Multikilowatt electron beams for pumping cw ion lasers

J. J. Rocca,[a] J. D. Meyer, Z. Yu,[b] M. Farrell, and G. J. Collins[c]
Department of Electrical Engineering, Colorado State University, Fort Collins, Colorado 80523

(Received 16 June 1982; accepted for publication 6 August 1982)

A glow discharge electron gun capable of producing a well collimated dc electron beam at energies between 1 and 6 keV and currents up to 1 A is described. The electron beam is produced in helium at pressures between 0.1 and 2 Torr without differential pumping. Beam generation efficiencies up to 80% have been measured. The electron guns are designed to pump cw ion lasers and are constructed to provide an optical path through the axis. Continuous-wave laser oscillation in Kr II has been obtained using electron-beam pumping of a He–Kr mixture.

PACS numbers: 41.80.Dd, 52.80.Hc

Previously, we reported the generation of well collimated electron-beam discharges with powers of 1 kW, at currents up to 0.1 A, using hollow cathode electron guns.[1] The hollow cathode electron guns operate in helium at pressures up to 1.4 Torr. Here, we report a large increase in the current of glow discharge created electron-beams for cw laser excitation by means of a new electron gun design which uses the enhanced secondary electron emission from oxide surfaces. Electron-beam discharge powers up to 5 kW and currents up to 1 A have been obtained. We have operated this new glow discharge electron gun at pressures between 0.1 and 2 Torr in helium, without differential pumping. Operation of the glow discharge at higher pressures is also possible; however, the electron beam becomes poorly collimated as the gas density increases.

Glow discharge electron beams have been used in the past for metallurgy applications.[2] We have designed our electron gun for the excitation of lasers and have already demonstrated the utility of the electron-beam created plasmas as a new active medium for cw ion lasers.[3–5] Electron-beam created plasmas, having a large density of energetic electrons, are an attractive approach to the increase of both the power and efficiency of cw ion lasers, as well as extending their spectral range into the vacuum ultraviolet.[5]

The structure of the glow discharge electron gun is shown in Fig. 1. The gun provides a 0.5-cm-diam optical path through the axis. This permits one to easily match the electron-beam plasma volume with the volume of an optical resonator. Electron emission is produced by the bombardment of the cathode front face both by ions and by fast neutrals created by resonant charge transfer in the cathode sheath. The secondary electrons produced at the cathode surface are accelerated along the electric field lines throughout the cathode dark space to form the well collimated electron beam shown in Fig. 2. To confine emission to the cathode front face the rest of the cathode walls are shielded. An insulating ceramic tube covers the external cathode walls and a quartz tube shields the inner cathode walls. The cathode is made of aluminum and is water cooled to allow for adequate heat dissipation of multikilowatt dc operating conditions. When the cathode surface facing the glow discharge is covered with a thin layer of oxide (Al_2O_3) it provides a secondary emission coefficient nearly 10 times greater than for pure aluminum.[6]

The distance between the insulating shield and the cathode is approximately 1 mm. The cathode front face is made concave to focus the electron beam, as shown in Fig. 2. We have used as a radius of curvature, both 6 and 9 cm on a cathode face 3.1 cm in diameter. The position of the anode is not important and does not have any influence on the electron-beam characteristics as long as the distance between electrodes is kept larger than the cathode dark space.

Energetic ions and neutral atoms which impinge on the cathode surface rapidly sputter off the thin native oxide layer. When this coating is removed the emissivity of the cathode drops by more than an order of magnitude and the material of the cathode itself starts to be sputtered into the discharge. This can be seen by eye as a color change in the region close to the cathode surface. However, it is possible to maintain a stable oxide layer by adding a few milliTorr of O_2 into the discharge.[7] In this way the cathode oxide layer is continually restored and no change was observed in the emission characteristics after 10 h of operation at high current. In earlier studies, we also observed that after several minutes of discharge operation a dark circle was formed in the central region of the emitting face of the cathode. This region was seen to have considerably less electron emission than the surrounding aluminum oxide surface, producing a doughnut shaped electron beam. Auger electron analysis of the cathode surface determined that the major elemental components of the low emissivity cathode region were C (49.6%), Al (38%), and O (10.4%). The presence of carbon is known to cause a strong attenuation in the electron emissive characteristics of a surface.[8] When all elements of the discharge tube and electron gun are carefully cleaned and handled prior to operation, no carbon deposit is observed on the

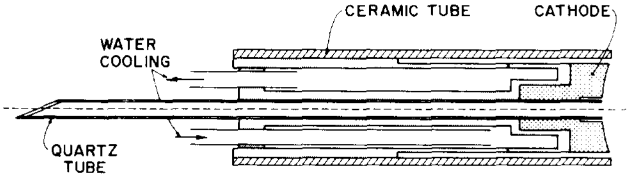

FIG. 1. Structure of the glow discharge electron gun.

---

[a] Spectra-Physics Industrial Fellow.

[b] Permanent address: Department of Physics, Fudan University, Shanghai, China.

[c] Alfred Sloan Foundation Fellow.

0003-6951/82/090811-03$01.00

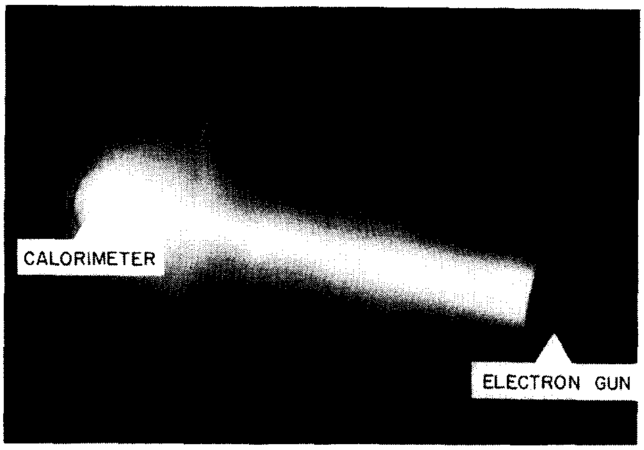

FIG. 2. Electron-beam discharge without applied magnetic field.

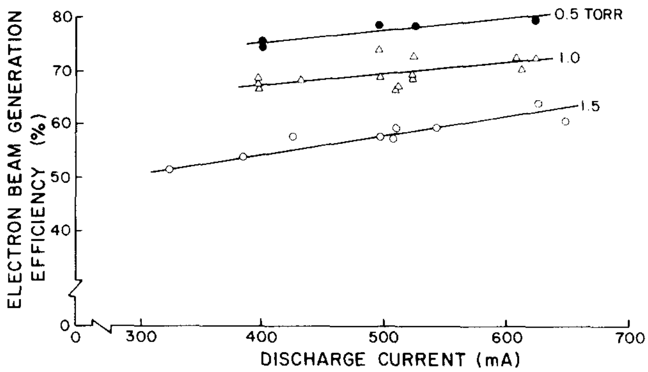

FIG. 4. Electron-beam generation efficiency as a function of discharge current for an aluminum cathode. The He pressure in Torr is shown. Twenty mTorr of oxygen was also added to the discharge chamber.

cathode face and emissivity of the electron gun remained unchanged.

The I-V characteristics of the electron-beam glow discharge with an aluminum cathode covered by a thin $\mathrm{Al_2O_3}$ film are shown in Fig. 3, with He pressure as a parameter. This with figure shows that electron-beam discharge currents over 1 A (cathode current density > 0.15 A/cm^2) and discharge powers of 5 kW have been obtained. The impedence of the electron-beam glow discharge is significantly reduced when an axial magnetic field (1–4 kG) is applied in the electron-beam drift region. The magnetic field helps to keep the electron beam collimated, allowing for the creation of a long laser active medium. The magnetic field is observed to increase the plasma density and the ion flux to the cathode, consequently enhancing secondary emission of electrons from the cathode and lowering the discharge impedance, as shown in the dashed curves of Fig. 3. If electron beams of lower energy are desired, magnesium can be used as cathode material with a thin coating of magnesium oxide on the cathode face. We have obtained electron-beam currents of 1.2 A at an energy of 1.5 keV by operating the electron gun with a Mg cathode in an atmosphere of 0.5 Torr of helium with 10 mTorr of oxygen.

We performed calorimetric measurements to measure the efficiency at which the electron beam is generated using an electron gun with a 2-mm-diam optical path. A calorimeter was situated 13 cm from the cathode emitting surface. The results of these measurements are shown in Fig. 4. The electron-beam generation efficiency is observed to increase as the discharge pressure decreases and as the current increases. This is primarily due to the increase of the secondary emission coefficient as a function of the energy of the impinging ions.[9] The energy of these ions and associated fast neutrals (created by charge transfer) increases with the discharge voltage.[10] A maximum electron-beam generation efficiency of 80% was measured at 0.5 Torr of helium and a beam current of 0.65 A.

The electron-beam profile was measured using an electrostatic energy analyzer. The electron analyzer was placed in a separate chamber maintained at a pressure below 10^{-5} Torr and connected to the electron-beam discharge chamber by a 50-μm-diam pinhole. The pinhole was 17 cm from the electron gun emitting face. The highest electron kinetic energy measured corresponds to the energy an electron obtains across a potential drop equal to the total discharge voltage, confirming that pratically all the discharge voltage drop occurs in the cathode dark space. The energy spectrum of the electron beam produced by a magnesium cathode has been measured at different discharge conditions, and usually presented an energy width at half-maximum of 100–300 eV.

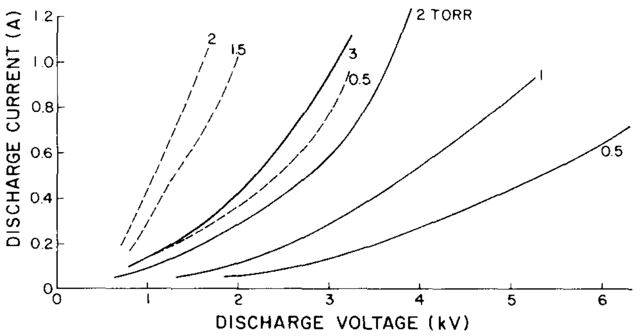

FIG. 3. I-V characteristics of the electron-beam discharge in helium with 20 mTorr of oxygen added to the discharge chamber. Solid line: without magnetic field. Dashed line: operating the electron gun at 13 cm from a solenoid producing a magnetic field of 3.2 kG. Fringing field at the cathode front face 40 G.

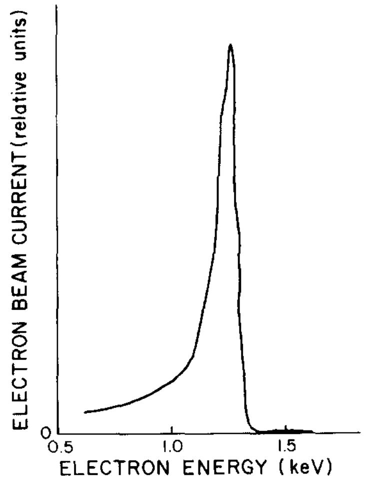

FIG. 5. Energy spectrum of the electron beam produced by a glow discharge magnesium electron gun measured at 17 cm from the cathode face. Discharge current is 400 mA. Discharge voltage is 1.31 kV. He pressure is 0.6 Torr with the addition of 10 mTorr of O_2.

Figure 5 shows the energy profile of an electron beam produced by a magnesium cathode glow discharge at a current of 0.4 A in He at 0.6 Torr.

Using a similar laser set up to that in Refs. 3 and 4 we have obtained cw laser oscillation of the 4694-Å transition of Kr II using electron-beam pumping of a He–Kr gas mixture. Using an output coupler with an unoptimized transmissivity of 1.5% a laser output power of 5 mW was obtained at a discharge current of 700 mA, using an axial magnetic field of 1.25 kG to collimate the electron beam. The optimum gas mixture was 0.1 Torr of Kr and 2.2 Torr of He.

In summary, we have obtained well collimated electron beams of energy between 1 and 6 KeV at currents up to 1 A. We present the design parameters of the glow discharge electron gun that can produce the multikilowatt electron beam at pressures between 0.1 and 2 Torr in helium without differential pumping. The electron gun has been designed for the longitudinal excitation of cw ion lasers and presents a clear optical path through the axis that permits one to easily match the electron-beam created plasma volume with the volume of an optical resonator. A maximum electron-beam generation efficiency of 80% has been measured. cw laser oscillation on the 4694-Å transition of Kr II using electron-beam pumping of a He-Kr gas mixture is reported.

The authors want to thank Allan Brown for the calorimetric measurements and R. Dugdale for helpful discussions. This work was supported by the National Science Foundation and AFOSR Grant No. 80-0268.

[1] J. J. Rocca, J. D. Meyer, and G. J. Collins, Phys. Lett. A**87**, 237 (1982).
[2] R. A. Dugdale, J. Mater. Sci. **10**, 896 (1975).
[3] J. J. Rocca, J. D. Meyer, and G. J. Collins, Appl. Phys. Lett. **40**, 300 (1982).
[4] J. D. Meyer, J. J. Rocca, Z. Yu, and G. J. Collins, IEEE J.Quantum. Electron. **18**, 326 (1982).
[5] J. J. Rocca, J. D. Meyer, Z. Yu, and G. J. Collins, presented at the XII International Quantum Electronic Conference, Munchen, June 1982.
[6] N. G. Burrow and R. B. Burtt, J. Phys. D **5**, 2231 (1972).
[7] R. E. Hurley and J. H. Holliday, Vacuum **28**, 453 (1978).
[8] E. N. Sickafus, Phys. Rev. B**16**, 1448 (1977).
[9] G. Carter and J. S. Colligon, *Ion Bombardment of Solids* (Elvesier, New York, 1968).
[10] W. D. Davis and T. A. Vanderslice, Phys. Rev. **131**, 219 (1963).

Plasma channel formation with ultraviolet lasers

C. A. Frost, J. R. Woodworth, J. N. Olsen, and T. A. Green
Sandia National Laboratories, Albuquerque, New Mexico 87185

(Received 15 April 1982; accepted for publication 25 August 1982)

The beam from a low-divergence KrF laser ($\lambda = 248$ nm) has been used to generate long plasma channels in low pressure gases. Current-carrying channels 60 cm in length were produced with 5 mJ of laser energy. Channels exceeding 1 m in length were also initiated. The ionization source producing the plasma is laser-induced resonant two-step photoionization of organic molecules which are seeded in a buffer gas.

PACS numbers: 52.50.Jm, 52.75.Kq, 28.50.Re

In particle-beam-fusion accelerators, current-carrying plasma channels have been suggested as a means of transporting intense particle beams through the three-to-four meter distance from the multiple-diode sources to the fusion target.[1] Channels initiated by exploding wires have already demonstrated efficient transport of electron beams (> 90% efficiency)[2] and ion beams (> 50% efficiency)[3] over distances of approximately one meter. For repetitively pulsed fusion drivers, laser-induced ionization has been proposed as a method of producing plasma channels.[1,4] We have examined the suitability of UV-laser radiation for the initiation of plasma channels. The channels studied here were formed by resonant two-step photoionization of organic molecules which were added to a buffer gas in trace amounts. This technique, which forms and controls a plasma channel almost entirely by ionization, is in contrast to a technique previously studied by one of the authors.[5] In the previous study, CO_2-laser radiation was resonantly absorbed in low-pressure NH_3, causing gas heating which produced a rarefaction zone with only a slight amount of ionization. It is anticipated that UV-laser-initiated plasma channels will more closely resemble the exploding wire-initiated channels since both techniques produce intense ionization in the ambient gas rather than relying primarily on gas heating.

A number of organic molecules undergo resonant two-step photoionization in an intense UV-laser field. In separate investigations directed towards UV-laser triggering of multimegavolt gas switches[6] and collective-ion accelerators,[7] we have studied promising candidate molecules. First, we determined one-photon absorption cross sections of a number of molecules at the various rare-gas-halogen laser wavelengths.

TABLE I. Promising additives.

Additive	Laser wavelength (nm)
Tripropylamine $(CH_3CH_2CH_2)_3N$	248, 222
Fluorobenzene C_6H_5F	248
NN-Diethylaniline $C_6H_5N(C_2H_5)_2$	307, 248