APPLIED PHYSICS LETTERS VOLUME 83, NUMBER 14 6 OCTOBER 2003

Generation of powerful electron beams in a dense gas with a dielectric-barrier-discharge-based cathode

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(Received 28 April 2003; accepted 11 August 2003)

An electron beam source based on a dielectric barrier discharge and a perforated anode working in a dense gas is described. Electron beams with current densities up to 60 A/cm^2 and pulse durations of 150 ns were generated. Stable operation of the device at a repetition frequency of 200 Hz has been demonstrated. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1616649]

Pulsed electron guns based on electron emission from cold cathodes or glow discharges are commonly recognized as simple and reliable means for large-area electron beam production. The working gas pressure is usually lower than 1 Torr[1,2] and the efficiency can be as high as 75%–80%.[3] At these low pressures, energetic electron beams with current densities in the order of several A/cm^2 and voltages of up to 100 kV can be produced.[4]

High current glow discharge electron beam generators have found various applications ranging from surface processing and plasma etching[1] to preionization and direct pumping of gas lasers.[3,5,6] However, prospective applications are limited by the maximum obtainable current, operating gas pressure, and the fact that usually the electrons have to pass through a thin fragile metallic foil which sets strong bounds on the repetition rate.

In discharge-based systems, the current delivered by the electron beam source increases with the gas pressure. To increase the current density further, one must therefore raise the operational pressure of the device. In systems with large-area metal electrodes, the increase of pressure causes problems because the discharge tends to become unstable. These instabilities lead to arcs that short-circuit the discharge and damage the electrode surface. As a result, the accelerating voltage cannot be made higher than a few hundred volts in such devices.

To overcome these problems and to improve the general performance of large-area electron beam sources based on glow discharges, we suggest a particular concept for an electron gun.[7] Instead of a metallic cathode–anode system, it is proposed to use a dielectric barrier discharge (DBD) module as the source of electrons. The operational cycle of the device, illustrated in Fig. 1, consists of two stages. Initially, a discharge is produced between the mesh anode (3) and the dielectric (2) by a high voltage pulse applied to electrode (1). Electrons flow to the dielectric and charge it negatively, thereby terminating the discharge. In this way, a temporary or virtual cathode is formed on the dielectric surface.

During the second stage, the dielectric-covered electrode (1) is switched to ground potential and a new discharge will start. The electrons are now accelerated in the thin layer of the cathode fall region, thereby gaining an energy linearly proportional to the applied voltage. The accelerated electrons are subsequently emitted from the DBD region via a perforated mesh anode.

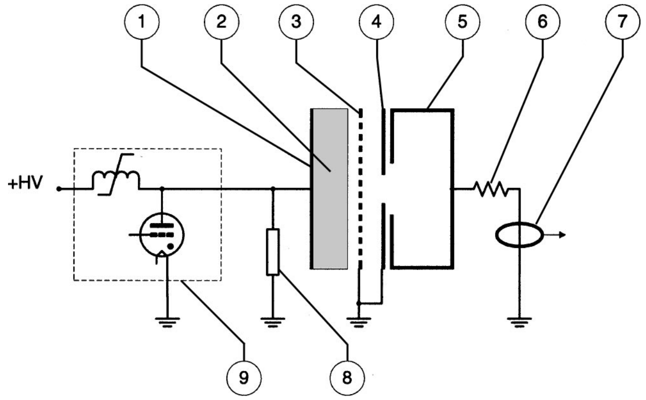

FIG. 1. Experimental setup: (1) metal electrode, (2) ceramic cylinder, (3) mesh anode, (4) screen, (5) Faraday cup, (6) 2 Ω resistor, (7) Rogowski coil, (8) high voltage probe, and (9) high voltage pulser.

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The device has several advantages over known electron beam generation techniques. We have shown that it works in a stable mode at a gas pressure of several hundreds of mbar. Operation at gas pressures up to 1 bar and at repetition rates up to 10 kHz should be possible. Contrary to a metal cathode, in which minor fluctuations in the current density develop rapidly into arcing, a cathode based on DBD has a negative feedback and prohibits strong current fluctuations. Compared to systems working under vacuum or low gas pressure conditions, in our device, the current density limitation due to space-charge effects is less pronounced due to the higher gas pressure. This means that our system, which can work in an over-voltaged mode, can deliver a higher current density than low-pressure devices.

The experimental setup is shown in Fig. 1. The main part of the electron beam generator is a dielectric cylinder (2) (diameter 10 cm, thickness 5 mm) made of ceramic with high dielectric constant $\varepsilon \sim 1000$. For these parameters, the specific capacitance of the dielectric is $\sim 0.18\ \mathrm{nF/cm^2}$, while its breakdown voltage is ~ 40 kV. A metallic electrode (1) is deposited on the rear side of the dielectric. A stainless steel mesh anode (3) with a geometrical transparency of 0.7 is placed at a distance of 1 mm from the front side of the dielectric. The anode aperture was $50\ \mathrm{cm^2}$. The electron beam current density was measured with a Faraday cup (5). To avoid capturing of secondary electrons by the Faraday cup, it was set under a retarding potential of ~ 100 V. The electric current of the beam was measured with a Rogowski coil (7). The e-beam generator was fed by a power supply (9) delivering high voltage pulses with amplitudes of up to 30 kV and rise times of ~ 140 ns. Pulse repetition rates of the device were up to ~ 200 Hz, the limit of which was imposed by the power supply. The voltage between the electrodes of the e-beam generator was measured with a high voltage probe (8). Helium was used as the working gas in all experiments. It should be noted that the e-beam parameters had no observable change during several tens of hours operation at a repetition rate of 200 Hz.

Typical oscilloscope traces of the voltage U_v applied to the e-beam generator under vacuum conditions, of the voltage U_d applied to the e-beam generator under discharge conditions, and of the e-beam current J_b collected by the Faraday cup, are shown in Fig. 2. Under vacuum conditions there is no discharge, so that no electron beam is generated. The reversal of the voltage is due to discharging of the ~ 3 nF stray capacitor, formed by the rear electrode and the anode holder of the generator. Traces U_d and J_b correspond to a discharge in He gas at a pressure of 20 mbar. Initially, U_d closely follows with U_v. After approximately 100 ns, a positive spike due to gas breakdown appears. From Fig. 2, the peak e-beam current and the breakdown voltage U_{br} (which is the difference between the initial applied voltage and the voltage at the moment of start of the discharge) can be determined. It should be noted that the breakdown voltage U_{br}, which can be higher than the charging or initial voltage (see Fig. 2), determines the maximum kinetic energy of the generated electrons.

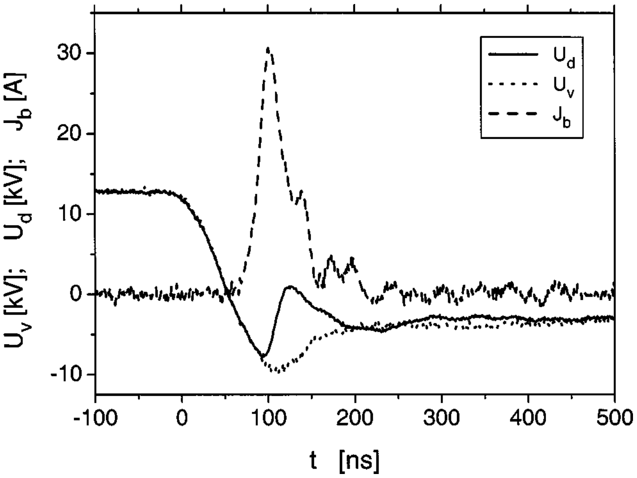

FIG. 2. Oscilloscope traces of the discharge voltage and beam current. Dotted line: voltage pulse U_v in vacuum (10^{-4} mbar) without gas discharge. Solid line: voltage pulse U_d at 20 mbar of He. Dashed line: e-beam current J_b collected by the Faraday cup.

The dependence of the e-beam peak current density on the He gas pressure is shown in Fig. 3. The charging voltage is varied from 7.5 to 20 kV. The current density J_b was defined as the ratio between the peak current collected by the Faraday cup and the area of the hole in the screen $(0.78\ \mathrm{cm^2})$. It is seen from Fig. 3 that for a charging voltage of 20 kV, J_b has a maximum value of $60\ \mathrm{A\,cm^{-2}}$ at a pressure of about 15 mbar. It is seen that at low pressures $(\leqslant 20\ \mathrm{mbar})$, J_b increases sharply. This can be explained by the well-known fact that the current grows approximately with the square of the pressure.[8] As the pressure increases further, J_b slowly decreases. Remarkably, the current density at 70 mbar is still higher than $1\ \mathrm{A\,cm^{-2}}$.

The dependence of the breakdown voltage U_{br} on the gas pressure is also measured. It is seen in Fig. 4 that the breakdown voltage is approximately constant at pressures below ~ 40 mbar. For higher pressures, the breakdown voltage decreases. The decrease of J_b at high pressures is related to the decrease of U_{br}. The breakdown voltage has an apparently nonstatic character in our conditions. For $p = 40$ mbar, the pd value is equal to ~ 7 mbar cm (where the distance d between the dielectric and the anode is 0.17 cm). At this pd value, the static breakdown voltage of He should be ~ 200 V,[8] whereas in our experiments a breakdown voltage of 20 kV is measured. This is due to operation of the

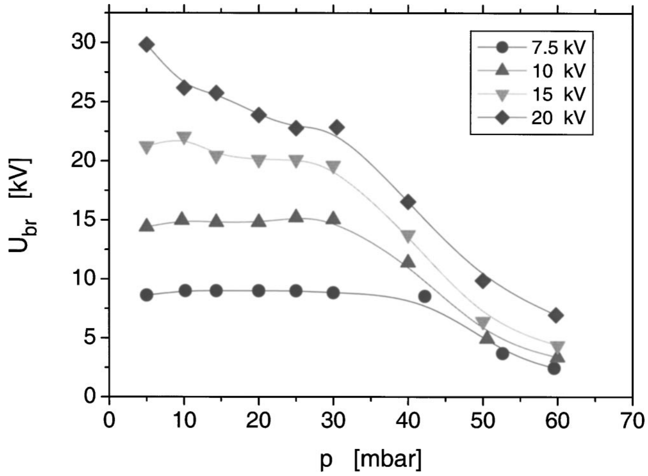

FIG. 3. Breakdown voltage U_{br} as a function of gas pressure for different charging voltages.

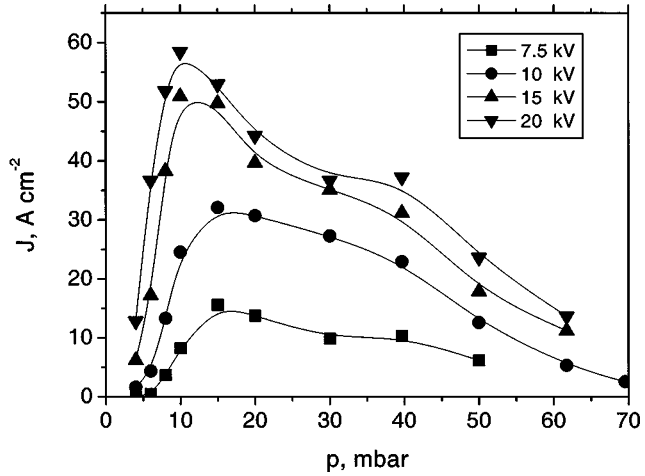

FIG. 4. E-beam peak current density J_b as a function of gas pressure for different charging voltages.

system in a pulsed mode. The decrease in U_{br} is closely related to the decrease in the discharge formation time, which is ~100 ns at 20 mbar He (see Fig. 2) and drops down to ~50 ns at $p = 70$ mbar. This means that a reduction of the voltage rise time down to ~10 ns, which should be easily attainable, would extend the range of operational gas pressures by several times.

In conclusion, we have presented a particular design for a large-area electron beam generator. The DBD enables the production of a homogeneous, large-area electron beam. The substantial increase in the operational gas pressure in this electron gun results in much higher current densities as compared to other gas-discharge-based electron beam generators. A current density of 60 A/cm^2 was reached at nominal electron beam energy of 30 keV and with a beam cross section of 50 cm^2. The prospects for scaling up the electrode surface are good. The suggested electron gun design is robust: no sign of electrode degradation or performance deterioration was found after several tens of hours of operation. The system described here operates with a maximum repetition rate of 200 Hz, which is limited by the existing power supply. There are no basic restrictions for a further increase of the repetition rate into the multi-kilohertz domain.

The authors greatly appreciate the support of the Dutch Scientific Foundation (NWO) and the Stichting Technische Wetenschappen (STW) for enabling the stay of S.V.M. at the University of Twente. The support from the Russian Foundation for Basic Research (RFBR 02-02-81008) is also acknowledged. The authors would like to express their appreciation to Dr. I. Lindsay for reading the manuscript.

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