases monotonically to some pressure value, and then it stops growing or is essentially retarded at high inputs. These dependences show that an optimum value of mixture pressure for the available pump system is in the range from 200 to 250 Torr.

A portion of helium in the mixture of repetitive-pulsed CO_2 lasers actually makes 50 % and above, and combinations of molecular components are different depending upon the requirements to radiation pulse shape. The dependence of pulse energy on the portion of CO_2 in the molecular part of the mixture has been studied. In accordance with the experimental results presented by Fig.8, a portion of He made 60 % at the total mixture pressure 240 Torr. Thus it is evident that there exists some optimum value in the relationship between CO_2 and N_2. The optimum value of CO_2 in the molecular component of the mixture is 20 to 25 %.

The optimum generation mode with regard for energy is not always suitable for heat treatment technology due to short pulse duration. The increase of duration at the cost of build-up of N portion in the mixture causes some reduction of pulse energy. It is evident from the presented graphs that pulse energy is reduced no more than 15 % at N portion increase from 75 to 85 %, and the corresponding variation of peak power and duration can result in considerable change of the technological process efficiency.

One of the promising applications of repetitive-pulse IPTL-2 laser is punching holes in sheet materials. Sieves are in large demand for various industries. They are used where highly effective homogeneous mixing of components is desired: in rocket engines for mixing fuel and oxidizer, in production of homogeneous diet and baby nutritives, in chemical industry. Sieves find a wide application in wine industry, cheese-making, in production of mixed feed, macaroni foods, juices, etc.

Manufacturing of sieves requires good reproducibility of hole shape and diameter, high efficiency of punching. The developed IPTL-2 laser is best suited for these requirements, because hole punching is performed with it as effectively as with pulsed solid-state lasers, but in contrast to the latter, high efficiency is achieved. Give now a few examples of punching holes in metals. Table 3 contains the parameters of laser radiation used in hole punching.

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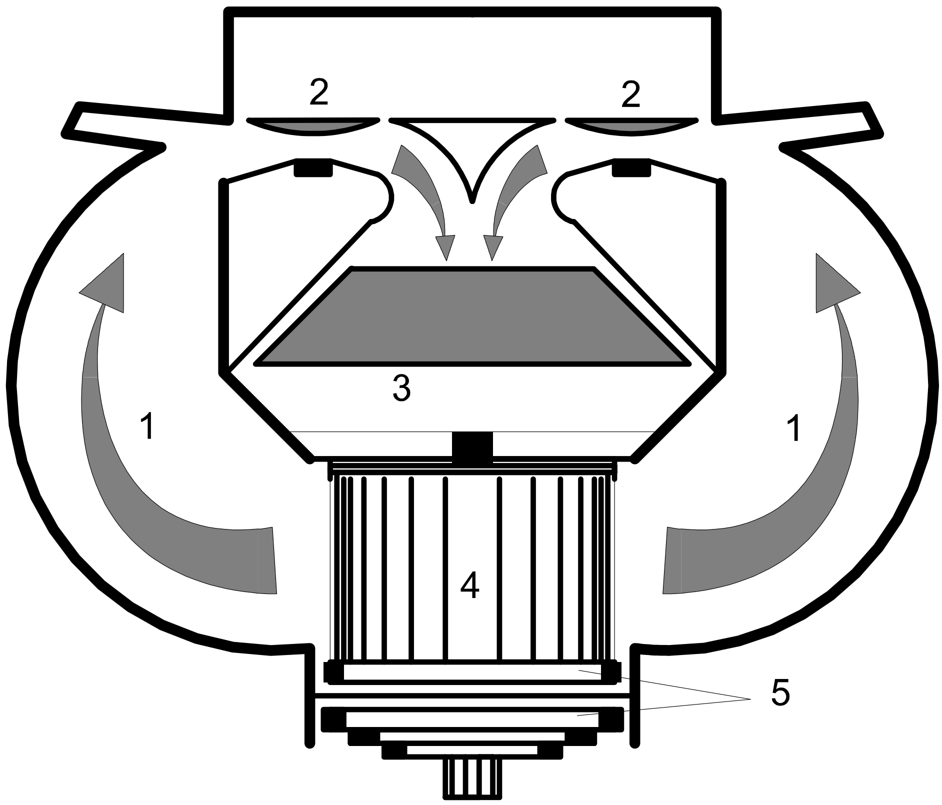

Fig.1. Diagram of laser unit. 1- gasdynamic channel; 2- gas-discharge chambers; 3- heat exchanger; 4- fans; 5- magnetic clutch halves.

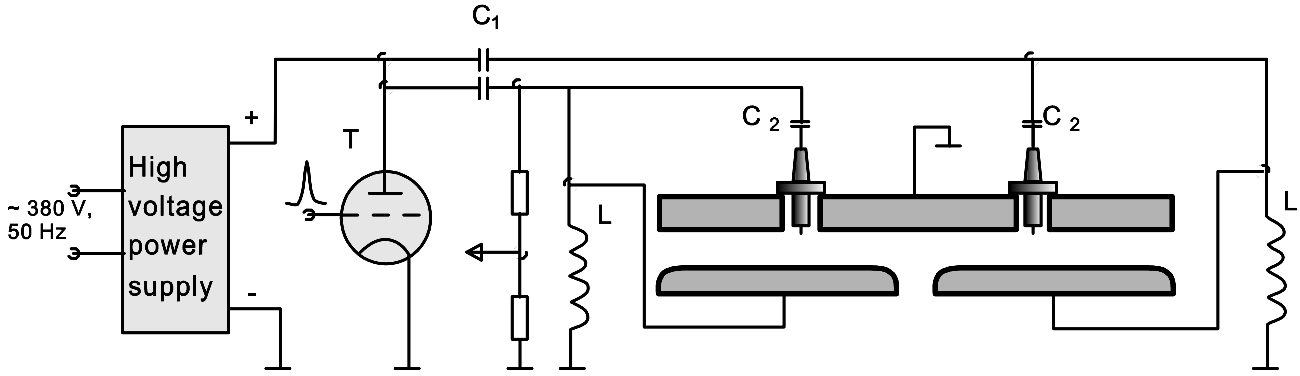

Fig.2. Basic pulse circuit of one channel: T- thyratron; C_1-main discharge capacitance; C_2-auxiliary discharge capacitance; L- charging inductance.

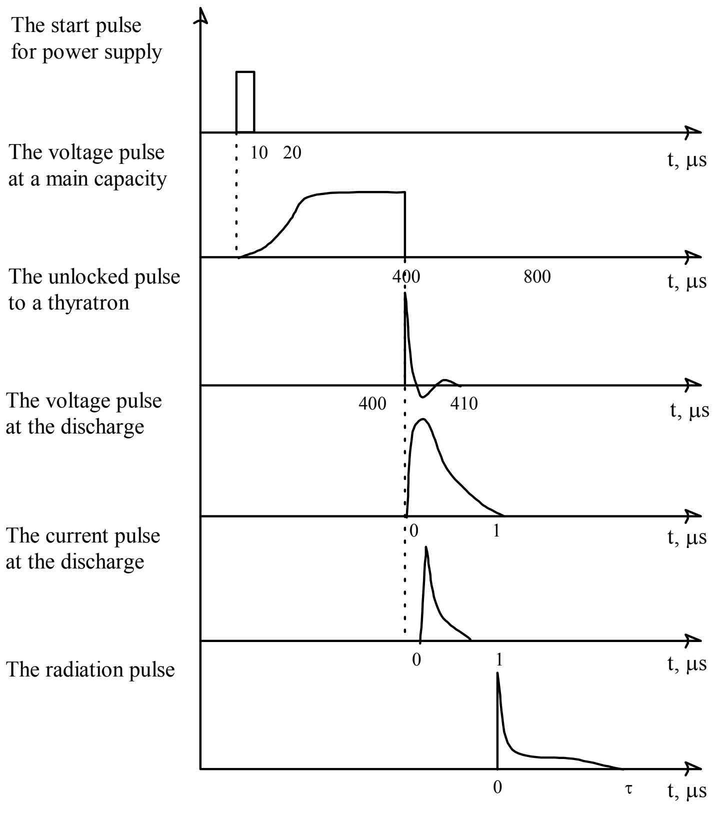

Fig.3. Dynamics of discharge and generation development in laser.

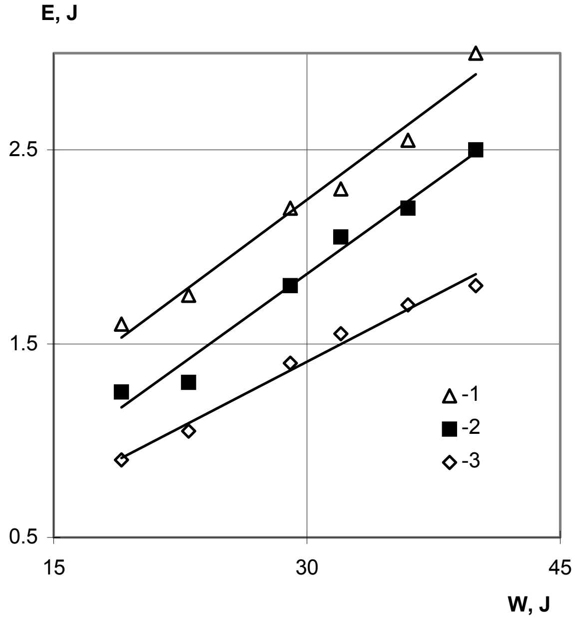

Fig.4. Radiation pulse energy as function of: energy input to discharge.
1 - CO_2:N_2=1:6; P_{mol}=10.6 kPa. 2,3 - CO_2:N_2=1:1; P_{mol}= 5.3 kPa.
He partial pressure, 24 kPa.

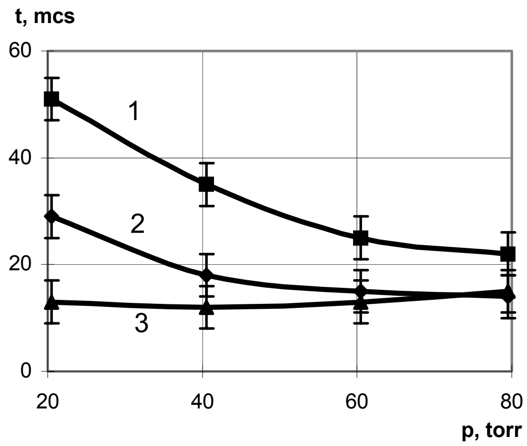

Fig.5. Laser-pulse duration as function of pressure of molecular components.
1 - CO_2:N_2=1:6; 2 - CO_2:N_2=1:3; 3 - CO_2:N_2=1:6.
He partial pressure, 180 Torr.

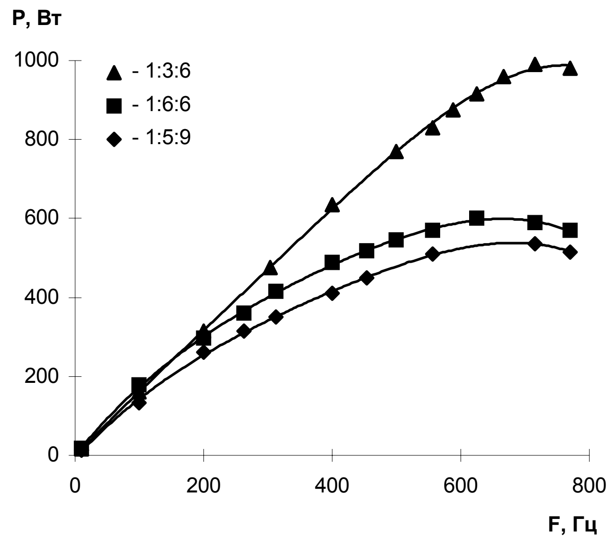

Fig.6. Dependence of radiation mean power in a single beam upon pulse repetition rate for different laser mixture compositions CO_2:N_2:He.
The mixture pressure is 210 Torr.

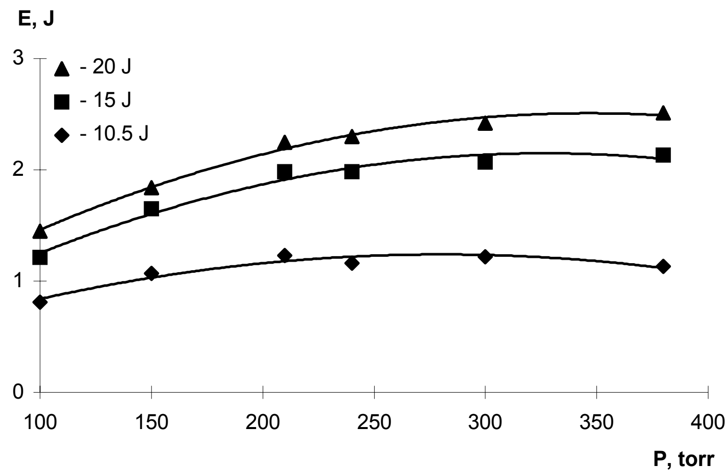

Fig.7. Energy in a single pulse as a function of laser mixture pressure at different pumping energy. The mixture composition is CO_2:N_2:He=1:3:6.

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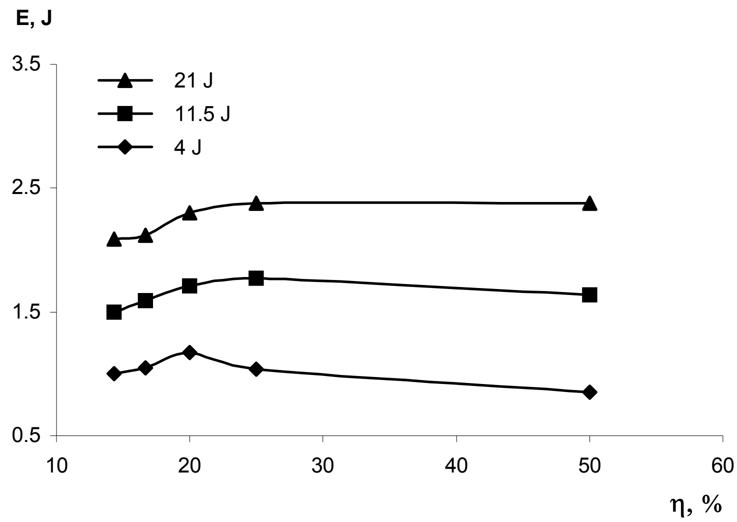

Fig.8. Radiation pulse energy depending on CO_2 portion in the molecular part of the laser mixture for different pumping energy. The total pressure is 240 Torr. Helium content makes 60 % of the total pressure.