# HIGH-VOLTAGE TEST OF A 500-KV PHOTOCATHODE DC GUN FOR THE ERL LIGHT SOURCES IN JAPAN

R. Nagai#, R. Hajima, N. Nishimori, JAEA, Tokai, Naka, Ibaraki 319-1195, Japan
T. Muto, M. Yamamoto, Y. Honda, T. Miyajima, KEK, Oho, Tsukuba, Ibaraki 305-0801, Japan
M. Kuriki, H. Iijima, Hiroshima Univ., Higashi-Hiroshima, Hiroshima 739-8530, Japan
M. Kuwahara, S. Okumi, T. Nakanishi, Nagoya Univ., Nagoya, Aichi 464-8601, Japan

*Abstract*

A 500-kV, 10-mA photocathode DC gun has been developed in a collaboration effort of JAEA, KEK, Hiroshima Univ. and Nagoya Univ. We have utilized a segmented cylindrical ceramic insulator and guard-ring electrodes to prevent any damage to the insulator from electrons emitted by the support-rod electrode. The high-voltage test of the gun has been successfully done with up to 550kV. The cathode electrode, anode electrode, and beam line apparatuses are now under fabrication. A beam test of the gun will be started soon. The high-voltage test and up-to-date status of the gun development will be presented in detail.

## INTRODUCTION

An energy-recovery linac (ERL) is considered as a promising device which will open a new era of photon science and industry [1,2]. Since the flux and the brilliance of such light sources rely on emittance and current of the electron beam, the electron gun is the most critical component in the ERL light sources.

A 500-kV, 10-mA photocathode dc gun has been developed in a collaboration effort of JAEA, KEK, Hiroshima Univ. and Nagoya Univ. 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 [3]. The 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 [4]. The gun 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. In this paper, we present design of the electron gun, results of a high-voltage test and up-to-date status of the gun development.

## DESIGN OF THE ELECTRON GUN

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 [5]. In order to reduce any voltage ripple, a LC filter was utilized in the C-W generator. This type of high-voltage circuit is considered to be 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.

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 been used in photocathode dc guns [6,7]. Stable operation at a voltage of 500 kV, however, has not yet been achieved using such insulators. We adopted a segmented insulator where multiple hoops of ceramics and nickel-plated Kovar electrodes were alternately stacked and blazed. A photograph of the fabricated ceramic insulator used in our 500-kV gun is provided in Fig. 1.

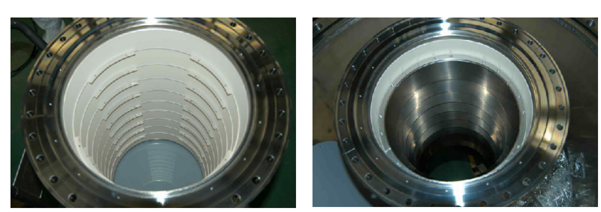

Figure 1: Segmented ceramic insulator, without (left) and with (right) guard-ring electrodes.

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 protect the ceramic insulator surface from any

#nagai.ryoji@jaea.go.jp

electron emitted from the support-rod electrode. 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% $Al_2O_3$. Neighboring Kovar hoops were connected by 500 MΩ resistor to divide the applied voltage uniformly.

In the design of the guard-ring electrodes, electric field distributions were calculated using POISSON [8] 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. 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 because the break-down field for 500 kV at a general vacuum gap is about 10 MV/m [9]. Maximum electric field near the nose of the support rod is 14.3 MV/m. The electric field will be relaxed down to about 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 [10] code. The results of numerical calculations on the emitted electron trajectories in the normal configuration are shown in Fig. 2. As revealed in Fig. 2, 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 [9]. It is also known that the breakdown field drops strongly as the gap is increased, which is called the total voltage effect [11,12]. 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 [13]. 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 $6\times10^{-13}$ Pa m/ s at 300 K after 20 h of 150 °C baking [14]. This outgassing rate is 2–3 orders smaller than that of a general SUS chamber [15]. Ultrahigh vacuum is important to keep a NEA surface of photocathode for long life operation.

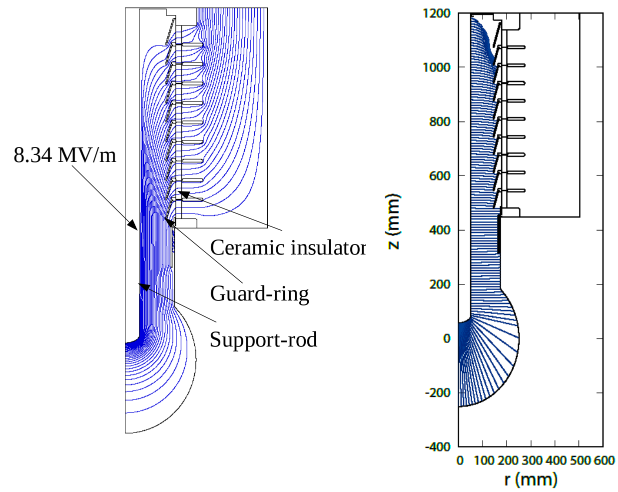


Figure 2: Field distribution (left) and emitted electron trajectories (right) of the gun.

The 500-kV gun 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).

## HIGH-VOLTAGE TEST

The 500-kV gun was assembled 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 $3\times10^{-8}$ 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 $5\times10^{-8}$ Pa. The C-W generator was interlocked with the pressure and radiation levels to prevent any excessive discharge during the conditioning. The interlock levels were, respectively, a pressure of $5\times10^{-6}$ 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 1μA by the constant current circuit of the C-W generator.

Figure 3 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.

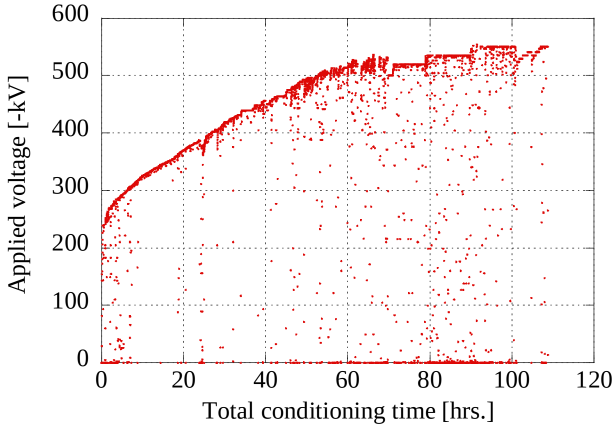


Figure 3: Applied voltage vs total time in the high-voltage conditioning.

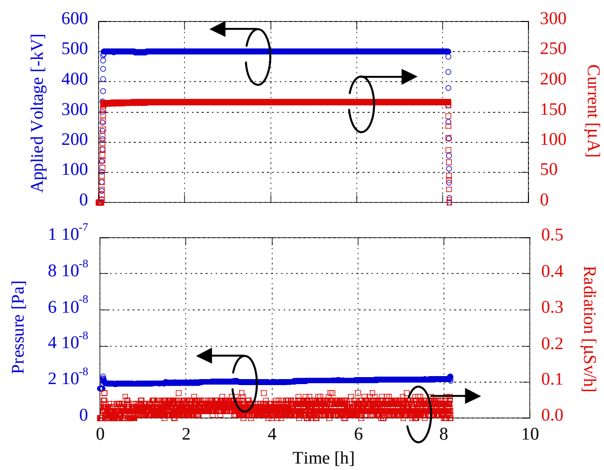


Figure 4: Results of a long-time holding test for 8 h at a generator voltage of 510 kV.

A long-time holding test for 8 h at a generator voltage of 510 kV was carried out as shown in Fig. 4. 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. 4, 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. 4, 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 about 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.

## CURRENT STATUS

Current status of the 500-kV gun development is as follows: the cathode and anode electrodes were installed. The electrodes for the maximum surface electric field not to exceed 11 MV/m at 500 kV while keeping the distance between the electrodes 100 mm. NEG pumps with a pumping speed of 7.2 $m^3$/s have been installed in the gun chamber. A photocathode preparation system was connected to the gun chamber. The beam test will be soon started.

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## REFERENCES

[1] S. M. Gruner, et al., Rev. Sci. Instrum. 73, 1402 (2002).
[2] R. Hajima, et al., Nucl.Instrum. Methods Phys. Res. A 608, S57 (2009).
[3] KEK Report No. 2007–7/JAEA-Research 2008–032 (2008) (in Japanese), edited by R. Hajima, et al.
[4] R. Nagai, et al., Rev. Sci. Instrum. 81, 033304 (2010).
[5] R. Nagai, et al., Proceedings of the Fourth Annual Meeting of Particle Accelerator Society of Japan, 2007 (in Japanese), pp. 676–678.
[6] K. Smolenski, et al., AIP Conf. Proc. 1149, 1077 (2009).
[7] C. Hernandez-Garcia, et al., AIP Conf. Proc. 1149, 1071 (2009).
[8] J. H. Billen and L. M. Young, LA-UR-96–1834 (1996).
[9] P. G. Slade, The Vacuum Interrupter: Theory, Design, and Application (CRC Press, Boca Raton, FL, 2007).
[10] M. J. de Loos and S. B. van der Geer, Proceedings of EPAC-1996, pp. 1241–1243.
[11] W. T. Diamond, J. Vac. Sci. Technol. A 16, 707 (1998).
[12] W. T. Diamond, J. Vac. Sci. Technol. A 16, 720 (1998).
[13] F. Furuta, et al., Nucl. Instrum. Methods Phys. Res. A 538, 33 (2005).
[14] H. Kurisu, et al., J. Vac. Soc. Jpn. 49, 254 (2006) (in Japanese).
[15] H. Kurisu, et al., J. Vac. Sci. Technol. A 21, L10 (2003).