High-voltage testing of a 500-kV dc photocathode electron gun

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(Received 17 January 2010; accepted 13 February 2010; published online 16 March 2010)

A high-voltage dc photocathode electron gun was successfully conditioned up to a voltage of 550 kV and a long-time holding test for 8 h was demonstrated at an acceleration voltage of 500 kV. The dc photocathode electron gun is designed for future light sources based on energy-recovery linac and consists of a Cockcroft–Walton generator, a segmented cylindrical ceramic insulator, guard-ring electrodes, a support-rod electrode, a vacuum chamber, and a pressurized insulating gas tank. The segmented cylindrical ceramic insulator and the guard-ring electrodes were utilized to prevent any damage to the insulator from electrons emitted by the support-rod electrode. © *2010 American Institute of Physics.* [doi:10.1063/1.3354980]

I. INTRODUCTION

An energy-recovery linac (ERL) is a new class of electron accelerator to generate a small-emittance and high-average current electron beam at high-repetition rate.[1] Now, ERL is considered as a promising device for high-power free-electron lasers,[2,3] next-generation x-ray light sources,[4] high-flux γ-ray sources,[5,6] high-power terahertz sources,[7] and high-energy physics applications.[8] An electron gun to produce a small-emittance electron beam with high-average current is the most important component for an ERL to exploit its full potential because the emittance and current of the ERL beam are determined by performance of its electron gun.

A dc electron gun is able to generate a high-current electron beam of ultrasmall initial emittance, when it is equipped with a semiconductor photocathode having a negative electron affinity (NEA) surface.[9] Such electron guns are under development for future ERLs in many laboratories.[10–13] The goals of these gun development programs are average current of 10–100 mA and normalized emittance of 0.1–1 mm mrad. To suppress emittance growth by space charge effect, the gun voltage must be 500 kV or higher.[14,15] In the electron gun, the acceleration voltage should also be applied between a short gap to generate a high-brightness electron beam.[16] A support-rod electrode, therefore, needs to be located in the center of the ceramic insulator. This particular configuration brings difficulties in achieving high-voltage operation. Field-emitted electrons from the support-rod electrode may cause damage to the ceramic insulator.[10–12] As a result, stable operation of such electron guns at 500 kV has not yet been achieved in spite of the intensive gun development efforts in the world.

A 500-kV, 10-mA photocathode dc gun has been developed in a collaboration effort of Japan Atomic Energy Agency (JAEA), High Energy Accelerator Research Organization (KEK), Hiroshima University and Nagoya University. The electron gun was designed to satisfy the requirements of future x-ray light sources based on the ERL technology and will be installed at the Compact ERL, a test facility under construction.[17] The electron gun consists of a Cockcroft–Walton (C-W) generator, a segmented cylindrical ceramic insulator, guard-ring electrodes, a support-rod electrode, a vacuum chamber, and a pressurized insulating gas tank. In this paper, we present details of the electron gun design and results of a high-voltage testing.

II. DESIGN OF THE ELECTRON GUN

A. High-voltage circuit

The high-voltage circuit used in the 500-kV gun is a conventional C-W generator with a capacity of 50 kW (500 kV and 10 mA). The circuit design was optimized to obtain a voltage ripple smaller than 10^{-4}. This is necessary because the voltage ripple, which appears at twice the frequency of the drive circuit, is one of the major sources of fluctuations in a train of electron bunches, which are jitters in emittance, bunch shapes, arrival time, and average energy after full acceleration.[18] In order to reduce any voltage ripples, a LC filter was utilized in the C-W generator. The voltage ripple (peak-to-peak) of a C-W generator with a LC filter driven by sinusoidal input current is given by

$$\Delta V = \frac{1}{16\pi f^2 L_f C_f} \frac{nI}{2fC_s}, \qquad (1)$$

where f is the drive frequency, n is the number of stages, C_s is capacitance of a stage, I is the output current, and L_f and C_f are the filter parameters. As Eq. (1) reveals, the voltage ripple can be effectively reduced by increasing the drive fre-

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TABLE I. Parameters of the C-W generator.

Maximum voltage (beam operation)	500 kV
Maximum voltage (conditioning)	550 kV
Maximum current	10 mA
Drive frequency	40 kHz
Stage capacitance	2.4 nF
Number of stages	12
Filter inductance	2.0 H
Filter capacitance	0.2 nF
Ripple (peak-to-peak as designed value)	1.2×10^{-5}

quency. A drive circuit with a frequency of 40 kHz was therefore developed to obtain the ripple as small as 1.2×10^{-5}. The C-W generator and the drive circuit were manufactured by Nisshin Pulse Electronics Co., Ltd. The parameters of the C-W generator are listed in Table I. This type of high-voltage circuit is considered to be feasibly scalable to a 500-kV, 100-mA gun with maintaining the voltage ripple at smaller than 10^{-4}.

We have prepared two sets of output resistors for the C-W generator. One is 100 MΩ to avoid damage to the electrodes at high-voltage conditioning, and the other is 66.6 kΩ to protect the diodes of the generator at beam operation. In addition to the output resistors, the driver is equipped with a current control circuit to avoid damage due to slow discharge.

B. Ceramic insulator and guard-ring electrodes

The ceramic insulator is the most critical component in the development of a high-voltage dc electron gun. It needs to be well insulated and appropriately resistant to avoid any local concentration of the electron charge that can irreversibly damage the ceramic due to cracking or punch through. Ceramic insulators that incorporate surface resistivity using a special coating and ceramic insulators with bulk resistivity have to date usually been used in photocathode dc guns.[10,11] Stable operation at a voltage of 500 kV, however, has not yet been achieved using such guns.

A segmented insulator was adopted for use in the 500-kV gun where multiple hoops of ceramics and nickel-plated Kovar electrodes were alternately stacked and blazed. The design is similar to the JAEA thermionic cathode gun (250 kV) used for a high-power FEL (Ref. 19) and the polarized electron gun (200 kV) at Nagoya University,[20] both of which have been operated with a good robustness. A photograph of the fabricated ceramic insulator used in the 500-kV ERL gun is provided in Fig. 1 together with the old insulator used in the 250-kV FEL gun. The ceramic insulator for the 500-kV gun was fabricated by Hitachi Haramachi Electronics Co., Ltd.

Guard-ring electrodes were installed on each Kovar hoop on both the inner and outer sides. Geometry of the support-rod electrode and guard-ring electrodes is important for stable operation of the 500-kV photocathode dc electron gun. The inner guard-ring electrodes shield the ceramic insulator to protect it from any electron emitted from the support-rod electrode directly hitting the ceramic surface. In the design of the guard-ring electrodes, we also paid attention to surface electric field along the support rod and guard rings. The number of segmentations and the shape of the guard-ring electrodes were optimized to minimize the surface electric field. After the optimization, the geometrical parameters were fixed to be as follows: ten segmentations with the length of the segmentations being 65 mm, the outer diameter of the ceramic insulator 400 mm, the thickness of the ceramic insulator 20 mm, and the diameter of the support rod 101.6 mm. The ceramic insulator was made of 99.8% Al_2O_3 (A99P as made by Shinagawa Fine Ceramics Co., Ltd.). Neighboring Kovar hoops were connected by 500 MΩ resistor to divide the applied voltage uniformly.

FIG. 1. Segmented ceramic insulators for the 250-kV JAERI FEL gun (right) and the 500-kV ERL gun (left). The guard-ring electrodes are not installed at the 500-kV insulator.

In the design of the guard-ring electrodes, electric field distributions were calculated using POISSON (Ref. 21) code. Simulation results at a support rod voltage of 500 kV are shown in Fig. 2. The cathode and anode electrodes are not taken into account in the calculations because our initial high-voltage testing took placed without the cathode and anode electrodes to evaluate the high-voltage performance of the ceramic insulator, the guard-ring electrodes, and the support-rod electrode. As seen in Fig. 2, the guard-ring electrodes can be installed in two different geometries. The normal configuration is preferable from the viewpoint of the surface electric field on the support-rod electrode and the guard-ring electrodes. We found that the maximum electric field on the rod near the bottom end of the ceramic insulator is 8.34 MV/m and the maximum electric field on the guard rings is 6.83 MV/m. These values are fairly acceptable be-

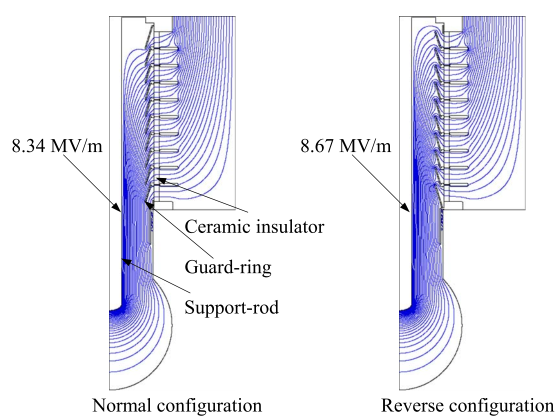

FIG. 2. (Color online) Results of numerical calculations on the field distribution in two different geometries of the guard-ring electrodes: normal configuration (left) and reverse configuration (right).

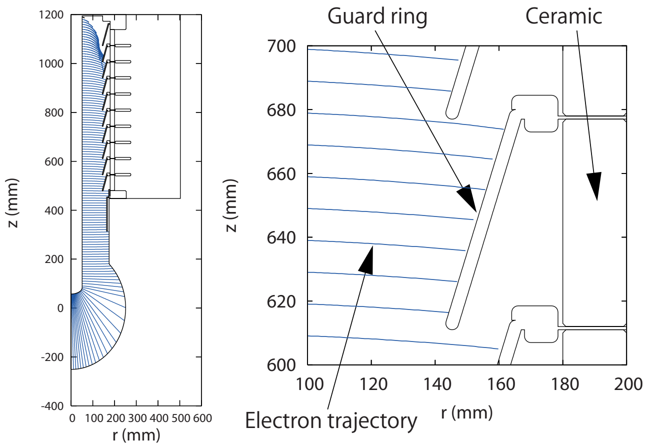

FIG. 3. (Color online) Results of numerical calculations on the emitted electron trajectories in the normal configuration.

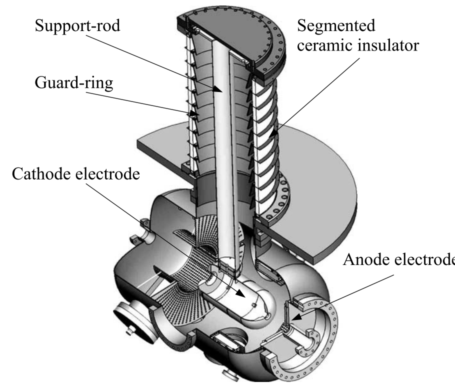

FIG. 4. Schematic view of the 500-kV dc photocathode electron gun.

cause the break-down field for 500 kV at a general vacuum gap is about 10 MV/m.[22] With the reverse configuration, the electric field has rather larger values, the maximum electric field on the rod near the bottom end of the ceramic insulator is 8.67 MV/m and the maximum electric field on the guard rings is 13.9 MV/m. This configuration is suitable for suppressing secondary electron emissions from the ceramic surface triggered by x-rays emitted from the cathode and anode electrodes, although the surface electric field is rather challenging. Maximum electric field near the nose of the support rod is 14.3 MV/m with either configuration. The electric field will be relaxed down to ~ 10 MV/m after installation of the cathode and anode electrodes for the beam operation.

The trajectories of field emitted electrons from the support-rod electrode were calculated by GPT (Ref. 23) code. The results of numerical calculations on the emitted electron trajectories in the normal configuration are shown in Fig. 3. As revealed in Fig. 3, the ceramic insulator gets shielded by the guard-ring electrodes from any electrons emitted by the support-rod electrode.

Electrical breakdown field between a metal gap depends on the gap distance, material, and surface treatment of the electrodes.[22] It is also known that the breakdown field drops strongly as the gap is increased, which is called the total-voltage effect.[24,25] In case of a small gap (≤ 1 mm), a systematic measurement of dark current between electrodes made of stainless steel (SUS), copper, molybdenum, and titanium revealed that a combination of molybdenum cathode and titanium anode shows the highest breakdown field.[26] It is not clear that a large-gap system such as our 500-kV gun follows the small-gap result. Nevertheless, we decided to use titanium for the 500-kV gun for the positive result at a small-gap system, low outgassing rate, and machinability. In the 500-kV gun, the support rod, the guard rings, the cathode and anode electrodes, and the vacuum chamber were made of titanium alloy with a special chemical polishing, which has outgassing rate of 6×10^{-13} Pa m/s at 300 K after 20 h of 150 °C baking.[27] This outgassing rate is 2–3 orders smaller than that of a general SUS chamber.[28] Ultrahigh vacuum is important to keep a NEA surface of photocathode for long-life operation.

Figure 4 schematically depicts the final design of the 500-kV gun, which consists of the segmented ceramic insulator with the guard rings, the cathode and anode electrodes, the support rod, and the vacuum chamber. A pressurized insulating gas tank was designed to ensure that the high voltage circuit, output resistor, and ceramic insulator were all positioned in a straight line. This configuration was utilized to obtain an axially symmetrical field around the insulator and the power supply. After air has been sufficiently evacuated, SF_6 is filled to a pressure of +0.2 MPa (gauge pressure). Figure 5 shows a schematic view of the gun and the pressurized insulating gas tank, which contains the C-W generator, output resistor, and ceramic insulator.

III. HIGH-VOLTAGE TESTING

The 500-kV gun was assembled in the normal configuration in a clean room to eliminate any dust contamination. The ceramic insulator and the vacuum chamber were baked at 190 °C for 8 h. After the baking, the chamber was pumped down to a pressure lower than 3×10^{-8} Pa using two turbo molecular pumps (pump speeds of 1.0 and 0.06 m^3/s) and a scroll pump (pump speed of 0.2 m^3/min) connected in series.

The high-voltage conditioning was carried out with maintaining the base pressure lower than 5×10^{-8} Pa. The C-W generator was interlocked with the pressure and radiation levels to prevent any excessive discharge during the

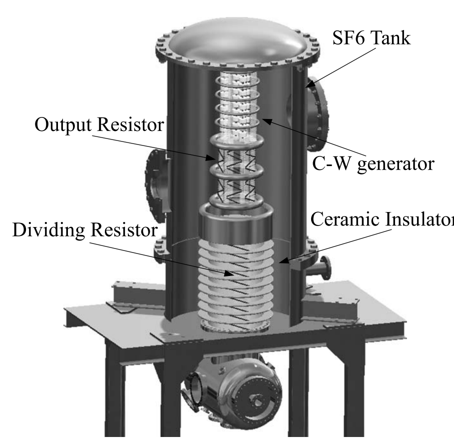

FIG. 5. Schematic view of the 500-kV dc photocathode electron gun together with the pressurized insulating gas tank.

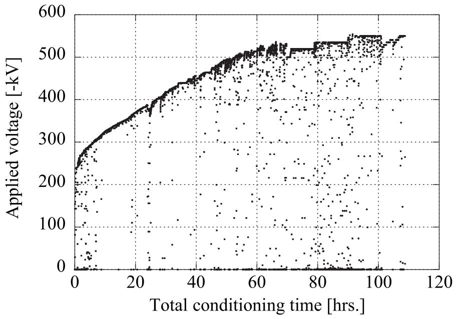

FIG. 6. Applied voltage vs total time in the high-voltage conditioning.

conditioning. The interlock levels were, respectively, a pressure of 5×10^{-6} Pa and a radiation dose rate of 3 μSv/h at a place 50 cm away from the vacuum chamber.

To prevent a fatal damage of the electrodes during the high-voltage conditioning, the discharging current was limited by two ways. The peak current of discharge was restricted by output resistor of 100 MΩ. The average current during discharge was clipped at a level less than 1 μA by the constant current circuit of the C-W generator.

Figure 6 plots the applied voltage against total conditioning time. High-voltage activity appeared at a voltage about 250 kV and the gun was conditioned at a speed of about 4 kV/h up to 500 kV. The conditioning was carried out more slowly above 500 kV.

Once the conditioning was completed up to 550 kV, we could apply the gun voltage from 0 to 550 kV in 3 min. Figure 7 shows the output current of the C-W generator, the pressure in the vacuum chamber, and the radiation dose rate 50 cm away from the vacuum chamber during the rapid increasing of the gun voltage. The good linearity between the current and the voltage seen in Fig. 7 indicates that the output current flows only through to the feedback resistors of the C-W generator and the divide resistors of the ceramic insulator and no additional current due to field emission exists. Further evidence for the excellent high-voltage performance of the gun can be found from the behavior of the pressure and the radiation. The vacuum level maintained the base pressure and the radiation dose rate was within a fluctuation of the environmental background 0.03–0.07 μSv/h.

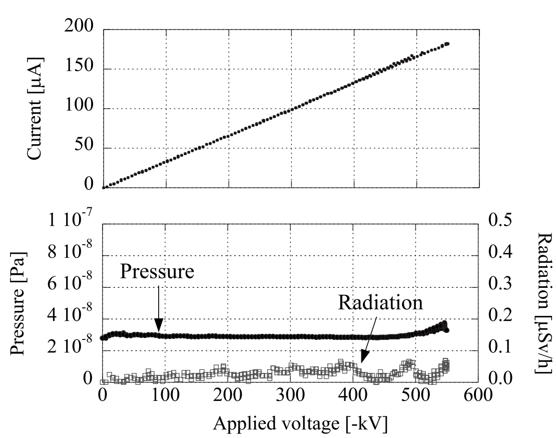

FIG. 7. Output current of the C-W generator, pressure in the vacuum chamber, and radiation dose rate 50 cm away from the vacuum chamber against applied voltage.

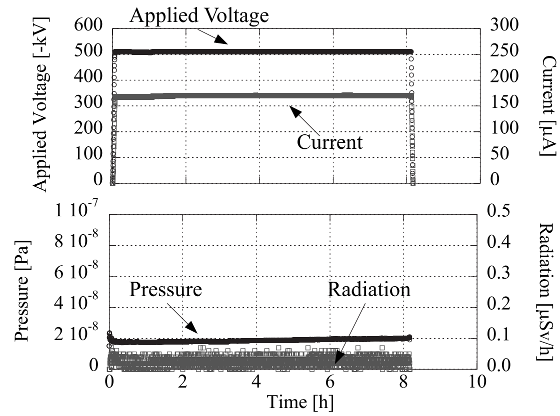

FIG. 8. Results of a long-time holding test for 8 h at a generator voltage of 510 kV.

A long-time holding test for 8 h at a generator voltage of 510 kV was carried out as shown in Fig. 8. The generator voltage of 510 kV corresponds to an acceleration voltage of 500 kV with taking a voltage drop at the output resistor into account. As seen in Fig. 8, the gun could hold the generator voltage of 510 kV stably without any discharge for 8 h. Since the gun did not produce any significant levels of radiation and maintained excellent vacuum as indicated in Fig. 8, dark currents in the system are negligible.

At the holding test, the maximum electric field near the nose of the support rod was estimated to be 14.3 MV/m from the POISSON simulation. This surface field will be reduced down to ~10 MV/m after installation of the cathode and anode electrodes for the beam operation. These results suggest that an operation of the gun at voltage higher than 550 kV is possible.

IV. CONCLUSION

We carried out a high-voltage testing of the 500-kV dc photocathode electron gun developed for future ERL light sources. The electron gun was successfully conditioned up to a voltage of 550 kV and a long-time holding test for 8 h was demonstrated at an acceleration voltage of 500 kV. The applied voltage satisfies the requirement of future ERL light sources for x-ray and γ-ray radiation. A key to the successful high-voltage operation is the especially designed ceramic insulator and guard-ring electrodes. The segmented cylindrical ceramic insulator covered with the guard-ring electrodes effectively prevents breakdown of high voltage and fatal damage to the ceramic, which are triggered by electrons emitted by the support-rod electrode. The successful result obtained with the chemically polished titanium electrodes in the 500-kV gun will be a good starting point to study electrode material and surface treatment suitable for vacuum high voltage insulation at a large gap.

ACKNOWLEDGMENTS

This work was partially supported by the MEXT Quantum Beam Technology Program, the KEK Promotion of collaborative research programs in universities, and the JSPS Grants-in-Aid for Scientific Research in Japan (20360424).

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