PUMPING OF METAL VAPOR LASERS BY THE LONGITUDINAL RUNAWAY ELECTRON BEAM

G.V. Kolbychev, P.D. Kolbycheva, and O.B. Zabudskii

Institute of Atmospheric Optics,
Siberian Branch of the Russian Academy of Sciences, Tomsk
Received December 21, 1992

Some results of experiments on developing metal vapor lasers with the longitudinal pumping by runaway electron beams (REB) are presented. The problems of the REB propagation through a long and narrow laser tube are studied. An optimal version of a magnetic system arrangement capable of superposing several REB's into a single narrow beam and guiding it along a laser tube axis with a high overall efficiency is proposed. Laser tubes are designed and laser emission has been observed in Cd and Zn vapors pumped by the REB. The data obtained can make a basis for developing and constructing lasers on vapors of other chemical elements as well.

Runaway electron beams (REB's) generated in a middle–pressure gas discharge[1,2] with an efficiency of 60–80% can be used for laser pumping. The nanosecond range of the REB pulse duration, high pulse repetition rate (up to 10^5 Hz), as well as operating pressures of a buffer gas (1–20 kPa) in an electron gun make it particularly promising for pumping self–terminated metal vapor lasers.

The REB guns are operable in metal vapor as well, when a hollow cathode–anode geometry is used.[3] Nevertheless, the longitudinal geometry is preferable, when the guns are placed in the cold region of the laser cavity, and the REB's are injected into the heated region along the laser axis. But in this case some problems arise associated with the need (*i*) to efficiently turn, (*ii*) to compress and confine it in a channel, and (*iii*) to guide the strongly absorbed REB through a long and narrow laser channel. For the rates of a REB current increase being ~ 10^9 A/s, some phenomena can be observed in the beam–induced plasma. They are *e*–beam charge neutralization, space discharge, oscillations of different kinds and instabilities, and so on.[4,5] All of them strongly affect the REB transportation within the working region of the cavity. The current theoretical data make it impossible to evaluate a role of these factors in our conditions, while, in addition, most of the experimental data have been obtained for relativistic electrons. For these reasons elucidation of a real picture of REB propagation in the laser cavity has become the primary object of our concern. At the next stage the development of an optimal version of a REB control system providing for a maximum REB energy deposition to the working region of the laser has been done. And finally, at the third stage a design and test of the metal–vapor laser cavity pumped with a set of REB guns has been undertaken. This paper presents the results of the above–mentioned experiments.

1. MEASUREMENTS OF ELECTRIC FIELDS IN THE REB–INDUCED PLASMA

The investigation was performed with the use of a glass drift tube of internal diameter 16 mm and 260 mm in total length. A REB gun and a mobile REB collector were placed at the opposite ends of the tube. The collector could be moved along the axis of the tube. Twelve electrostatic probes were placed along the tube with the gap between the probes of 20 mm. The probe consisted of Mo rod 7 mm in length and 50 μm in diameter directed radially from the tube wall to its axis. A set of electromagnet coils surrounded the tube. The 18–mm long coils were spaced by a 4–mm gap to provide sufficiently homogeneous magnetic field inside the tube and a free access to the probe contacts simultaneously. The probe signals were alternately taken by a resistive voltage divider mounted in a removable lock and put to an S1–55 oscilloscope synchronized with the REB gun.

The gun of runaway electrons was power supplied by connecting its cathode through a TGI1–1000/25 thyratron to a KVI–3 capacitor of 1–nF capacity charged by a voltage pulse of the amplitude U_0 varying from 7 to 11 kV at a repetition rate of 250 Hz. When the tube was filled with helium at a pressure of 1–3 kPa, the average energy of electrons in the REB was ~ $0.8{\cdot}U_0$ (eV). The REB current at the collector and a current through the gun anode were measured with 5– and 1–Ω resistive shunts, respectively. Estimated error introduced by the probes into the spatial distribution of the electric potential along the tube did not exceed 30 V and was negligible compared to the signals measured with these probes.

The tests showed that without an axial magnetic field the REB was completely disintegrated on the first 130–170 mm path along the tube. For this reason in our next investigations of the electric field profile the collector was placed at a distance of 140 mm from the gun anode.

Measurement results on the profile of a volume electric potential φ(x) along the discharge tube are shown in Fig. 1 for two cases: (*i*) without magnetic field and (*ii*) in the presence of an axial magnetic field with the strength of 30 kA/m. Typical oscillogram of the potential pulse measured at the center of the tube and its time position with respect to the REB current pulse at the collector are shown in Fig. 2. In the investigations we obtained the following results:

0235-6880/93/03 153-03 $02.00

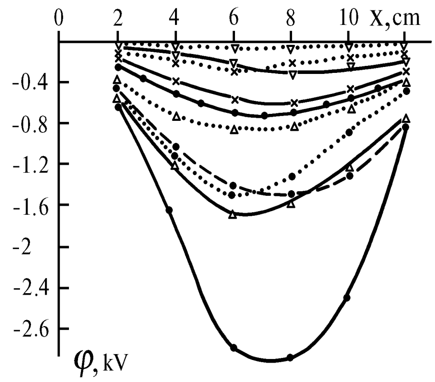

FIG. 1. A distribution of the volume electric potential along the tube. The point $x = 0$ *corresponds to the gun anode and* $x = 140$ mm *corresponds to the collector position. Helium pressure:* ∇ – 1.66, x – 2.0, Δ – 2.33, and • – 2.66 kPa. *The voltage applied to the gun:* 7 *(dashed–dotted lines),* 9 *(dashed lines), and* 11 kV *(solid lines). Dotted lines present the case in which the axial magnetic field of* 30 kA/m *strength is switched on and the voltage applied to the gun is* 11 kV.

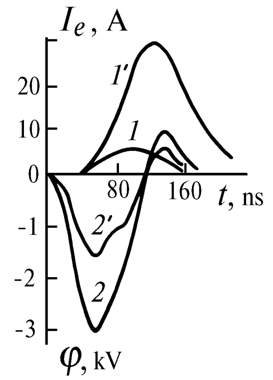

FIG. 2. Oscillograms of the REB current pulse measured at the collector (1, 1′) and of the volume potential measured at the middle of the drift tube (2, 2′), when the axial magnetic field is switched off (1, 2) and switched on (1′, 2′). Helium pressure is 2.66 kPa *and the voltage applied to the gun is* 11 kV.

1. Behavior of the volume potential pulses was practically the same in all our measurements. First, the volume potential amplitude increases monotonically from the anode to the center of the tube and then decreases in the same way along the direction toward the collector. Second, the signal of the probe reaches its maximum at the beginning of the REB when its current is yet small. When the REB current increases up to its amplitude value, the volume potential has been already significantly reduced. The reduction (with respect to the signal amplitude) is stronger, the higher is the voltage of the gun power supply, that is, the higher is the REB current and the rate of its increase.[1] Note that the signals appear at all probes simultaneously during the time for the signals to reach their amplitude values, in any case no noticeable time delay was observed within the time scale of pulse durations. The recorded changes of the pulse shapes along the tube were also within the limits of the measurement error (± 5–7%). All changes in the signals shapes were found to occur on their trailing edges when the gas pressure in the tube and the power supply voltage were low.

2. The electric field strength in the drift space of the tube, due to the charge of the REB, reaches several hundred V/cm and is the cause of the corona discharge on the collector and of the neutralization of the current of a spatial charge on both electrodes. Without an axial magnetic field the neutralization current flows preferably to the anode, because the near–anode plasma has a higher conductivity. As the measurements show, the neutralization current from the drift space is about 1/3–1/2 of the total anode current even though a distance between the anode and the collectors is rather small (~ 45 mm). The discharge between the spatial charge and the anode was found to occur in the drift space near the anode, when the strength of the electric field in the tube is higher than 100 V/cm. This fact is confirmed by appearance of an undershoot in the near–anode probe signals. With increase of voltage at the gun or of the gas pressure the drift space, which is occupied with this discharge, is being expanded toward the REB collector, but it never reaches it, though the electric field strength is sufficiently high here.

3. In the presence of the axial magnetic field with the strength of 30 kA/m, the beam's plasma looks like a filament ~ 8 mm in diameter, and its brightness is almost invariable along the tube. In this case the spatial potential is twice as low as the original one (at high helium pressure) and four times as low as that at low pressure. The REB current on the collector increases also from 4 to 6 times, and the increase of the collector current equals the decrease of the anode current. The qualitative picture of the volume potential distribution along the tube remains unchanged, when the magnetic field is switched on (see Fig. 1).

4. Analysis of physical processes in the drift space during the growth of the pulsed volume potential shows that the normalized field strength E/P is the basic characteristic here and the rate of increase of the REB current ($\mathrm{d}I_e/\mathrm{d}t$) is the initial parameter, which is determined by the REB gun. From our experimental data we have obtained the following relation: $E/P \sim (\mathrm{d}I_e/\mathrm{d}t))^{0.5\pm0.04}$ between E/P and ($\mathrm{d}I_e/\mathrm{d}t$) in the presence of the axial magnetic field. Here E is the strength in the near–anode region of the drift space. It should be noted, that as the amplitude–time parameters of the REB current pulse depend strongly on the operating conditions,[1,2] the volume potential magnitude increases strongly with increase of the gas pressure and the gun power supply voltage, as can be seen from Fig. 1.

Thus, the above investigations enabled us to determine the behavior of the pulsed volume potentials in the drift tube and its effect on the REB propagation. The relation obtained allows us to extrapolate the experimental results for longer drift tubes and other parameters of the pulsed REB current what is important for the REB application to pumping lasers.

2. OPTIMIZATION OF THE MAGNETIC SYSTEM OF THE LASER

In the course of our experiments we have tested several versions of the magnetic system for holding and superposing electron beams from several guns, as well as for compression of the resulting beam and its efficient guide through a long and narrow laser tube. To this end we have tested magnetic prisms and lenses in combination with the wide and narrow aperture solenoids.

The tests have shown that the most difficulties are connected with the necessity of matching the above–mentioned operations, because each of them requires a particular configuration of the magnetic field. So, a wide–aperture solenoid does not provide the superposition of several *e*–beams. The short focus lenses are also ineffective for the same reason, but they can be used if the complete coincidence of beams is not required. The miniature magnet prisms are very economical, but it is very difficult to match them to the systems for holding the *e*–beams. Therefore the efficiency of injecting the total *e*–beam into the narrow laser tube did not exceed 50–60%. The best results we obtained with narrow solenoids. In this case by proper adjustment of the positions of the REB guns and solenoid we succeeded in performing all the operations with the overall efficiency of ~ 90%. The magnetic field strength of from 70 to 100 kA/m provides a two times compression of the electron beam plasma filament compared to the diameter of a single beam generated by an individual electron gun.

To design the laser cavity one should know the depth of REB penetration into the active medium. Therefore we measured this characteristic at a helium pressure of 1–2 kPa and with 100 kA/m strength of the axial magnetic field. The depth of the REB penetration was found to be about 0.7 of the entire free path of the electron beam determined by the Bethe–Miller formula.[6]

3. INVESTIGATIONS OF THE METAL VAPOR LASER PUMPING WITH THE RUNAWAY ELECTRON BEAMS

At the first stage we have examined the laser with a single REB gun. The gun was placed at one end of the cavity, while at the other end there was the electron collector at the distance of 500 mm from the gun. The gun of 30 by 30 by 6 mm dimensions generated the electron beam of 11 mm in diameter with the energy from 6 to 11 keV and the number of electrons per pulse $(1 - 3) \cdot 10^{13}$. The central part of the laser cavity was 12 mm in diameter and 360 mm in length and had several metal source reservoirs. It was mounted inside a heating tube and a solenoid. Temperature was measured with a chromel–alumel thermocouple placed outside at the base of these reservoirs. The external resonator was formed by a 100% reflection spherical mirror with 1–m radius of curvature and a plane mirror with 99% reflection coefficient.

The laser effect has been observed at both green (537 nm) and blue (441.6 nm) lines of Cd vapor. The oscillograms of the laser emission pulses and of the REB current at the collector are shown in Fig. 3. The lasing starts when the temperature in the metal source reservoir reaches 555 K and Cd–vapor concentration of 10^{13} cm^{-3}, as in the case with the gas discharge pumping. With increase of the Cd–vapor concentration up to $1 \cdot 10^{16}$ cm^{-3}, the laser power also increased. The temperature was not further increased to prevent vapor deposition on the tube windows. The helium pressure optimal for lasing was 1.6–2 kPa.

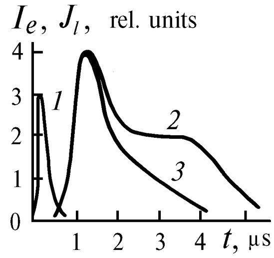

FIG. 3. Oscillograms of the REB current pulse measured at the collector (1) and the laser emission pulses at 537 nm *(2) and at* 441.6 nm *(3) (Cd vapor). Temperature is* 555 K, *helium pressure is* 1.64 kPa, *and voltage applied to the gun is* 11 kV.

At the second stage we have examined the laser tube with four REB guns mounted at the opposite ends in pairs, the REB gun construction and the electron beam parameter being the same as the above described. The electron collector was placed in the middle of the tube. A heated part of the laser tube was 12 mm in diameter and 500 mm long. The laser tube was placed inside a solenoid coil with 100 turns. All four REB guns were switched on by one and the same TGI1–1000/25 thyratron, so the guns were synchronized. A repetition rate of the REB pulses was 500 Hz. The tube was filled with Zn vapor and at a helium pressure of 3 kPa.

The tests have shown a good superposition of the REB's into one filament 5–6 mm in diameter and an efficient guiding of it through the heated zone of the laser tube. A lasing effect has been observed at 492–nm wavelength on a Zn II ion transition. A temporal behavior of the laser emission pulses was the same as for Cd shown in Fig. 3. Though the threshold for Zn–vapor pumping was about 3 times higher than that for Cd vapor[7] we used only one gun to obtain lasing for Cd.

In conclusion, the main results of the above investigations can be formulated as follows: Some particular features of the REB transportation through longitudinal and narrow dielectric tubes have been revealed and studied, the magnetic system for a longitudinal laser pumping by a set of the REB guns has been developed, and several metal vapor laser tubes with the REB pumping have been successfully tested. These results provide a basis for designing such lasers in the nearest future.

REFERENCES

1. P.A. Bokhan and G.V. Kolbychev, Zh. Tekh. Fiz. **51**, No. 9, 1823–1831 (1981).
2. G.V. Kolbychev and E.A. Samysshkin, ibid., No. 10, 2023–2037 (1981).
3. P.A. Bokhan and A.R. Sorokin, Pis'ma Zh. Tekh. Fiz. **10**, No. 10, 620–623 (1984).
4. M.A. Vlasov et al., ibid., No. 11, 652–655 (1984).
5. A.A. Valuev, P.I. Sopin, and G.A. Sorokin, Teplofiz. Vys. Temp. **27**, No. 4, 642–649 (1989).
6. L.I. Gudzenko and S.I. Yakovlenko, *Plazma Lasers* (Atomizdat, Moscow, 1978), 256 pp.
7. I.G. Ivanov, Avtometriya, No. 1, 19–34 (1984).