

# Chapter 1

## Carbon Dioxide Laser with an Output Energy of 3 kJ, Excited in Matched Regime

**Abstract** An investigation was carried out into a CO<sub>2</sub> laser with a pulsed pumping of a gas cell in the matched regime. The total energy of the output radiation was 3 kJ when the pressure of the mixture was 2 atm and the active volume was 50 L. When the active volume was 12 L, the energy deposited in a mixture of the CO<sub>2</sub>:N<sub>2</sub>:He = 1:2:2 composition was 0.6 kJ L<sup>-1</sup> atm<sup>-1</sup> and the radiation energy was ~80 J L<sup>-1</sup> atm<sup>-1</sup>.

In the most powerful laser systems excited by an electric discharge and stabilized by an electron beam, the discharge is supplied with power from a storage capacitor connected to a laser gap [1, 2] or by a pulse voltage generator [3, 4]. In the former case, the energy stored in a capacitor is considerably more than the energy deposited in the discharge so that after the end of an excitation pulse a high voltage remains for a long time (compared with the excitation pulse duration) on the electrodes. The advantage of such a nonmatched operation is that the voltage on the electrodes of a gas does not vary significantly during the pumping time. However, a residual voltage on the electrodes of a laser cell hinders—because of discharge contraction—attainment of a high field intensity in the gap and prevents deposition of large energies, particularly in the case of mixtures with low helium concentrations. When a pulse voltage generator is used to supply a gap, only part of the stored energy is deposited in the gas during the action of an electron beam [3, 4] and this imposes restrictions on the total efficiency and gives rise to a residual voltage on the electrodes.

The use of matched pumping of a CO<sub>2</sub> amplifier with a characteristic excitation time of ~1 μs was first reported in [5], but in this case the specific input energy did not exceed 200 J/L and the output energy characteristics were not given.

Our aim was to investigate the possibility of excitation of a CO<sub>2</sub> laser in the matched regime so as to ensure a high specific input energy and a high output energy in pulses of ~1 μs duration.

Our laser system consisted of a gas cell, a power supply, and an electron accelerator. The active medium was excited by a non-SSVD. The maximum active volume of the chamber was 50 L (20 × 20 × 125 cm). The chamber could be operated at pressures up to 2.5 atm. Experiments were carried out on an active volume of 50 L and also on a reduced active volume of 12 L (8 × 12 × 125 cm).

The electron accelerator provided an electron beam current of density  $\sim 0.5 \text{ A/cm}^2$  in the gas chamber and an acceleration voltage of  $\sim 300 \text{ kV}$  in a vacuum diode. Oscillograms of the acceleration voltage across this diode and of the electron beam current in the gas chamber were recorded (Fig. 1.1a, b). A special feature of the selected operation regime was the fact that the duration of the electron beam pulses was twice the duration of the discharge current pulses. The discharge in the chamber was delayed by  $-0.3 \mu\text{s}$  relative to the electron-beam current. Thus, the discharge occurred under conditions of constant electron-beam current density and constant electron energy, which was an important factor tending to increase the stability of the discharge, because it was possible to eliminate the low-energy electrons formed during the rising and falling parts of the acceleration voltage.

We used LC correction in a pulse voltage generator supplying the vacuum diode, so that the beam current pulses were nearly rectangular (Fig. 1.1b).

The gas chamber was supplied with a Marx pulse generator consisting of three parallel branches with five steps in each. This generator utilized IK-100/0.4 capacitors and the LC correction circuit contained IMN-100/0.1 capacitors. The equivalent capacitance of the pulse generator was  $0.24 \mu\text{F}$  and its wave impedance was  $p = 3.3 \Omega$ ; when the charging voltage was  $U = 58 \text{ kV}$ , the energy stored in the pulse generator reached  $10 \text{ kJ}$ . Spark gaps (through which dry air was blown) were employed in the generator and this ensured a high triggering stability ( $\pm 20 \text{ ns}$ ) and made it possible to synchronize the discharge current and beam current pulses.

The discharge current in our electrical circuit can be described using the following equation:

$$f(t) = (U_0/\omega L) \exp(-Rt/2L) \sin \omega t. \quad (1.1)$$

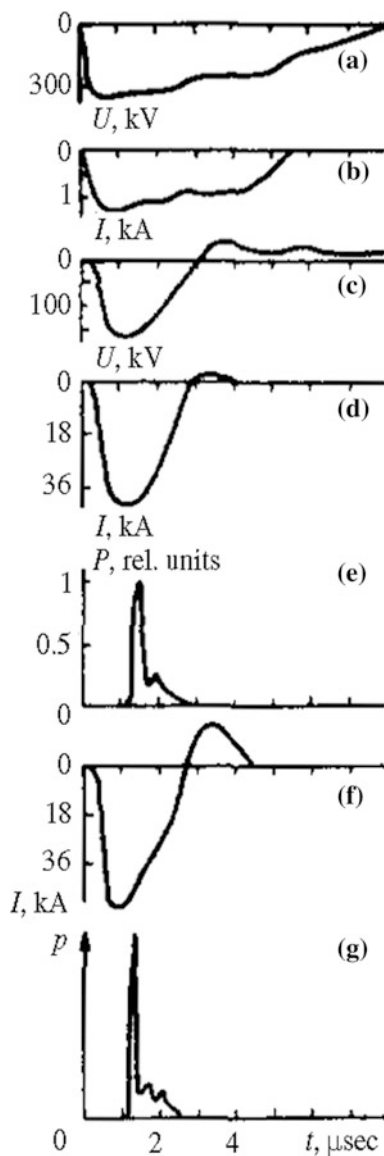
where  $\omega = (L/C - R^2/4L^2)^{1/2}$  is the oscillation frequency of the circuit;  $R$  is the active resistance included in the circuit. In our case,  $R$  is the resistance of the discharge plasma, which can be regarded (with a good approximation) as linear and constant in time because there is no change in the electron beam current during the discharge. The matched load condition is  $R = (LC)^{1/2} = \rho$  and it then follows from (1) that the discharge current pulse has the following parameters:

$$t_p = 2\pi(LC/3)^{1/2}; \quad t_m = 2\pi(LC/27)^{1/2}, \quad I_m = [U_0(LC)^{1/3}] \exp(\pi/3\sqrt{3}), \quad (1.2)$$

where  $U_0$  is the open-circuit voltage of the generator;  $t_p$  is the duration of the current pulses at the base;  $t_m$  is the time needed to reach the maximum value of the current;  $I_m$  is the maximum discharge current.

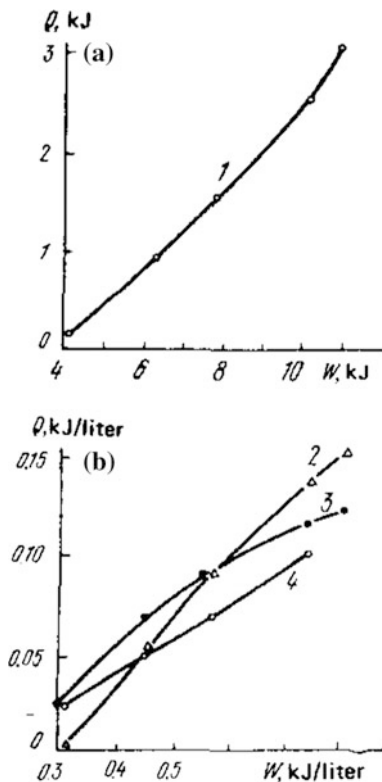
In practice, there is no need to satisfy the exact equality  $R = \rho$  because for  $0.75 \rho \leq R \leq 2\rho$ , the reduction in the peak power does not exceed 10 %. It is worth noting that an increase in  $R$  from  $0.75 \rho$  to  $2 \rho$  alters the voltage across the plasma from  $0.47U_0$  to  $0.74U_0$ . This should be allowed for in order to ensure the maximum efficiency of the laser. In the laser described above with the maximum active volume of  $50 \text{ L}$  for a mixture of the composition  $\text{CO}_2:\text{N}_2:\text{He} = 1:2:2$  at a pressure of  $2 \text{ atm}$  the plasma resistance was  $R = 3.8 \Omega$ . For a charging voltage of

**Fig. 1.1** Oscillograms of the voltage (a) and current (b) pulses in the accelerator, voltage across the gap (c), current in the chamber (e, f), and radiation pulses (d, g). The charging voltage of the pulse generators supplying the cell was 58 kV and the mixture has the composition  $\text{CO}_2:\text{N}_2:\text{He} = 1:2:2$ . The pressure was  $p = 2$  atm and the volume was 50 L (c–e) and 12 L (f, g)



$U = 58$  kV the oscillograms of the voltage across the plasma, discharge current, and radiation pulse had the form shown in Fig. 1.1c–e. The dependence of the total radiation energy on the energy stored in the pulse generator was determined for this case (Fig. 1.2a). The transverse distribution of the radiation in the output beam was nonuniform and the center of the energy density reached  $15 \text{ J/cm}^2$ ; at this energy density, the exit window was damaged. The total radiation energy reached 3 kJ and the efficiency was  $\sim 21\%$ . The radiation energy was measured by scanning a laser

**Fig. 1.2** Dependences of the total radiation energy on the input energy for an active volume of 50 L (a) and the specific output energy plotted as a function of the specific input energy when the active volume was 12 L (b). Composition  $\text{CO}_2:\text{N}_2$ : He = 1:2:2, pressure  $p = 2$  atm [1–3] and 1.2 atm [4]; exit window made of KRS (1, 3, 4) and of NaCl (2)



beam with an IKT-IM calorimeter, from which the sapphire window in the detection head was removed.

The possibility of attaining high input energies in the matched regime was investigated by reducing the active volume of 12 L ( $8 \times 12 \times 125$  cm). In the case of the 50 L volume, this could not be done because of the limited energy stored in the pulse generators supplying the gap. The plasma resistance then decreased to  $2.5 \Omega$ . Oscillograms of the discharge current and radiation pulse were also recorded for this case (Fig. 1.1f, g). The energy deposited during the second half-period did not exceed 10 %, so that the conditions could be regarded as practically matched. The amplitude of the voltage across the plasma was 136 kV ( $E/p = 8.5 \text{ kV} \cdot \text{cm}^{-1} \cdot \text{atm}^{-1}$ ) and the maximum input energy exceed  $0.6 \text{ kJ} \cdot \text{L}^{-1} \cdot \text{atm}^{-1}$ . The dependences of the radiation energy on the input at pressures of 2 and 1.2 atm in the mixture and also in various resonators were determined using exit mirrors in the form of NaCl and KRS plates (Fig. 1.2b). The maximum radiation energy obtained from the 12 L volume was 1.8 kJ. An increase in the input energy reduced the lasing efficiency, in agreement with the results of [3].

Our experimental study thus showed that it should be possible to achieve high specific energy inputs in large volumes if the matched regime is used.

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