DEVELOPMENT OF A 500-KV PHOTO-CATHODE DC GUN FOR THE ERL LIGHT SOURCES IN JAPAN*

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Abstract

Energy recovery linac (ERL) based next generation light source such as X-ray FEL requires high brightness electron gun. We have developed a 500-kV, 10-mA photocathode DC gun. A segmented ceramic insulator with guard rings is employed to improve stability and robustness at high voltage operation by keeping field emission electrons away from the ceramic surface. A Cockcroft-Walton power supply and the insulator are installed in a SF6 tank and high voltage test up to 550kV was successfully done without a metal rod which supports a cathode electrode. All the vacuum chambers are made of chemically polished titanium alloy with very low out-gassing. A GaAs photocathode is activated in a separate preparation system. Up-to-date status of the gun development will be presented in detail.

INTRODUCTION

Electron guns capable of delivering a high brightness electron beam with emittance lower than 1 mm-mrad and current up to 100 mA are being developed for next generation Energy Recovery Linac (ERL) Light Sources (LS) worldwide [1, 2, 3]. A DC photoemission gun with a GaAs photocathode is considered to be one of the most promising candidates, since such a photoemission DC gun illuminated with 532 nm laser light has successfully provided 9.1 mA beam for the JLab 10 kW IR Upgrade FEL [2]. The low emittance required for ERL-LS demands the DC high voltage equal to or greater than 500 kV for reduction of nonlinear image charge effects in low energy regime [4]. The accelerating field on the cathode surface should be as high as possible to suppress the space charge effects as well.

A 5-GeV ERL based hard X-ray source is a goal of our future synchrotron light source project in Japan [3]. An X-ray FEL oscillator is anticipated as one of the most attractive options for the 5-GeV light source [5]. An ERL test facility, the Compact ERL, is going to be constructed at KEK site to demonstrate reliable operation of the key components such as superconducting RF accelerators, energy recovery loop and a high current electron gun [6]. An ERL based high-flux Compton gamma-ray is proposed as a tool to identify the nuclide in the nuclear waste using nuclear resonance fluorescence based detection system [7].

We have developed a 500 kV DC gun for the Japanese ERL light sources [8, 9]. In the present paper, we describe our current status of development of a photoemission DC gun.

GUN DESIGN AND CONSTRUCTION

High Voltage Power Supply

A conventional Cockcroft-Walton (C-W) power supply is employed to provide 5 kW (500 kV and 10 mA) at maximum power for the beam. The circuit is designed for the voltage ripple to be smaller than 10^{-4}. This is because the injector stability such as DC gun voltage ripple and buncher phase fluctuation governs synchronization stability of ERL system. The voltage ripple of the C-W circuit followed by an additional LC filter employed to reduce the ripple is given by

$$\Delta V = \frac{1}{16\pi^2 f^2 L_1 C_1}\frac{nI}{2fC} \quad (1)$$

where f is the driver frequency, n is the number of stages, C is capacitance of a stage, L_1 and C_1 are filter parameters. Design parameters of Cockcroft-Walton circuits are listed in Table 1. A high voltage test was successfully done to 550 kV in a tank filled with 2 atm pressurized SF6 gas where only the power supply is installed. The power supply current almost linearly increases with the voltage. The maximum current at 550 kV is about 90 μA. Unfortunately, the driving frequency is lowered from 40 KHz to 23 kHz due to temperature increase of a switching device IGBT, which occurs after a continuous operation at 500 kV for duration longer than a few minutes. The voltage ripple is estimated to be $< 1 \times 10^{-4}$ from the parameters used for the measurements. The IGBT (SKM 300GB125D) used for the high frequency transformer will be replaced with the device suited for high frequency operation.

Ceramic Insulator

The high voltage terminal of the C-W power supply is connected to an end flange of a ceramic insulator. The cathode electrode should be placed close to an anode to provide high accelerating field on the cathode surface. A metal support rod hanging from the high voltage terminal of the insulator holds the cathode electrode, as shown in Fig. 1. A high electric field appearing on the support rod

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* This work was supported in part by MEXT Quantum Beam Technology Program, and JSPS Grants-in-Aid for Scientific Research in Japan (20360424).

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Table 1: Parameters of Cockcroft-Walton (C-W) circuit

parameters		value
driving frequency	f	40 kHz
stage capacitance	C	2.4 nF
the number of stages	n	12
filter inductance	L_1	2.0 H
filter capacitance	C_1	0.2 nF
ripple (design)		1.2×10^{-5}

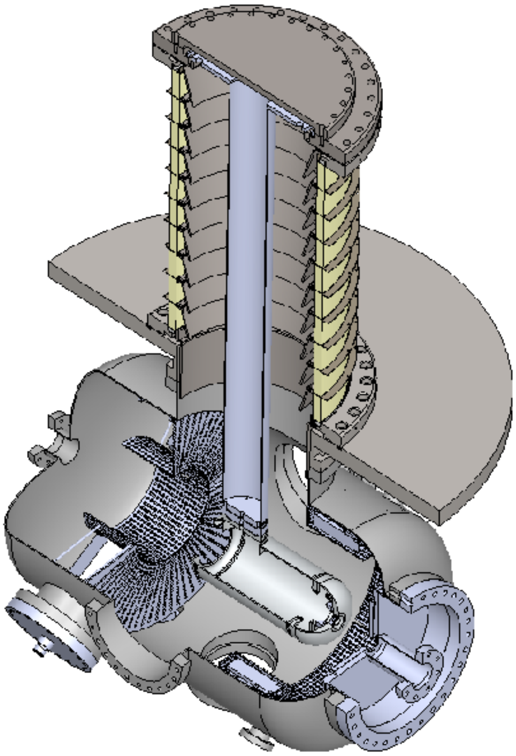

Figure 1: Cutaway of the JAEA/KEK 500-KV gun. The configuration is similar to Cornell gun [1].

induces field emission, which could result in voltage breakdown, insulator punch-through and other problems during high voltage conditioning.

In order to solve the field emission problem, we have employed a segmented insulator, where a number of ceramics are stacked in series with a Kovar ring electrode sandwiched between adjacent ceramics. This segmented design is similar to a 230 kV thermionic cathode gun for JAERI FEL [10] and a 200 kV polarized electron gun at Nagoya University [11]. The electric potential of each electrode is fixed with an external resistor connected between the Kovar electrodes. This helps to avoid an irregular potential distribution on the ceramic surface. A 500 MΩ resistor is used as each resistor in our case. We have also employed a guard ring, which is attached to each Kovar electrode to shield ceramic surface from field emission electrons. A ceramic insulator with a controlled bulk resistivity proposed at Daresbury Laboratory and an inverted insulator to eliminate the support rod structure studied at JLab are also promising ways to resolve the field emission problem.

The insulator with ten segmented ceramics placed in a SF_6 tank with inner diameter of 1000 mm is shown in Fig 2. The height is 730 mm and the end flange diameter is 520 mm. The size of each segmented ceramic are 400 mm in diameter, 65 mm length, and 20 mm thickness. The ceramics consists of 99.8 % alminium oxide Al_2O_3 called A99P made by Shinagawa Fine Ceramics. The silver brazing between Kovar ring and ceramic as well as tungsten inert gas welding between Kovar and SUS ring for end flange were performed by Hitachi Haramachi Electronics. No leak is observed so far after 200°C bake-out of the ceramics.

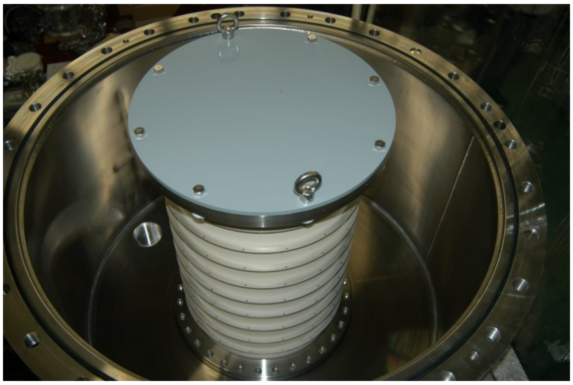

Figure 2: The segmented ceramic insulator in a SF_6 tank.

The shape of guard rings attached to outer and inner Kovar electrodes are optimized for the surface electric field on the support rod and guard rings to be minimized. The details of the optimization is described in Ref. [8]. The diameter of the support rod is 106 mm. A POISSON simulation shows that E_{max} = 7.9 MV/m on the rod and E_{max} = 8.4 MV/m on the guard rings.

A high voltage test of the ceramic insulator with guard rings was performed to 550 kV without a support rod. The top of Fig. 3 shows the currents of the high voltage power supply. The difference between the current with the insulator (solid line) and that of the high voltage power supply only (dashed line) represents the current running through 5 GΩ register connected between the HV and ground terminals of the ceramic insulator. A slight deviation from the ideal curve is seen above 450 kV. This could be attributed to corona generated from a mesh which shields the conditioning register installed between the high voltage power supply and ceramic insulator to limit the breakdown current. We will replace the mesh shield with a round shape metal shield. The bottom of Fig. 3 shows radiation measured with a NaI radiation monitor (solid line) and vacuum pressure as a function of the high voltage. The radiation monitor is placed 1.5 m underneath the bottom flange of the ceramics insulator. The radiation increase above 500 kV is also attributed to corona from the mesh shield. A

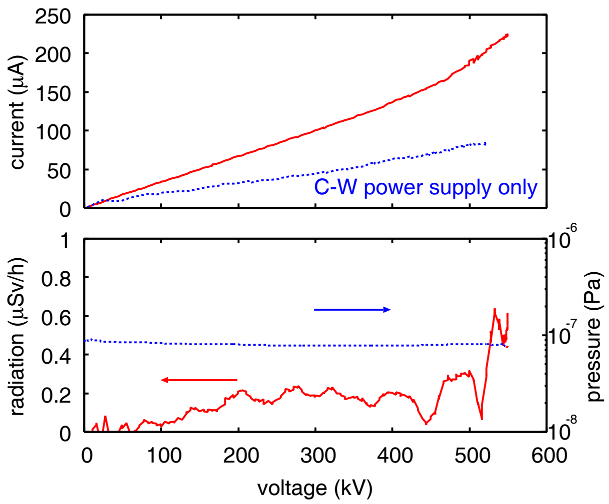

Figure 3: A high voltage test of segmented ceramic insulator without a support rod. The top shows the current of the C-W circuit as a function of voltage (solid line). The current of the C-W circuit only is given by the dashed line. The bottom represents radiation and vacuum pressure.

1000 l/s turbo pump (BOC Edwards: STP-1000) is used in the high voltage test. The base pressure is 5×10^{-8} Pa after 200°C/20 hours bake-out.

Figure 4 shows a high voltage conditioning performed prior to the measurement shown in Fig. 3. The conditioning to 550 kV was finished within three and half hours. Vacuum pressure rise to mid 10^{-5}Pa was frequently observed. The radiation sometimes reaches 3 μSv/h. For a quarter an hour, no vacuum pressure increase was observed at the end of the conditioning. The conditioning register used in the present test is 1 MΩ. We plan to replace 100 MΩ register for further test.

High voltage conditioning with a support rod is under way. Up to 420 kV is applied so far. A round shape cup is attached to the end of support rod instead of the cathode electrode shown in Fig. 2. No NEG pumps are installed yet. Radiation is greater than the conditioning without the support rod. The vacuum pressure sometimes rises to 1×10^{-4} Pa per discharge. The vacuum recovers to 1×10^{-7} Pa in minutes.

HV Vacuum Chamber

A NEA photocathode is mainly degraded by ion back-bombardment, where residual gas in cathode/anode gap or downstream vacuum chamber is ionized by the extracted electron beam and accelerated back to the photocathode [12, 13]. To achieve the vacuum pressure around 1×10^{-10} Pa is thus important to prolong the cathode lifetime. The extremely high vacuum demands a massive pump system and low outgassing material for the vacuum chamber. The chamber material used for our gun is chemically polished titanium. A study shows that the out-gassing rate of the material is two orders of magnitude smaller than usual stainless steels, 6×10^{-13} Pa m/s after 150°C/20h baking [14]. The flange of the vacuum chamber is made of an alloy named KS100. The hardness of KS100, similar to stainless steel, allows one to use the flange repeatedly. The rest of the chamber is made of a pure titanium.

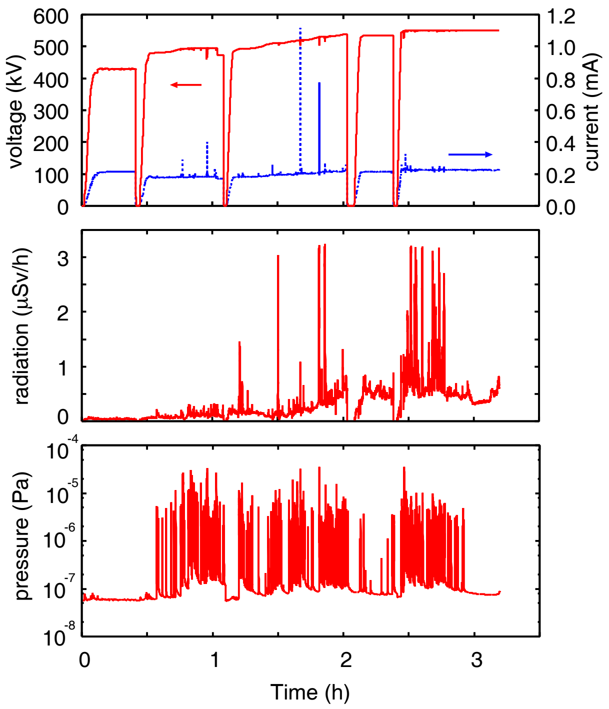

Figure 4: A high voltage conditioning result of the insulator without a support rod. The top shows voltage (solid line) and current of the C-W circuit as a function of time. The middle shows radiation and the bottom represents vacuum pressure during the conditioning.

Figure 1 shows cutaway of the high voltage vacuum chamber. A support rod hanging from the high voltage terminal holds a cathode electrode. The activated GaAs cathode will be inserted into the electrode head. The cathode/anode gap will be set to 100 mm for obtaining high accelerating field and avoiding the high-voltage breakdown. The diameter of the HV chamber is 508 mm, the length is 935 mm, and the surface area is roughly 1.4 m^2. The cathode/anode gap is surrounded by a NEG pump unit. Eight 400 l/s NEG pumps (SAES: CapaciTorr D400-2) will be employed at first. The number of the NEG pumps will be increased to twenty in the future. Five ICF203 ports behind the cathode electrode are used to install 2000 l/s NEG pumps. We will start with two 2000 l/s pumps. An ion pump will be employed to pump noble gases and methane.

CATHODE LOADING AND PREPARATION SYSTEMS

Figure 5 shows loading and preparation system of a photocathode, which is similar to other load-locked guns. The both chambers are made of chemically polished titanium as well as the HV chamber. A GaAs wafer installed into the loading chamber is heat cleaned to 550°C for three hours by a tungsten heater. The pressure rises to $1 - 2 \times 10^{-6}$Pa during the heat cleaning. The base pressure of the loading chamber equipped with a 300 l/s turbo pump (BOC Edwards: STP300) is 5×10^{-8}Pa after 200°C/8 hours bakeout.

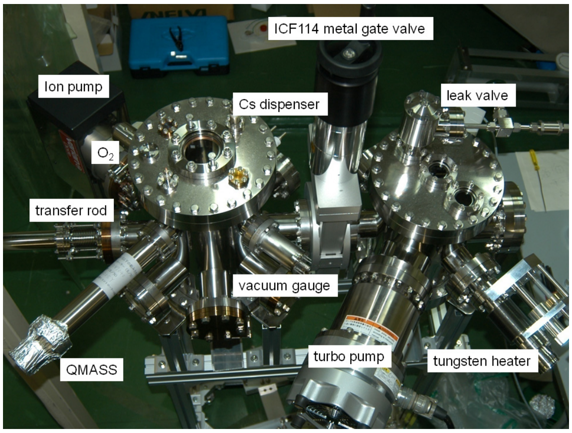

Figure 5: The loading and the preparation chambers of the 500-kV gun under an off-line test.

The cleaned wafer is transferred to the preparation chamber, and then it is activated by alternative application of Cs and oxygen. The preparation chamber is equipped with two 400 l/s NEG pumps (SAES: CapaciTorr D400-2) and a 45 l/s ion pump (ULVAC: PST-050AU). The base pressure is 2.4×10^{-9}Pa measured with an extractor gauge (ULVAC: AxTRAN). A residual gas analyzer (CANON/ANNELVA: M-201 QA-TDM) is used to examine the gas species in the preparation chamber. Typical partial pressures of gas species are listed in Table 2. The total pressure of the extractor gauge is corrected to 4.9×10^{-9}Pa, since the hydrogen is the main species of the residual gas. The partial pressure of other gas species are below the residual gas analyzer (RGA) detection limit.

Table 2: Typical preparation chamber RGA data

Species	Partial Pressure [Pa]
H_2	4.8×10^{-9}
CH_4	5.4×10^{-12}
NH_3	4.9×10^{-13}
H_2O	4.2×10^{-11}
CO/N_2	3.8×10^{-11}
CO_2	1.7×10^{-11}

The photo current is measured with a charge collector positively biased at 40 V, which is 1 cm in front of the photo cathode, as a function of time under continuous illumination of 17 μW HeNe laser. Typical quantum efficiency of 3 % and the 1/e cathode life longer than 20 hours are obtained for 0.25 μA beam. The base pressure during the photo current measurement is 5×10^{-8} Pa.

SUMMARY

We have developed a 500-kV photo-emission DC gun. High voltage tests of the Cockcroft-Walton circuit and the segmented insulator without the support rod were done up to 550 kV without any severe problem. A high voltage test with the support-rod is under way. A GaAs photocathode is activated in a newly developed photocathode preparation system. An effort to prolong the cathode life time will be further made.

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