PROGRESS IN A PHOTOCATHODE DC GUN AT THE COMPACT ERL

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Abstract

The next generation light sources such as energy recovery linac (ERL) light sources and X-ray FEL oscillator require high brightness electron gun with megahertz repetition rate. We have developed a DC photoemission gun at JAEA and demonstrated generation of a 500-keV electron beam from the gun. This demonstration was achieved by addressing a discharge problem that leads to vacuum breakdown of the DC gun. The problem is microdischarge at an anode electrode or a vacuum chamber, which is triggered by microparticle transfer or field emission from a cathode electrode. An experimental investigation has revealed that larger acceleration gap optimized to mainly reduce surface electric field of anode electrode results in suppression of the microdischarge events. The gun was transported to the compact ERL (cERL) at KEK. The commissioning of the injector system of the cERL is under way.

INTRODUCTION

Future energy recovery linac (ERL) light sources and megahertz repetition rate X-ray FELs require high-brightness and high-current electron guns capable of delivering an electron beam with emittance lower than 1 mm-mrad and currents up to 100 mA [1]. A DC photoemission gun with a GaAs or alkali photocathode is one of the most promising candidates for such guns, since the high-current beam of 9 mA has been routinely provided from the DC gun at Jefferson Lab FEL [2] and the record high current of 65 mA was recently demonstrated at Cornell photoinjector [3]. Meanwhile, the DC gun operational voltage, which is closely related to brightness of the electron beam [4], has been limited to 350 kV or lower mainly because of the field emission problem since when the first 500-kV DC photoemission gun was proposed in 1991 [5].

We have developed a 500-kV DC gun for ERL light sources in Japan [6] and demonstrated generation of a 500-keV electron beam from a DC photoemission gun [7]. This demonstration was achieved by solving two discharge problems. One is discharge on insulator ceramic surface caused by field emission generated from a central stem electrode. We have employed a segmented insulator with rings to guard the insulator against the field emission [8]. The other problem is discharge between the cathode electrode and the gun vacuum chamber wall including an anode electrode. Those discharge events during HV conditioning almost always accompany gas desorption. This is similar to gas desorption induced microdischarge observed in high voltage insulator system with a large gap [9, 10]. It may occur that microparticles on the anode are propelled to the cathode by explosive bursts due to gas desorption induced discharges and then serve as sources of field emission. Here the microparticles are weakly bound metal particles on the anode or the vacuum chamber wall. In fact we often experienced field emission site suddenly appeared at the cathode electrode during HV conditioning. The field emission starts at voltage much lower than the voltage just we reached by HV conditioning and exponentially increases with voltage. We also found the field emission sites could be removed by simply wiping the cathode electrode with a lint-free tissue after venting the gun chamber with dry nitrogen gas. These observations support our postulation that the sources of the field emission are microparticles transferred from the gun vacuum chamber or the anode by gas desorption induced discharges.

Similar field emission caused by microparticles is observed in high gradient RF cavities. In the process of superconducting RF cavities, high pressure rinsing technique is routinely used to remove residual small particulates [11]. It is however difficult to completely remove those microparticles on the DC gun chamber, because we cannot use the high pressure rinsing technique for a chamber equipped with a massive non evaporable getter (NEG) pumps. We decided to search for a DC gun configuration where microdischarge events are greatly reduced thus leading to suppression of microparticles transfer to the cathode.

In this paper, we study a configuration of gun vacuum chamber appropriate for operation of DC voltage ≥ 500 kV. Experimental results of HV conditioning are presented for different gap lengths. The results are compared in terms of applied voltage as a function of total gas desorption during HV conditioning. We found larger acceleration gap is better for high voltage operation owing to lower surface electric field of the anode electrode. The gun was transported to the compact ERL (cERL) at KEK. Some preliminary results of the commissioning of the cERL injector system are also presented.

DC PHOTOEMISSION GUN AT JAEA

The details of the gun system are described in Refs. [6,7]. A GaAs wafer on a molybdenum puck is used as a photocathode. The wafer is atomic hydrogen cleaned and transferred to the preparation chamber where cesium and oxygen are alternatively applied for negative electron

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affinity activation. The activated cathode is then transferred to the cathode electrode in the gun chamber. The photoemission beam is accelerated by a static electric field applied between cathode and anode electrodes. During the HV conditioning, the GaAs photocathode is replaced with a dummy puck made of stainless steel to avoid damages due to discharges.

The acceleration gap between cathode and anode electrodes is surrounded by twenty of 0.4 m^3/s NEG pumps (SAES getters: CapaciTorr D400-2) to reduce residual gas, which is the source of back-bombardment ions. These NEG pumps are covered with mesh HV shields made of titanium wire having a 1 mm diameter. Five ICF203 ports of the gun chamber, which are located behind the cathode electrode, are used to install five 2 m^3/s NEG pumps (SAES getters: CapaciTorr D2000). A 0.2 m^3/s ion pump (ULVAC: PST-200AU) is installed at the bottom of the gun chamber to pump noble gases and methane. The gun chamber, cathode and anode electrodes, and stem electrode are made of chemically polished (CP) titanium. After the gun system is assembled, the ceramic insulator and the gun chamber are baked at 170◦C for 50 h. A 1 m^3/s turbo molecular pump is used during the baking. After the activation of the NEG pumps, the base pressure of the gun chamber is measured to be 8×10^{-10} Pa (N2 equivalent) with an ionization gauge (ULVAC: AxTRAN).

A Cockcroft Walton high-voltage power supply (HVPS) is installed in a tank filled with a pressurized SF6 gas. The output of the HVPS is connected to the high voltage terminal of the segmented insulator through an output resistor. The value of the output resistor is 0.1 GΩ for HV conditioning and 67 kΩ for generation of high current beam. Because an external resistor of 5 GΩ is connected to the segmented insulator in parallel, the output voltage of the HVPS is 510 kV when 500 kV is applied to the insulator during HV conditioning. In the present paper, the voltage value represents the HVPS voltage unless otherwise specified.

HIGH VOLTAGE CONDITIONING WITH TWO DIFFERENT GAP LENGTHS

To study how the electrical breakdown occurs in a DC gun system, we assume the following scenario based on Refs. [9, 10]. First the microdischarge events on an anode including a gun chamber wall are initiated by microparticle transfer or field emission from a cathode. Then the positive ions in microdischarge plasmas are accelerated back to the cathode producing secondary electrons with a yield greater than unity per incident ion leading to an exponential increase of the discharge current. In some cases, microparticles on the anode are propelled to the cathode and then serve as a field emission site preventing us from continuing HV conditioning. Based on the above mentioned scenario, the amount of total gas desorption induced by discharges is chosen as a parameter to characterize HV conditioning. This is because the gas desorption is almost always accompanied by discharges during HV conditioning.

For vacuum vessel with volume V [m^3], pressure $p(t)$ [Pa] at time t, outgassing rate of Q [Pa m^3/s] and a vacuum pump with pumping speed of S [m^3/s], the pressure change is given by

$$V\frac{dp(t)}{dt} = Q - Sp(t). \tag{1}$$

When the vacuum vessel is filled with gases released by a discharge, the vacuum pressure $p(t)$ is considered to become much greater than the end vacuum pressure $p(\infty) = Q/S$. The constant outgassing rate from the chamber surface Q can be neglected since $p(t) \gg p(\infty)$ and Eq. (1) is written by $Vdp(t) = -Sp(t)dt$. The gas release upon discharge at time $t = 0$ is calculated to be

$$-V\int_{p(0)}^{p(t)} dp(t) = S\int_0^t p(t)dt. \tag{2}$$

The volume of vacuum vessel is considered to be the same for the gun configurations studied in the present paper. The pumping speed is also considered to stay constant regardless of pressure rise. During HV conditioning, pressure value of the gun chamber is recorded every 0.5 seconds. We set a threshold pressure above which the right hand side of Eq. (2) is calculated. The threshold pressure is set well above the base pressure, because Eq. (2) holds when the constant outgassing rate of vacuum chamber Q can be neglected. When the vacuum pressure exceeds the threshold value due to a discharge induced gas desorption, the pressure multiplied

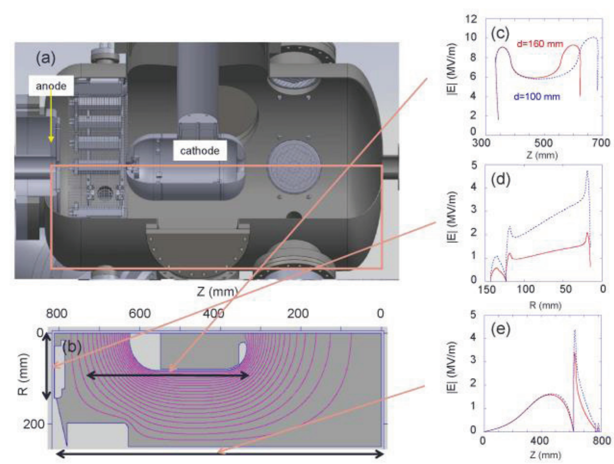

Figure 1: (a) Cutaway drawing of the gun chamber with 160-mm acceleration gap and (b) radial cross section showing the static electric field calculation for the gun chamber. The surface electric field distributions of the cathode as a function of Z (c) and the anode as a function of Z (d) and R (e) at 500 kV are represented by red solid lines. The blue dashed lines show corresponding field distributions with 100-mm gap.

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by 0.5 seconds and the pumping speed of the vacuum pump is integrated. This integration gives the total gas desorption during HV conditioning. The threshold pressure above which the right hand side of Eq. (2) is integrated is set to 1×10^{-8} Pa. The total pumping speed of NEG pumps is estimated to be $S=12m^3/s$ by taking into account of conductance of the NEG pump configuration.

Figure 1 (a) shows a cutaway drawing of the gun chamber for a 160-mm acceleration gap. The static electric field calculation result obtained with Poisson [12] with cylindrical symmetric axis along beam axis is shown in Fig. 1(b). The cathode surface electric field as a function of beam axis Z is shown by red solid line in Fig. 1(c). The anode electric field distributions as a function of Z and radius R are shown by red solid lines in Fig. 1(d) and 1(e), respectively. The blue dashed lines represent corresponding surface electric fields for 100-mm gap. The maximum surface electric field at cathode is decreased from 10.1 to 9.3 MV/m by changing the acceleration gap from 100 to 160 mm. The maximum surface electric field at NEG mesh shield is decreased from 4.4 to 3.4 MV/m, as shown in Fig. 1 (d). The most noticeable reduction is seen on the anode electrode where the maximum surface electric field is reduced from 4.7 to 2.1 MV/m. The electric field on the photocathode center is also decreased from 6.7 to 5.8 MV/m. The field decrease on the photocathode is not favorable for beam dynamics though, a numerical simulation shows the normalized beam emittance at the exit of an injector accelerator connected to the present DC gun is still numerically calculated to be $\leq$ 0.3 mm-mrad for bunch charge of 8 pC [13]. Further optimization of accelerator parameter sets is needed for 0.1 mm-mrad beam generation.

The top left of Fig. 2 shows HV conditioning as a function of time with 100-mm acceleration gap. The bottom left of Fig. 2 shows gun vacuum pressure during the conditioning as a function of time with 100-mm acceleration gap. We could reach 370 kV without discharge at the beginning of conditioning. The conditioning is interlocked by threshold set-point values of vacuum pressure and radiation monitor which is placed near the gun chamber. The threshold pressure above which the HV conditioning is interlocked is set to 1×10^{-7} Pa. Unfortunately after a discharge at 490 kV after 100 hours of conditioning, field emission started to be observed at voltage around 150 kV.

The high voltage as a function of the integrated gas release obtained with 100-mm acceleration gap is shown by the blue solid line in Fig. 3. The total amount of gas released during HV conditioning up to 500 kV was 2×10^{-2} Pa m^3. As an extrapolation of the blue line in Fig. 3 suggests, ten times more gas release would be required to reach 550 kV with this configuration. The amount of total gas release is roughly proportional to the total time required for the conditioning. Although the integrated time is 100 hours as shown in the left of Fig. 2, it took a month for the conditioning. This means that another several months are required for the conditioning to reach 550 kV, even if we have not suffered from field emission problems. At this point, we halted to continue the HV conditioning and changed the acceleration gap from 100 to 160 mm.

The right figures of Fig. 2 show HV conditioning (top) and gun vacuum pressure (bottom) as a function of time with 160-mm acceleration gap. We could reach 440 kV at the beginning of conditioning without discharge, while the discharge starts at 370 kV at 100-mm gap. From these two data at different gap lengths, discharge initiation voltage V_I in units of kV can be defined as a function of gap d in units of mm by

$$V_I = 67d^{0.37}. \quad (3)$$

After about 200 hours of conditioning, we reached 550 kV and could hold 10 minutes without discharge at 550 kV. The high voltage as a function of integrated gas release is shown by red solid line in Fig. 3. The threshold vacuum pressure above which gas desorption is integrated is set to 1×10^{-8} Pa. The total amount of gas released during HV conditioning up to 550 kV is 2×10^{-2} Pa m^3.

If we assume that the breakdown voltage V_B of our gun configuration is proportional to $d^{0.37}$ similarly to Eq. (3) and that V_B = 500 kV for 100-mm gap because the field emission site often appears after a discharge around 500 kV, the breakdown voltage might be given by

$$V_B = 91d^{0.37}. \quad (4)$$

Substitution of d = 160 mm yields V_B = 600 kV. This suggests that we do not need to be worried about the field emission which suddenly appears after a discharge near V_B, as long as the gun is operated at voltage below 550 kV. In other words, we have some safety margin for operation at 550 kV with gap d = 160 mm.

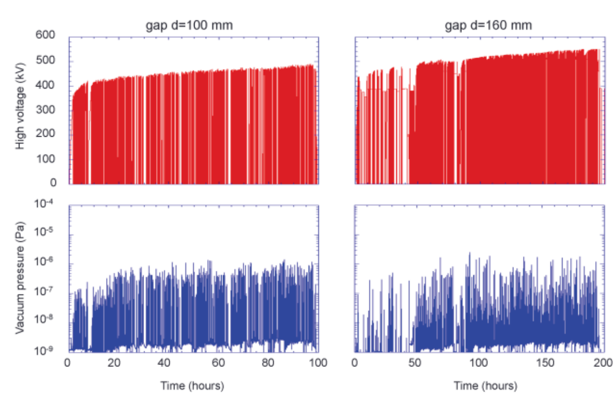

Figure 2: Left: High voltage (top) and vacuum pressure (bottom) as a function of time during HV conditioning with acceleration gap d = 100 mm. Right: High voltage (top) and vacuum pressure (bottom) as a function of time with acceleration gap d = 160 mm.

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GUN OPERATION AT THE CERL

After we successfully generated 500-keV electron beam from our DC gun at JAEA [7], the gun was transported to the compact ERL at KEK in October 2012 and connected to the following injector accelerator [14]. The beam commissioning of the cERL injector system was performed from April 2013 for two months. The thermal emittance at the gun exit was measured with solenoid scan method. The thermal emittance was measured to be less than 0.1 mm-mrad when the photocathode center was illuminated with a laser of spot size of about 1 mm in diameter at wavelength of 532 nm. The gun operational voltage has been limited to 400 kV [15]. This is because we found failures of two out of ten segments of our insulator after the gun transport from JAEA to KEK [7]. Short bars have been connected between the electrodes of the failed segments. The gun insulator has been operated with eight segments during the present injector commissioning instead of full ten segments. This is reason why the operational voltage has been limited to 400 kV. We plan to fix the problems of the failed segments after commissioning of the ERL loop in April 2014.

The emittance at the injector exit was measured as a function of bunch charge up to 8 pC with a slit scan and quadruple scan methods. The normalized emittance was measured to be 0.8 mm-mrad with bunch charge of 8 pC [15]. The reason why the measured emittance is higher than simulation value of 0.3 mm-mrad is under investigation. The beam energy at the injector exit is roughly 5 MeV.

The gun has stably been operated at 400 kV without any breakdown for 200 hours during the injector commissioning for two months. The gun vacuum pressure was measured to be 1.4×10^{-9} Pa with an extractor gauge when it was connected to the downstream injector accelerator. The quantum efficiency (QE) of GaAs cathode has been obtained from measurements of beam current with a beam dump or a beam-line Faraday cup at the cERL injector and measurements of laser power illuminated on the photocathode with power meters. The typical QE was 4% and its 1/e life time was measured to be 5000 hours. The GaAs cathode was activated before the commissioning and used during the commissioning without any reactivation. Since the beam current during the commissioning was less than 1μA, the measured cathode life is a kind of static life time under conditions that the gun high voltage was applied at 400 kV for 200 hours and that the gun was connected to the downstream accelerator system under operation.

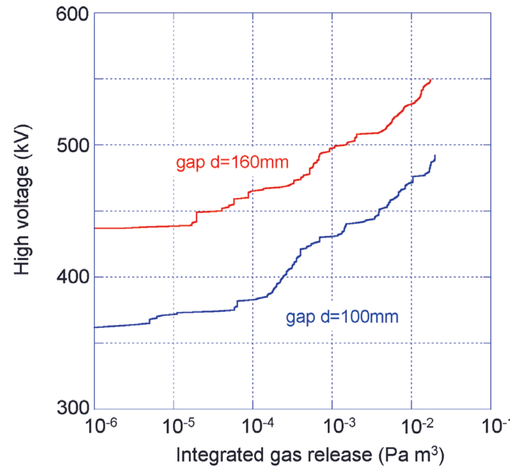

Figure 3: High voltage as a function of integrated gas release during the HV conditioning. The blue solid line is obtained with acceleration gap d = 100 mm. The red solid line is obtained with gap d = 160 mm.

SUMMARY

We studied a configuration of gun vacuum chamber of a photoemission gun appropriate for operation of DC voltage ≥ 500 kV. We found larger acceleration gap is better for high voltage operation owing to lower surface electric field of the anode electrode. The gun was successfully conditioned up to 550 kV without suffering from the field emission problem with acceleration gap length of 160 mm. We successfully generated 500-keV electron beam from the gun at JAEA. The gun was moved to the cERL at KEK in October 2012. Preliminary emittance results were already obtained in beam commissioning of the cERL injector system. From the commissioning result, the GaAs photocathode for our gun is shown to have enough long life time for the commissioning of the energy recirculation loop which is under construction at the cERL, although we need to develop a photocathode with longer life time for the future high current operation.

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