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High-power, high-pressure pulsed CO_2 lasers and their applications

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***Abstract*. The paper is devoted to problems associated with the construction of high-power pulsed CO_2 lasers and high-pressure amplifiers and to an analysis of the possible ways of their solution. Prospects of the development of such lasers and their applications in technological processes are considered. Original designs of a laser complex for obtaining the carbon-13 isotope and a superatmospheric-pressure CO_2 amplifier are presented.**

Keywords: *CO_2 laser, X-ray preioniser, voltage pulse generator, laser acceleration of electrons, laser separation of isotopes, technological applications.*

1. Introduction

The scientific community all over the world has been evincing a keen interest during recent years towards the application of pulsed high-power superatmospheric-pressure CO_2 lasers for solving a number of fundamental physical problems such as acceleration of charged particles by a light wave and the development of highly bright sources of coherent X-rays. The development of high-power (exceeding 1 TW) picosecond laser systems emitting at a wavelength of 10 μm paves way for other applications of laser radiation, which were inaccessible earlier; these applications include:

(i) generation of picosecond X-ray pulses in a laser plasma for application in X-ray microlithography and microscopy;

(ii) production of multiply charged ions in a laser plasma for their subsequent accumulation and use in Supercollider accelerator systems;

(iii) laser-controlled discharges and formation of a lightning-rod;

(iv) nonlinear propagation of laser radiation (tunnel and Kerr effects);

(v) influence on biological objects and application in medicine;

(vi) mode-selective laser chemistry;

(vii) study of molecular excitation by phase-modulated ultrashort pulses;

(viii) study of the electron – phonon energy exchange during the interaction of laser radiation with solid targets; laser-induced acceleration of solids;

(ix) study of electromagnetic fields and currents generated in picosecond laser plasma.

It should be stipulated at the very outset that by using the term 'high-pressure laser', we will mean a CO_2 laser pumped by a self-sustained volume discharge and having an active-medium pressure above 0.5 atm (i.e., in the range of gas density in which a continuous self-sustained volume discharge cannot be realised). In addition, analysis of the formulated problems will be mainly carried out on the basis of the results obtained at the D.V. Efremov Scientific Research Institute of Electro-physical Apparatus (NIIEFA), as well as at the institutes cooperating with the NIIEFA at various stages. In this study, we analyse the state-of-the-art of the development and application of high-power pulsed CO_2 lasers. In addition, we present the results of the original design of a laser complex for the production of the carbon-13 isotope and of the superatmospheric-pressure CO_2 amplifier.

2. Wide-aperture atmospheric-pressure CO_2 lasers

First advances made towards an increase in the radiation power of transversely excited atmospheric-pressure (TEA) CO_2 lasers were achieved by increasing the aperture of pump systems (the length of the amplifying medium is limited by the radiation resistance of optical elements and does not exceed 1 m). In Russia, this direction was extensively developed at the Troitsk Institute for Innovation and Fusion Research (TRINITI) [1, 2], Astrofizika Research and Production Association [3, 4], General Physics Institute, Russian Academy of Sciences [5 – 10], High-Voltage Research Institute at Tomsk Polytechnic University [11, 12], All-Russian Scientific Research Institute of Experimental Physics – Russian Federal Nuclear Center, [13], and D.V. Efremov Scientific Research Institute of Electrophysical Apparatus (NIIEFA), Federal State Unitary Enterprise [14 – 17].

It was shown that the deterioration of volume discharge stability due to strong absorption of UV radiation in the working mixture is the main obstacle appearing upon increasing interelectrode gaps. The interelectrode gap usually does not exceed 10 – 15 cm when the traditional method of excitation of the laser active medium is employed. Consequently, the term 'wide-aperture CO_2 laser' is applied to CO_2 lasers (amplifiers) with an aperture area exceeding 100 cm^2.

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Recall that the traditional pumping of the medium requires the fulfilment of the two necessary conditions: (i) a minimal initial electron concentration N_0 must be produced in the entire active volume and (ii) the voltage must be increased very rapidly to a value exceeding the static breakdown voltage. In addition, the maximal uniformity of the electric field must be provided in the discharge gap of the laser (problem of electrode profiling). When the interelectrode gap (or gas pressure) is increased, it becomes extremely difficult to satisfy these conditions. Nevertheless, first advances in the development of lasers with an aperture area exceeding 100 cm^2 were made precisely due to the technical development and implementation of the main elements in the laser pump system (careful profiling of electrodes, the use of multichannel spark UV sources, the employment of low-inductance generators of pulsed voltage, etc.).

At the beginning of 1980s, it was proposed for the first time that soft X-rays be used for solving problems associated with long-range action and uniformity of preionisation of gaseous media in excimer lasers (long-range action of preionisation corresponds to the maximum distance from the radiation source for which the preionisation electron concentration exceeds a preset level) [18, 19]. An X-ray preioniser has the following advantages over the preionisers in which an electron beam or UV radiation is used: (i) high penetrability; (ii) low working voltage of the X-ray source (and, hence, the absence of biological protection), and (iii) the possibility of using a thick output window.

As regards structural simplicity and reliability, an X-ray preioniser occupies an intermediate position between a UV source and a high-energy electron beam source.

Soft X-rays were used for preionisation in TEA CO_2 lasers with an interelectrode gap of 20 cm [20, 16] and in a high-pressure (4-atm) CO_2 laser [21]. In all cases, the traditional scheme was employed for exciting a discharge with preionisation by a short ($\sim$100 ns) X-ray pulse. A direct comparison of the discharge characteristics in the case of UV and X-ray preionisers, which was carried out in [17], revealed that the use of X-rays makes it possible to slightly increase the percentage of active molecules in the gas mixture and the interelectrode gap width. The specific parameters of the laser remain virtually unchanged in this case. It was shown in [17] that the use of X-rays instead of UV preionisation made it possible to increase the interelectrode gap to 22 cm and to obtain a volume discharge with a concentration of molecular gases up to 40 % without adding readily ionisable impurities.

A different approach was developed in [6, 7] for the formation of a self-sustained volume discharge. The essence of this approach is that the necessary initial conditions in the discharge region are created as a result of its preliminary drift-filling with electrons produced by an external ionisation source in the cathode region of the discharge gap. In this case, the following conditions must be met to substantially alleviate the requirements imposed on the long-range action of the ionisation source and the duration of the voltage front. First, the lifetime of free electrons must be sufficient for drift-filling of the discharge region. Second, the source of near-cathode ionisation must operate during the entire stage of charge formation. The requirements to the shape of the electrodes become considerably milder in this case. The possibility of the formation of a volume discharge in such an 'acute-angle' geometry is ensured by the fact that the electric field is strongly suppressed at the cathode and enhanced at the anode (relative to its average value in the gap) due to the formation of a negative volume discharge during filling of the discharge gap with electrons. Due to repulsion of electrons in the flow, maximum amplification of the field is achieved in the central region of the anode. Consequently, ionisation processes are initiated precisely in this region rather than near the sharp edge of the cathode. The voltage across the discharge gap should not increase too rapidly since otherwise the electron concentration cannot follow the variation in the external field and the screening of the cathode edge proves to be inefficient. The evolution of this principle made it possible to design a pump device for TEA CO_2 lasers with an interelectrode gap of 60 cm [8, 9].

3. Superatmospheric-pressure CO_2 amplifiers

The interest in ultrahigh-power picosecond laser systems emitting in the IR region (including CO_2 laser systems) has increased in recent years. The development of ultrahigh-power laser systems with an ultrashort pulse duration (from nano- to picoseconds) was stimulated to a considerable extent by studies in the field of laser-controlled nuclear synthesis. As a result of competition between several possible approaches to solve this problem using various types of lasers, solid-state laser systems emitting at a wavelength of 1.06 μm and shorter have received wide recognition.

Picosecond CO_2 laser systems emitting in the 10 μm range, which for several reasons proved to be less efficient for heating thermonuclear targets, have been used not so frequently. However, in a number of fundamental physics problems in the field of interaction of ultrahigh-power laser radiation with matter, the effect expected for a fixed laser radiation intensity increases substantially with the radiation wavelength. For example, in the case of laser-induced acceleration of electrons, the relative increment of the electron energy after interaction with the laser field averaged over the electron cluster increases with the laser radiation wavelength as λ^2. Estimates show that for a light pulse duration of $\sim$10 ps and a radiation power of 1 TW, the accelerating gradient is $\sim$1 GeV m^{-1}, which is much larger than in modern linear accelerators (in which this value is up to 100 MeV m^{-1}). This approach may result in the development of a new generation of accelerators, in which non-traditional methods for accelerating charged particles will be used.

It follows from the available literature that three large-scale middle-IR laser facilities at various stages of readiness exist at present in the world.

The facility designed at the Brookhaven National Laboratory, USA, is intended for generating a single laser shot of duration $\sim$10 ps with an energy up to 30 J (the peak power is 3 TW) [22]. It is planned that pulsed radiation be used in experiments on laser acceleration of electrons. The facility includes a master oscillator, an eight-pass multi-isotope preamplifier (with an aperture area of 5 cm^2 and a working mixture pressure of 5 atm), and a three-pass output amplifier (with an aperture area of 80 cm^2 and a working mixture pressure of 10 atm). The terminal amplifier is at the stage of launching.

The facility at the University of California in Los Angeles is intended for generating single two-wave pulses

(with tuning to an arbitrary pair of lines from the emission spectrum of the CO_2 laser) with an energy of 170 J and a duration of 160 ps (the peak power is 1.1 TW) [23]. It is planned that a radiation pulse will be used for studying acceleration of electrons in the plasma (the so-called beat-wave scheme). The device is already in operation.

The facility at the General Physics Institute, Russian Academy of Sciences (Moscow) (designed in cooperation with NIIEFA) generates a train of $\sim$150-ps pulses with a total energy of $\sim$20 J and is intended for studying the interaction of laser radiation with matter [24].

A project for generating a high-power gamma-ray beam by backward Compton scattering of picosecond 10-μm laser pulses from a relativistic electron beam is being developed in Japan (High-Energy Physics Laboratory) [25]. It is planned that gamma-rays will be used for obtaining a polarised electron beam in the Japanese linear collider.

The design of all the facilities is based on the master oscillator – amplifier scheme because the fundamental structural features of the systems for shaping and compression of single picosecond 10-μm laser pulses limit the output energy of the oscillator to a value of $\sim 10^{-5}$ J. This necessitates their further amplification by 5 or 6 orders of magnitude while preserving the temporal characteristics of the pulse. This problem can be solved only by using a superatmospheric-pressure amplifier. The working pressure of the amplifier should provide the correspondence between the bandwidth of the amplifying medium and the duration of the pulse being amplified, and its aperture and energy contribution should ensure the required energy extraction in a single pulse or a train of pulses (taking into account the admissible radiation load on the optical elements of the amplifier). For the 10R band of the CO_2 molecule, the overlap of individual rotational – vibrational transitions due to collision broadening occurs at a pressure of $\sim$10 atm. The width of the gain band of the active medium increases in this case up to 13 cm^{-1}, which makes it possible to amplify pulses with duration up to 1 ps.

The development of high-pressure CO_2 amplifiers were initiated at the NIIEFA and General Physics Institute, Russian Academy of Sciences, at the end of 1980s and became a logical continuation of studies of wide-aperture atmospheric-pressure CO_2 lasers [7 – 10, 14 – 17].

The possibility of obtaining a volume discharge in a volume of 0.3 L for an interelectrode gap of 4 cm and an active mixture pressure of up to 6 atm was demonstrated at the NIIEFA [26]. The gas was preionised by X-rays. The results of these studies formed the basis of the development of high-pressure amplifier (HPA) with a geometrical size of $4 \times 5 \times 55$ cm in the discharge region.

Figure 1 shows the scheme of the facility [27]. As a source of preionisation, an explosive-emission diode with a perforated braking anode and an explosive-emission cathode made of graphite fibres was used. For an accelerating gap of 4 cm and a working voltage of 70 kV, the total duration of the gun current was 1.5 μs for a peak current of $\sim$5 kA. The X-ray source was 50-μm thick aluminium foil, which simultaneously served as the output window.

The pump discharge was fed by an 8-stage pulse voltage generator (PVG) assembled according to the *LC* generator circuit with an 'impact' capacitance of 6.25 nF. The maximum idle voltage of the PVG was 400 kV. To reduce the time of energy contribution to the pump discharge, we used an intermediate capacitive storage (not shown in Fig.1), which was located close to the discharge chamber. A 'fast' capacitor was connected with the *LC* generator through an inductance that prevented the reverse energy transfer from the intermediate storage to the PVG. It was found during experiments that, to achieve the maximum transfer of the energy stored in the *LC* generator to the load, the capacitance of the intermediate storage and the filter inductance must be selected carefully for each specific composition and pressure of the active medium. For example, for the $CO_2 : N_2 : He = 2 : 1 : 17$ mixture and for $p = 5$ atm, these parameters must be 12 nF and 10 μH, respectively.

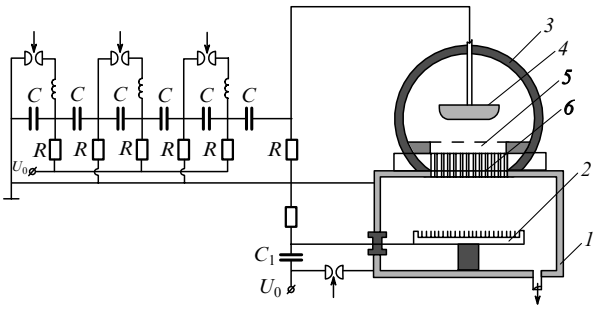

Figure 1. Scheme of the facility: (*1*) X-ray source; (*2*) electron gun cathode; (*3*) discharge chamber; (*4*) cathode; (*5*) anode; (*6*) braking anode; C_1 is the capacitance of the main storage, and U_0 is the charge voltage.

Figure 2 shows the dependences of the laser module generation energy on the charging voltage of the PVG for the $CO_2 : N_2 : He = 2 : 1 : 17$ mixture in the pressure range 3 – 5 atm. The unstable telescopic resonator with a magnification $M = 2$ embraced a part of the active medium with a volume of 0.7 L. The different form of these dependences can be explained by different values of the intermediate

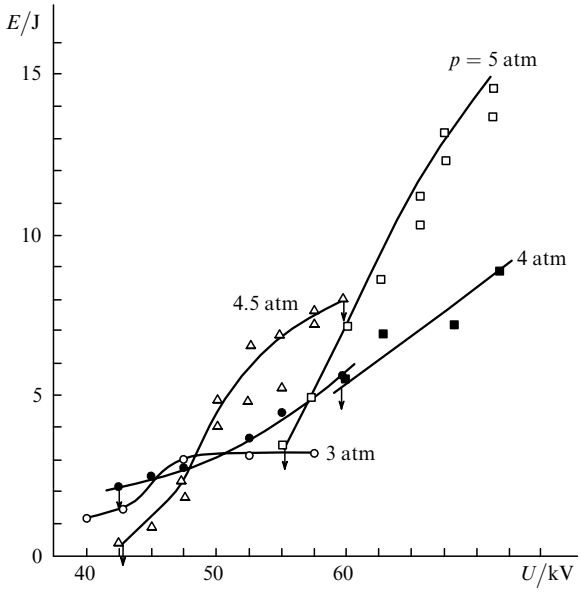

Figure 2. Dependences of the output energy of the laser module on the charge voltage for the $CO_2 : N_2 : He = 2 : 1 : 17$ mixture in the pressure range 3 – 5 atm.

storage and decoupling inductances for different pressures of the mixture. The maximum generation energy (15 J) was achieved for $p = 5$ atm and a specific energy contribution to the discharge of 150 J L^{-1} atm^{-1}, which corresponds to an energy removal of $\sim$20 J L^{-1}.

In 1995, the amplifier was brought to the General Physics Institute, Russian Academy of Sciences, and built in into the device intended for generating picosecond radiation pulses. After modification of some parts of the amplifier and launching of the master oscillator, a regenerative amplification regime was realised on the test bench at the General Physics Institute at a gas mixture pressure up to 6 atm. The total energy of the train of pulses achieved 24 J for a pulse duration of $\sim$120 ps [28].

The results of calculations and experiments showed that the amplifier intended for obtaining 10-μm picosecond pulses with a peak power of $\sim$1 TW, which can be used for solving many fundamental and applied problems, must possess the following parameters:

Discharge volume/cm	$(5-10)\times 10\times 100$
Interelectrode gap/cm	5–10
Gas mixture composition	$CO_2 : N_2 : He$
Gas mixture pressure/atm	5–10
Concentration of molecular gases (%)	no less than 15
Specific energy contribution/J L^{-1} atm^{-1}	no less than 100
Small-signal gain/cm^{-1}	no less than 0.02

The main problem arising in the scaling of the pump systems of the amplifier is to increase the inductance of the discharge circuit of the power supply and, accordingly, to reduce the rate of energy supply to the pump discharge. This problem can be solved only by using an intermediate capacitive energy storage located in the vicinity of the discharge chamber. In our scheme, the PVG is the charging unit for the 'fast' storage device. This idea was successfully implemented in the design of the prototype of the amplifier using a set of low-inductance commercial capacitors. For the HPA with an aperture area exceeding 50 cm^2, such an approach is ruled out for two reasons. First, it is virtually impossible to assemble a capacitor bank for a voltage of $\sim$ 1 MV; second, the external position of the intermediate storage relative to the discharge chamber does not solve the problem completely in view of the large geometrical size of the chamber. Calculations show that the discharge chamber designed for a voltage of $\sim$1 MV and an active medium pressure of $\sim$10 atm must be made of a metal and must have an outer diameter of $\sim$1 m. The problem of a low-inductance connection of the external intermediate storage device with the electrode pump system (the problem of through high-voltage terminals) is strongly complicated in this case. To overcome these obstacles, an original design was proposed, in which the discharge chamber and the intermediate storage (water capacitor) are combined in a single unit (Fig. 3) [29].

At present, the X-ray preioniser, PVG, gas-supply, evacuation, control, and synchronisation systems have been built, mounted, and adjusted. The parameters of the parts and systems mentioned above correspond to the rated values. In addition, the system producing desalted, deionised distilled water intended for filling the water capacitor (intermediate storage) has been manufactured and tested.

Figure 4 shows the current and voltage oscillograms obtained at the X-ray source and the signals from the X-ray sensor and the system of electron concentration measurement. The structure of the X-ray preioniser is similar to that of the X-ray source of the prototype amplifier [27].

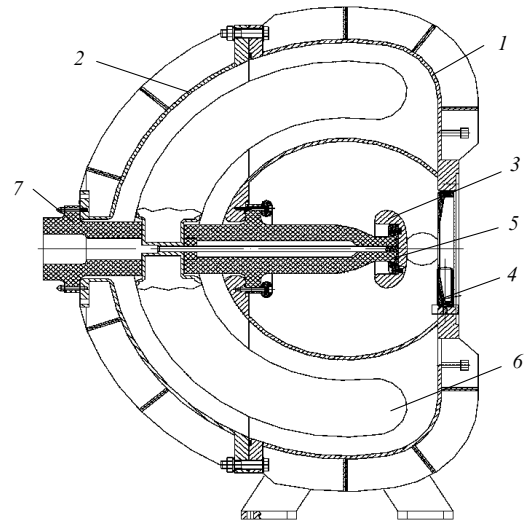

Figure 3. Discharge chamber: (*1*) outer case; (*2*) inner case; (*3*) profiled electrode (cathode); (*4*) grid electrode; (*5*) through insulator; (*6*) high-voltage plate of the water capacitor; (*7*) high-voltage lead.

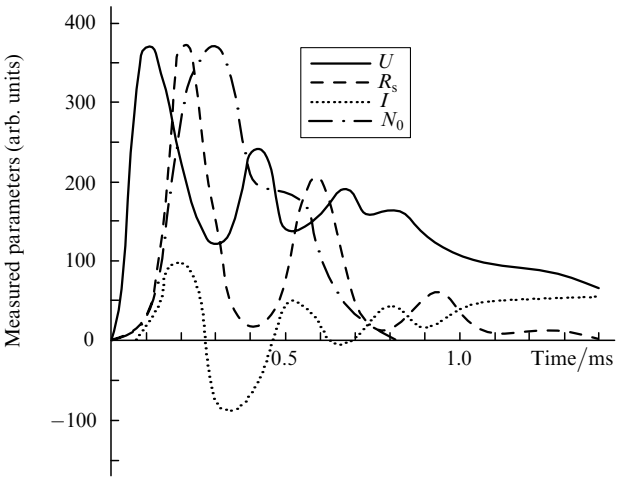

Figure 4. Oscillograms of current I and voltage U of the X-ray source and R_s signals from the X-ray sensor determining the radiation dose and from the system for measuring the electron concentration N_0; signal R_s amounts to 0.18 rem $pulse^{-1}$ for $U = 80 - 30$ kV, $N_0 = (2-4)\times 10^8$ cm^{-3}, and $I_{max} = 7$ kA.

To improve the electron beam homogeneity over the area of the explosive-emission cathode, a pulsed circuit with a peaking capacitance was used for feeding the preioniser; this makes it possible to attain 1.5-fold overvoltage across the vacuum diode at the initial stage. The form of the preioniser voltage and current is oscillatory and the behaviour of X-rays and the signal from the electron concentration measuring system is analogous to the behaviour of the voltage. A careful selection of parameters of the power supply system makes it possible to substantially reduce the preioniser voltage and current modulation (Fig. 5).

Measurement of the degree of inhomogeneity of the X-ray beam using a special instrument at various distances from the output window of the preioniser shows that the

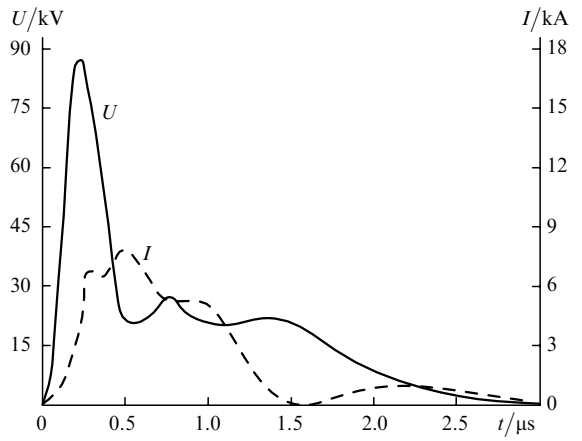

Figure 5. Oscillograms of voltage and current of the X-ray preioniser in a matched regime.

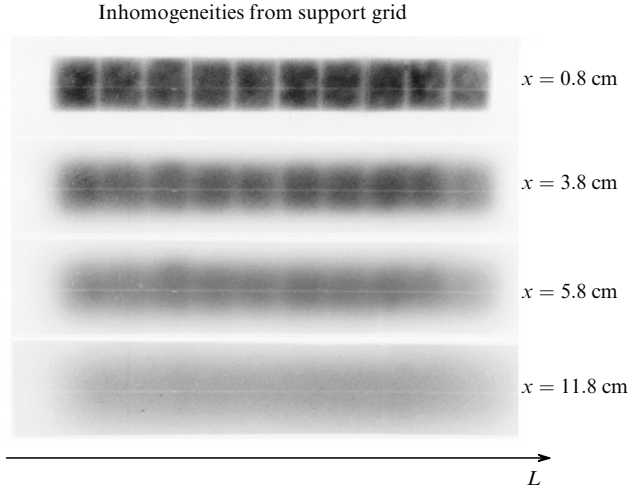

Figure 6. Photograph of the emission of the visualising (phosphor) screen; x is the distance from the output foil.

main reason for the nonuniformity are transverse stiffening ribs in the structure of the support grid of the separating foil (Fig. 6). Deviation of the flux density from the mean value in the transverse beam cross section near the output window amounts to $\sim 35\,\%$. With increasing distance, the inhomogeneity rapidly decreases and amounts to less than 5 % at a distance of 12 cm from the foil (in the region of the discharge gap cathode of the HPA) (Fig. 7).

The concentration N_0 of the preionisation electrons and its dependence on the distance from the output window of the preioniser were also measured. In the $CO_2 : N_2 : He = 2 : 1 : 17$ mixture at a pressure of 5 atm, $N_0 = 8.6 \times 10^8$ cm^{-3} at a distance of 7 cm from the target (at the centre of the working volume of the pump system). The mean value of N_0 decreases by a factor of 2.5 upon a change in the distance to the output foil from 2 to 12 cm.

The megavolt PVG was assembled in accordance with the Howell – Fitch 16-stage scheme.

The main task of project No. 2521 of the International Centre of Science and Technology being financed by the European Commission, is the completion of the discharge chamber with an integrated intermediate water storage and its launching as a part of the HPA as well as the construction of the HPA-based International picosecond

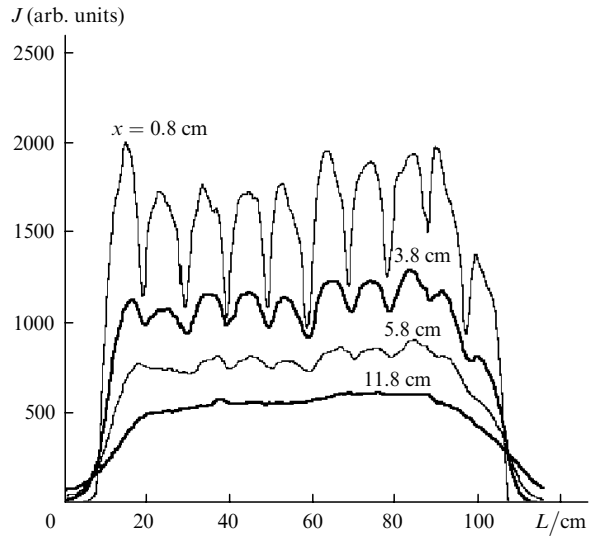

Figure 7. Spatial distribution of the X-ray current density (densitograms of images shown in Fig. 6).

terawatt CO_2 laser facility in Russia for experiments on the interaction between laser radiation and matter.

4. Repetitively pulsed CO_2 lasers for medium-mass isotope separation

Isotopes of elements having a medium mass (in particular, carbon and oxygen isotopes) are in great demand at present. Stable isotopes of these elements are widely used as markers in chemistry, biology, physiology, biochemistry, and medicine for studying the mechanism of formation of chemical compounds, metabolism in living organisms, the molecular heredity, etc.

During the last two decades, commercial units have been constructed in the USA, UK and CIS countries for obtaining the high-concentration ^{13}C isotope using low-temperature rectification of CO. However, the isotope products obtained by this method are very costly, which hampers their use in many cases.

For commercial enrichment of carbon-containing raw materials, it is possible in principle to use chemical, laser, and centrifugal technologies for obtaining the ^{13}C isotope. Chemical and centrifugal technologies are economical for processing large amounts of raw materials; however, certain difficulties are encountered in the instrumentation and the development of the operation conditions required for obtaining highly enriched products.

The laser separation of isotopes, whose high efficiency is caused by an exceptionally high selectivity of laser excitation of molecules, appears as the most promising [30]. One of the most efficient methods of laser isotope separation is the multiphoton IR dissociation of molecules (the method was developed and implemented at the Institute of Spectroscopy, Russian Academy of Sciences). The discovery of isotope-selective dissociation of BCl_3 and SF_6 molecules was reported for the first time in [31 – 33].

It was proposed to use the multiphoton dissociation of Freon-22 (CF_2HCl) molecules caused by radiation from a repetitively pulsed CO_2 laser for isotopic enrichment of carbon [34]. This process has a number of advantages providing its successful realisation on commercial scale. First, the raw material (Freon-22) is produced in large

amounts and is relatively cheap. After extracting the ^{13}C isotope molecules, Freon can be returned to the producers. Second, the CO_2 laser is most powerful and useful for industrial application and the 9P(20) line chosen for resonant excitation of Freon molecules is characterised by the highest intensity in the CO_2 laser emission spectrum. Tetrafluoroethylene obtained after dissociation is quite stable and suitable for further processing.

Analysis [35] showed that a two-stage process implemented by two methods is a practically realisable and economically advantageous technique for obtaining highly enriched ^{13}C isotope. At the first stage, large amounts of the initial raw material are processed in accordance with laser technology with preliminary enrichment to a ^{13}C concentration amounting to 10 % – 30 %. At the second stage, comparatively small amounts of carbon obtained at the first stage are processed by centrifugal technology; as a result, the concentration of the end product becomes higher than 99.0 %.

The studies carried out under the aegis of the International Science and Technology Centre at the Institute of Spectroscopy, Russian Academy of Sciences, Troitsk Institute for Innovation and Fusion Research (TRINITI), NIIEFA, and Central Design Office for Machine Building culminated with the development of a separation complex for producing ^{13}C isotopes.

The complex (Fig. 8) includes a high-power TEA CO_2 laser and an isotope separation reactor, in which Freon

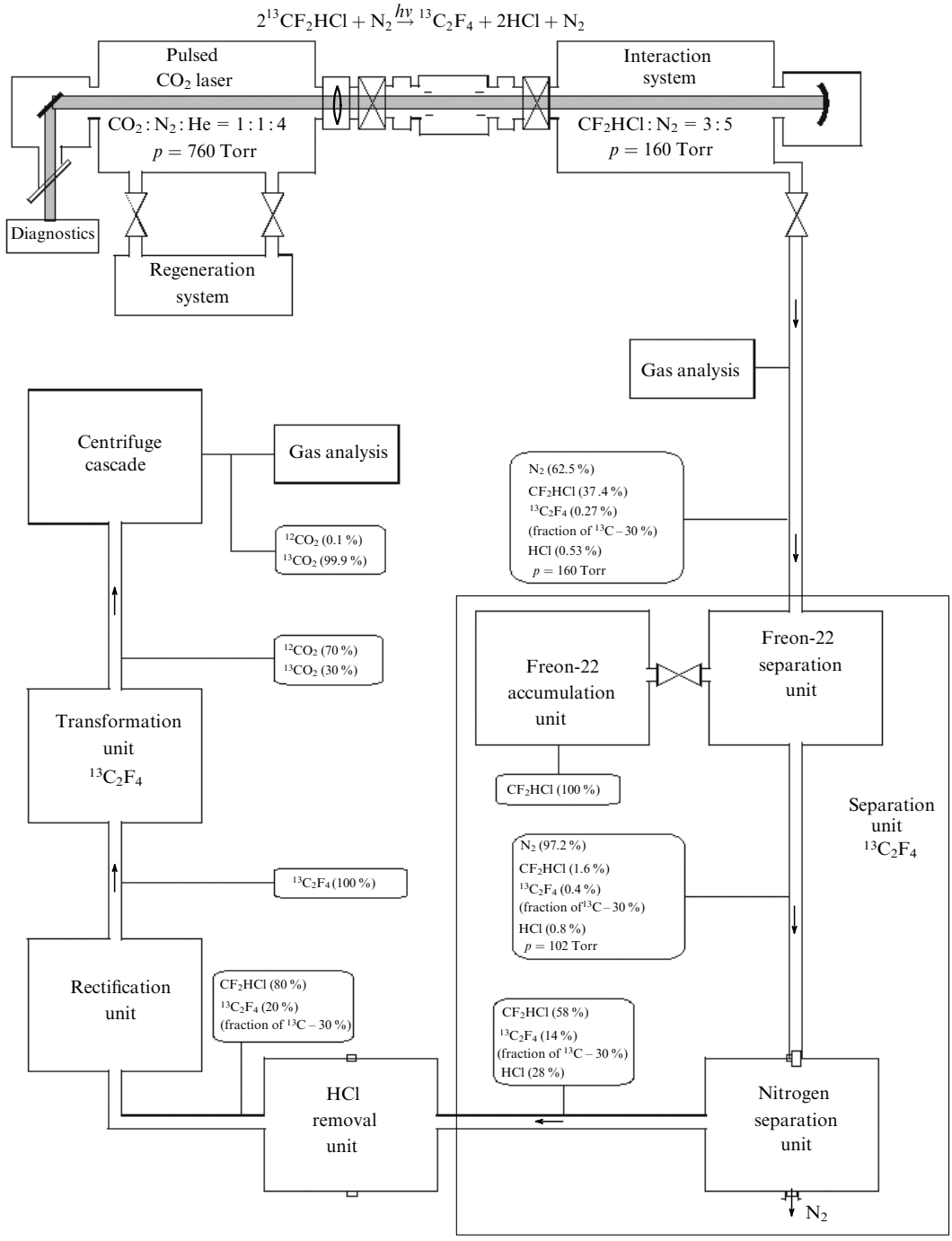

Figure 8. Block diagram of the technological complex for laser separation of carbon isotopes.

molecules containing isotope ^{13}C dissociate; the laser and the reactor have a common optical resonator [36]. A detailed description of auxiliary devices of the complex is given in [37–41].

The implementation of this technology of carbon isotope separation requires a reliable high-power CO_2 laser with the following parameters:

Radiation wavelength/μm	9.6
Pulse energy/J	20
Energy density at the laser output/J cm^{-2}	no less than 10
Pulse duration/μs	no more than 0.5
Average power/kW	4
Pulse repetition rate/Hz	200

The service life of the laser without replacement of elements must be at least 5×10^7 pulses; the total service life is at least 10^{10} pulses. The laser must operate continuously for 12 h per day, 300 days per year.

Lasers with parameters satisfying the technological requirements did not exist at the beginning of the development of the above technology; consequently, the development of a reliable CO_2 laser became a major problem.

The main obstacle emerging in attempts at increasing the average power, reliability, and duration of continuous operation of TEA CO_2 lasers is associated with the complexity and high cost of pulsed technique units applied in systems of pumping by a 'fast' self-sustained discharge. Analysis of rated parameters of these units (in particular, hydrogen thyratrons produced commercially in developed countries) shows that the practically attainable average power level of a technological TEA CO_2 lasers lies between 0.5 and 1.0 kW. Due to the known peculiarities of a high-pressure self-sustained discharge, the service life of an electronic switch might be substantially lower than that guaranteed by the producer. Thus, the possibility of a further increase in the average power of repetitively pulsed CO_2 lasers should be associated either with advances in the field of pulsed technology, or with the development of new non-traditional schemes for exciting a self-sustained discharge, which make it possible to substantially alleviate the requirements to elements of pulsed power supply of the laser.

Our studies prove that an increase in the average laser power without a noticeable overloading of pulsed power supply system elements can be achieved by implementing the three main principles: modular construction of the electrode system of the discharge; elimination of high-current switching units from the pump discharge circuit; and the maximum possible increase in the build-up time for voltage across the discharge gap.

In the laser investigated here, the discharge was excited from the PVG designed in accordance with the *LC* generator (Fig. 9). The most important advantage of this scheme is that the duration, build-up rate, and amplitude of the currents through the switching unit and the main discharge gap are determined by different discharge loops. Obviously, the longer the front of voltage build-up, the smaller the values of parameters in the thyratron-switched circuit. A special impedance bond with secondary winding (L_1, L_2, L_3) in the commutator circuit ensures UV preionisation of the discharge gap throughout the duration of voltage build-up. Figure 10 shows oscillograms of the voltage U across the discharge gap, the current I_d through the discharge gap and the current I_c through the commutator, obtained for different values of the charging voltage U_0. An analysis of the oscillograms allows us to formulate the advantages of the discharge excitation technique proposed by us over the traditional approach:

(i) in a circuit with 'extended' front, the discharge gap

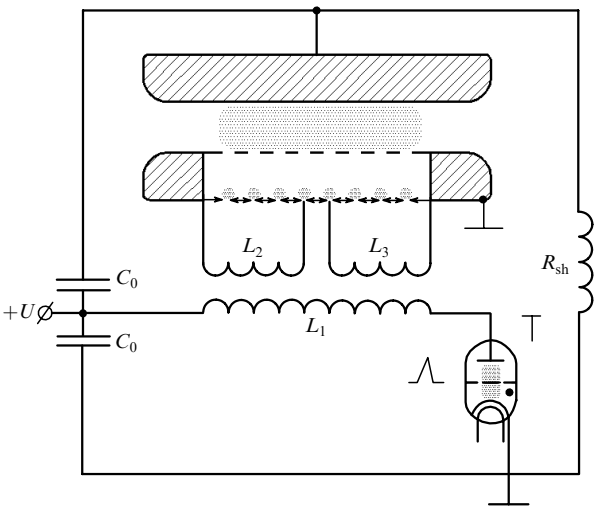

Figure 9. Circuit for exciting the pump discharge.

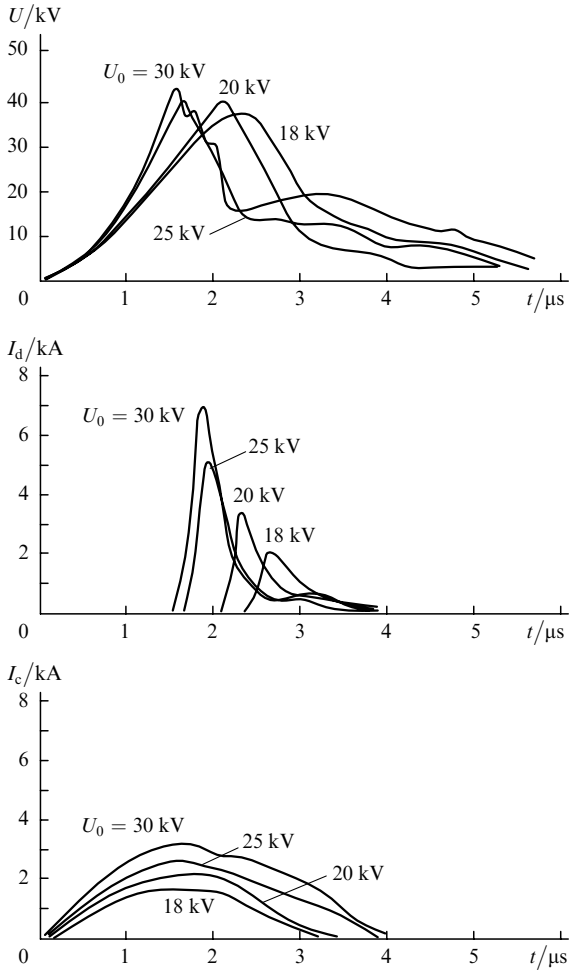

Figure 10. Oscillograms of discharge voltage U, current I_d through the main discharge gap, and current I_c through the commutator (thyratron) for different values of charge voltage U_0; the preionisation mixture $CO_2 : N_2 : He = 1 : 1 : 4$, $p = 0.6$ atm.

commutation voltage is virtually independent of the charging voltage U_0;

(ii) in the entire range of variation in U_0, the current through the discharge gap is stronger than the current through the thyratron, the difference between the two increasing steadily with U_0.

Another problem in the development of commercial TEA CO_2 lasers is associated with the need to maintain the chemical composition of the working gas mixture at a constant level, since changes in the composition of the active medium induced by numerous plasma-chemical reactions in the discharge considerably affect the radiation power and service life of TEA CO_2 lasers. The conventional approach for sustaining the chemical composition is the replenishment – evacuation of the working gas mixture which, however, involves a considerable expenditure of gases, including the expensive helium gas which constitutes about 80% of the working mixture. Moreover, a significant amount of toxic products (CO, O_3, NO_2, C_nH_m, etc.) is formed in the gaseous mixture during the discharge.

Catalytic regeneration of the working mixture, involving purging of impurities that are harmful for the discharge and suppression of CO_2 dissociation, is a more economical although technically more complicated method. This technique was used by us in the device 'Spektr'. It involves a partial evacuation of the working mixture from the gaseous circuit of the laser, passing it through the regenerator, and returning it to the laser circuit. The complex mixture regeneration technology consists of three stages: (i) filtering away of particulate pollutants, (ii) adsorptive purification of the working mixture from organic substances, water and plasma-chemical reaction products, and (iii) catalytic conversion of CO into CO_2.

The use of regenerative technique made it possible to increase the time of continuous operation of the laser 'Spektr' by more than an order of magnitude without replacing the gaseous mixture for pulse repetition rates up to 150 Hz. The duration of such an operating cycle for a pulse repetition rate of 150 Hz is at least six hours. The concentration of CO_2 is maintained at a constant level. Chromatographic measurements show that oxygen and carbon dioxide are not accumulated during the entire period of the laser operation. Discharge contraction is not observed in this case and the laser radiation energy does not vary by more than 15 % from its initial value.

In designing an optical resonator, we also used the nontraditional approach. The radiation energy density required for the development of multiphoton dissociation (up to 10 J cm^{-2}) with an appreciable length of the region of interaction of laser radiation with the substance being separated cannot be attained in traditional optical schemes. In traditional experiments on laser separation of carbon isotopes, the typical energy density of frequency-stabilised radiation extracted from the laser is 2.5 – 3.5 J cm^{-2} and the beam divergence amounts to $(3-5)\times10^{-3}$ rad.

For multiphoton dissociation of Freon, this density is close to the critical value and is bounded from above by the radiation resistance of transmitting materials. In our experiments, the length of the region of interaction of radiation with matter did not exceed 1 m and no more than 20 % of radiation power was spent on the dissociation of molecules of the substance. To use the radiation effectively, the region of interaction should be increased to several meters; in this case, however, the radiation energy density decreases due to beam divergence by a factor of several units and becomes smaller than the critical value.

To solve this problem, the active medium in the laser was combined with the absorbing medium in the isotope separation unit of the resonator from which radiation did not come out. The main elements of the optical resonator combining the laser and isotope separation blocks (see Fig. 8) are the diffraction grating, forming KCl lenses, and a spherical mirror [36]. Instead of the diffraction grating with a 60 % reflection to the first diffraction order, which is usually employed in a selective resonator for radiation extraction, a diffraction grating reflecting the primary radiation beam (up to 95 %) to the first diffraction order was used in our facility. A small part of radiation, which inevitably passes to the zeroth diffraction order, is extracted from the resonator for diagnostics of the laser radiation parameters.

The forming lens is used to reduce the laser beam cross section in the reactor zone. Energy densities that are unattainable in traditional optical schemes are obtained by appropriate selection of the gain in the laser block and the absorption coefficient in the interaction zone.

A cascade of gaseous centrifuges is used for the final enrichment of CO_2 to 99 % in ^{13}C isotope [42, 43]. An extraction coefficient of about 50 % with an intermediate enrichment of CO_2 in the ^{13}C isotope to 20 % – 40 % is attained for an optimal productivity of the laser – centrifuge complex operating in the cascade mode. For a theoretical extraction coefficient of $\sim$50 % and a ^{13}C isotope concentration of about 25 %, the actual productivity of the cascade in the ^{13}C isotope post-enrichment is 1 kg of the element per year.

The equipment required for a complete cycle of production of the ^{13}C isotope, including the laser unit, the isotope separation block, the block for separating tetrafluoroethylene, as well as the cascade of gas centrifuges, has been constructed, installed, and adjusted. The productivity of the ^{13}C isotope in the laser unit of the complex was as high as 1.2 g h^{-1}. This is quite sufficient for completing the technological cycle and starting the commercial operation of the device.

Thus, it can be stated that a new technique has been developed in Russia for laser-centrifugal production of the ^{13}C isotope.

5. Application of high-pressure lasers in technology

5.1 Processing of materials

Repetitively pulsed CO_2 lasers of a moderate average power have been used successfully in thermal technologies for over two decades. The fields of application of such lasers include scribing of ceramic plates, trimming of nominal resistors, marking of components, piercing of holes, cutting, welding, etc. (see [44] and the literature cited therein). For this purpose, TEA lasers with low-pressure (less than 0.5 atm) combined discharge pumping are normally used. The application of high-peak-power lasers (for example, TEA lasers) is hampered by a low-threshold breakdown of the gas surrounding the target. Moreover, it was shown in [45] that, for a fixed pulse energy, the energy consumption per unit volume of the material being removed (for example, during drilling) increases sharply for pulse durations below

20 and above 80 μs. Investigation of cutting and welding processes led to identical results [46]. Hence, we believe that the prospects of technological applications of CO_2 lasers with a high peak power (except the case of unfocused beams) are associated with the development of lasers with a pulse repetition rate of 1–2 kHz and a pulse energy not exceeding 0.1–0.2 J.

5.2 Laser sources of multiply charged ions

Ion beams are widely used for technological purposes for improving physicochemical, physicomechanical, electrophysical, and magnetic properties of surfaces, as well as the entire volume of materials, and also for the formation of structures that cannot be formed on the surface and in the layers near it by traditional chemical and thermal treatment. To improve the fatigue strength, wear resistance, corrosion stability and radiation resistance of materials, any doping impurities can be introduced in them by ion implantation (doping) [47]. The technological potentialities of ion implantation for high ion energies are mainly due to their enhanced penetration power.

The use of bi-, tri-, and tetravalent ions in commercial ion implanters raises the upper limit of the energy range of devices by a factor of 2, 3, and 4, respectively, while preserving the charging voltages. Considerable technical difficulties are encountered during attempts to further increase the charge state for high ion flux densities by traditional methods (high-voltage discharges, etc.). It should be noted that an increase in the ionicity leads to a considerable decrease (up to two orders of magnitude in comparison with the singly charged state) in the ion currents and accordingly lowers the productivity of implantation units. This explains the growing interest towards high-current laser sources of multiply charged ions which also make it possible to generate ions of nearly all elements.

In the Pulse Plasma Laboratory of Troitsk Institute for Innovation and Fusion Research (TRINITI), investigations are being carried out on the generation of multiply charged ion fluxes for a radiation power density of the CO_2 laser $P \leqslant 4 \times 10^{13}$ W cm^{-2}, pulse duration $\tau_p = 13 - 30$ ns and pulse energy $E \leqslant 100$ J [48, 49]. Depending on the problem to be solved, the laser system may consist of a simple free-running unit or an amplifying circuit with pulse compression, including a master oscillator, a nonlinear absorption cell and an amplifier. The latter circuit, based on the atmospheric pressure amplifier available in the laboratory, is rated to ensure generation of pulses of duration 200–500 ps with an energy of 5–10 J. The existing designs make it possible to create laser devices operating in the repetitively pulsed regime with a pulse repetition rate of 1–10 Hz.

In collaboration with the Russian Federal Research Centre TRINITI, D.V. Efremov Scientific Research Institute of Electrophysical Apparatus (NIIEFA), Moscow Physical Engineering Institute, Joint Institute for Nuclear Research and the Russian Research Centre 'Kurchatov Institute', the Russian Federal Research Centre 'Institute of Theoretical and Experimental Physics' has developed a basically new type of technological equipment – a system comprised of a high-power repetitively pulsed IR laser, a chamber for interaction with the target block and a unit for extracting a high-current beam of ions and nuclei from the device [50–53]. This system, which is essentially a laser plasma ion injector, makes it possible to generate intense beams of highly ionised atoms and nuclei of elements (including rare and radioactive isotopes) and inject them to electrophysical devices, thus opening new prospects of development in science and technology.

The injector is based on a unique ultrahigh-power (more than 5 GW) CO_2 laser with a pulse repetition rate up to 1 Hz. The pump discharge module based on a self-sustained discharge with X-ray preionisation, was first constructed in 2001 at the Institute of Theoretical and Experimental Physics. The active volume of the laser chamber of the module (~40 L) is first ionised by an X-ray beam with a radiation dose of about 3 rem. The high-voltage generator with a stored energy of 6 kJ and an idle voltage of 400 kV, developed as a power supply for the discharge, was constructed entirely from domestic components. In the free-running regime, the output energy up to 250 J was obtained in a 90-ns pulse.

The facility described above has the following potentialities:

(i) it can produce ions of most elements in the Periodic Table;

(ii) it can generate a high-intensity short (1–100 μs) ion pulse with a record-high brightness; and

(iii) it can operate in the repetitively pulsed regime with a service life of several hundred hours.

5.3 Production of nanopowders

Following the development of technologies of synthesis of nanostructured bulk materials in recent years with improved mechanical parameters and new electromagnetic and optical properties [54], considerable attention is being paid to the production of nanopowders. A large number of methods have been developed for production of nanopowders and a detailed analysis of such materials has been carried out (see, for example, [55, 56]). Because of a low efficiency and a high energy consumption, lasers were not used for these purposes for a long time. At the same time, the technique of vaporisation of materials by laser radiation followed by the condensation of vapour has been known since long and has always attracted attention due to the high purity and small size of the obtained particles, economy and variety of the starting materials. The competitiveness of this technique with other methods has been demonstrated only recently.

Considerable advances in this direction were made at the Institute of Electrophysics, Ural Division, Russian Academy of Sciences, Yekaterinburg. The design and characteristics of a device for producing nanopowders of metal oxides (average particle size 15 nm) at the rate of 20 g h^{-1} for a radiation power of 30–40 W were described in [56]. Nanopowders were produced by evaporating the target material using radiation from a repetitively pulsed CO_2 laser. The following conclusions were drawn from the experimental investigations:

1. The pulsed CO_2 laser allows a fourfold decrease in particle size in air under normal conditions and a power not exceeding the lowest values obtained for CW lasers.

2. The efficiency of using radiation for the production of nanopowders (equal to the ratio of the specific energy of vaporisation of the initial target material in J g^{-1} to the total specific energy spent on producing a unit weight of the nanopowder) is less than 10 %, and can be increased even for the same average power by lowering the radiation period and increasing the pulse repetition rate.

3. The technology and the facility developed by us allow

production of pure nanopowders of complex composition with a quite narrow size distribution of particles using targets made of coarse powders of commercially available chemical compounds or mechanically mixed components. To obtain the desired composition, one should take into account that concentration of the component with a higher boiling point decreases compared to its concentration in the raw material.

5.4 Laser acceleration of electrons

The problem of developing accelerators with a high rate of particle acceleration acquired an urgency after the closure of the project aimed at developing a giant accelerating superconductor supercollider. Hence pioneering (mainly, experimental) research activity in recent years has been aimed at exploring the actual possibilities of enhancing the acceleration rate.

Modern terawatt picosecond lasers can provide intensities up to $10^{18} - 10^{19}$ W cm^{-2} in the focal region, which corresponds to an electric field strength of up to $\sim$60 GV cm^{-1}. Most of the technologies being developed are based on the use of high-power CO_2 lasers. Two types of laser accelerators are being developed. The direct interaction of an electron beam with laser fields is used in inverted free electron lasers and in the inverted Cherenkov accelerator. In the second type, (transverse) laser fields are used for plasma formation and production of longitudinal accelerating fields. These include the laser wake field accelerator and the laser beat wave accelerator. In these cases, electrons are accelerated by longitudinal electric fields formed as a result of spatial periodic modulation of the plasma charge density (plasma waves).

Physical processes in laser accelerators are quite complex and require further investigations. Considerable attention was paid in the Soviet Union during 1960–1980 to the development of new methods of electron acceleration and a clear ascendancy was attained on the theoretical front. At present, most of the significant experimental studies are being carried out in the USA, and Russia is clearly lagging behind in this field.

6. Conclusions

Thus, on the one hand, there has been an undisputed progress in the development of high-pressure, high-power pulsed CO_2 lasers. On the other hand, the successful applications of these lasers in basic research and technologies can be expected only in the future. In our opinion, further progress in this direction is connected with the creation of terawatt picosecond and femtosecond CO_2 lasers. It is in this case that the advantage of a longer wavelength of CO_2 lasers compared to solid state lasers, will be realised. First of all, this concerns the highly bright X-ray sources and projects of charged particle acceleration by light waves. This is confirmed by a considerable financial support of these projects by the world community.

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