Constructions and Preliminary HV Conditioning of a Photocathode Direct-Current Electron Gun at IHEP *

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As one of the most important key technologies for future advanced light source based on the energy recovery linac, a photocathode dc electron gun is supported by Institute of High Energy Physics (IHEP) to address the technical challenges of producing very low emittance beams at high average current. Construction of the dc gun is completed and a preliminary high voltage conditioning is carried out up to 440 kV. The design, construction and preliminary HV conditioning results for the dc gun are described.

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The linac-based free electron laser (FEL) and the energy recovery linac (ERL)-based light source are the two major types of the next-generation light sources. With a minor number of photon beam lines, FEL has higher brightness, shorter pulse length and higher coherent features. Moreover, ERL has the good beam performance of the linac and good operation efficiency of the storage ring machine. Although, with many photon beam lines, its brightness and coherent degree are not as high as those in the case of FEL. Hence, both FEL and ERL cannot be replaced by each other. Based on this point, the Institute of High Energy Physics (IHEP) has proposed the suggestion of 'one machine two purposes', and both FEL and ERL will share the same super-conducting linac for having a high efficiency.[1]

Presently, there are still many technical challenges to ERL, especially on the electron sources, which can deliver a high brightness electron beam with a low emittance and high current up to 100 mA. A dc electron gun is able to generate a high-current electron beam with a low initial emittance, when it is equipped with a semiconductor photocathode having a negative electron affinity (NEA) surface.[2] Such kinds of guns are being developed for future ERLs in many laboratories worldwide.[3–6] The goals of these gun development programs are for average current of 10–100 mA with normalized emittance of 0.1–1 mm·mrad. The recent experimental results from JLab and Cornell demonstrated that a photocathode dc electron gun with a GaAs or multi alkali photocathode is one of the most promising candidates.[7,8]

Since 2012, a photocathode dc electron gun has been supported by IHEP as an innovative project. The overall design of the dc gun is shown in Fig. 1, which consists of a 100 MHz/1.3 GHz drive laser system, a GaAs photocathode preparation system, a Cockcroft–Walton HV power supply, two segmented cylindrical ceramic insulators, a vacuum gun chamber, a pressurized insulating gas tank, and a short beam line. Table 1 lists the main parameters of the dc gun. Beam dynamics studies on a photo-injector for an ERL test facility based on this dc gun and two 1.3 GHz 2-cell superconducting RF cavities as the energy booster has been presented in Ref. [9].

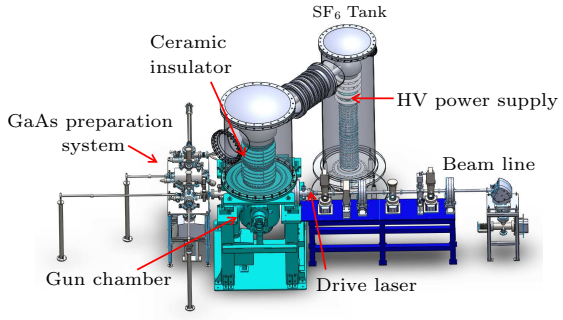

Fig. 1. Overall design of the photocathode dc electron gun at IHEP.

Corresponding to the two operation modes of the photocathode dc electron gun, two laser oscillators are working at 1.3 GHz and 100 MHz, respectively, which are adopted in the drive laser system. Requirements of the laser for both operation modes are listed in Table 2.

The drive laser is a conventional master oscillator power-amplifier (MOPA) system, in which the 100 MHz and 1.3 GHz oscillators are integrated into one laser system with a 2×2 fiber coupler to simplify the whole laser system. Both oscillators can use the same amplifier, pulse compressor, frequency con-

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version device, pulse shaping sets and optical transport line, as shown in Fig. 2. To date, the IR output power of the main amplifier in which Yb-doped photonic crystal fiber is used as gain media has already reached up to 27 W.

Table 1. Main parameters of the dc gun.

Parameter	Design value
High voltage	350–500 kV
Cathode material	GaAs:Cs/O
Quantum efficiency	5–7% (initial), 1%
Life time	20 h
Drive laser	2.3 W, 530 nm
Repetition rate	100 MHz, 1.3 GHz[a]
Nor. emittance	(1–2) mm·mrad@77 pC (0.1–0.2) mm·mrad@7.7 pC
Bunch length	20 ps
Beam current	(5–10) mA

[a]Two operation modes: (1) 100 MHz-7.7 mA-77 pC, (2) 1300 MHz-10 mA-7.7 pC.

Table 2. Laser requirements for two operation modes.

Parameters	1st mode	2nd mode
Electron bunch charge	77 pC	7.7 pC
Pulse energy at cathode	18 nJ	1.8 nJ
Pulse repetition rate	100 MHz	1.3 GHz
Power at cathode	1.8 W	2.3 W
Pulse length (flat top)	20–30 ps	20–30 ps

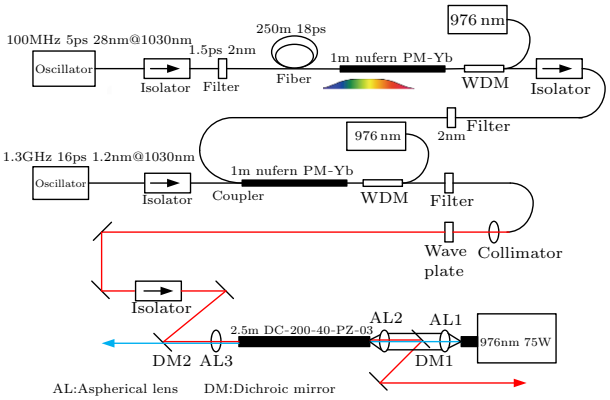

Fig. 2. Layout of the photocathode drive laser system.

The scheme of laser pulse modification and shaping is shown in Fig. 3, in which the output pulses are compressed using two transmission gratings. With an LBO crystal as a second harmonic generator, more than 5 W green light is obtained, which can meet the power requirements of the photocathode. A series of four YVO4 birefringent crystals are used for longitudinal pulse shaping to stretch pulse length to a width >20 ps. A laser pulse with a length of 28 ps has been measured in a recent experiment. For transverse laser shaping, the commercial shapers for generating flat-top beams do not work well since these products work well only under ideal conditions. It is preferable to simply image the laser on the cathode through a pinhole to generate a truncated Gaussian distribution.

A photoemission source, usually referred to as a photocathode electron gun or photo-injector, is based on the photoelectric effect. The basic principle of this electron source is that a cathode (called a photocathode) is illuminated by a pulse of laser light. Electrons are emitted from the cathode material as a consequence of the absorption of photons. The energy of photons must be greater than the work function of the material. To a first approximation, the higher the intensity of the photon source is, the greater the number of emitted electrons is.

The GaAs semiconductor photocathode, which is able to generate a high-current electron beam with ultra-small initial emittance due to its high quantum efficiency and low thermal emittance from a negative electron affinity surface, is used for electron emission in the IHEP photocathode dc electron gun.

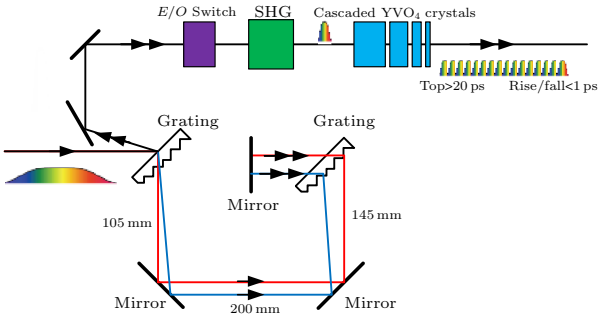

Fig. 3. Laser pulse modification and shaping.

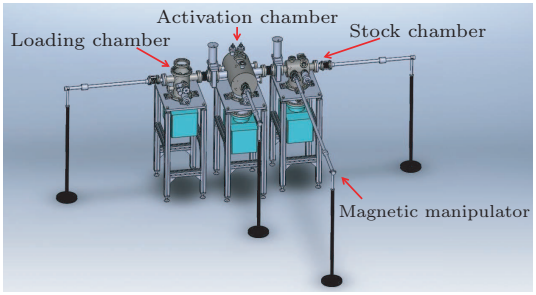

Fig. 4. Structure of the photocathode preparation system.

Schematic design of a GaAs photocathode preparation system is shown in Fig. 4. There are three load-lock vacuum chambers in the cathode preparation system including a loading chamber, an activation chamber and a stock chamber. These three chambers are required to achieve a very high vacuum environment to preserve QE and lifetime of the GaAs photocathode during its activation process. The cathode pucks are transferred among these three chambers and the electron gun chamber by the movement of magnetic manipulators. Vacuum test results show that the ultimate vacuum of stock chamber made of titanium achieved 2.4×10^{-12} mbar, and that values of activation chamber and loading chamber made of SUS-316L are 5.0×10^{-11} mbar and 4.0×10^{-10} mbar, respectively.

Experimental study on the activation process of a GaAs photocathode has been carried out using Zn-doped p-type GaAs wafers. These GaAs wafers with

diameter 15 mm were first heated from the backside by using a halogen bulb to a temperature of approximately 580℃ in the loading chamber. Once the wafers have cooled down to room temperature, the activation process would be performed through a co-deposition of Cs and O onto the surface in the activation chamber. Cs was evaporated by using commercial alkali metal dispensers from SAES, which were operated at a fixed dc current and O_2 was admitted into the chamber alternately through a leak valve. A GaAs photocathode with an 8% initial quantum efficiency has been obtained. The dark lifetime, which is determined regardless of the effect caused by beam extraction, was measured when the photocathode was not illuminated, or was shortly illuminated with a very low laser intensity to check the QE. As shown in Fig. 5, the dark lifetime of a GaAs photocathode after Cs/O activation can keep a 1% QE more than 1000 h.

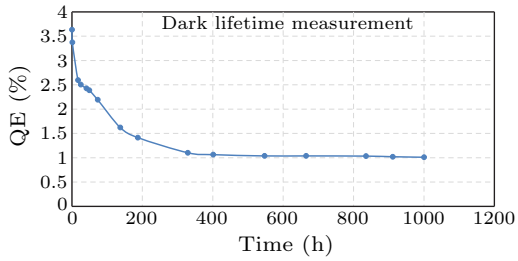

Fig. 5. Dark lifetime measurement of a GaAs photocathode after Cs/O activation.

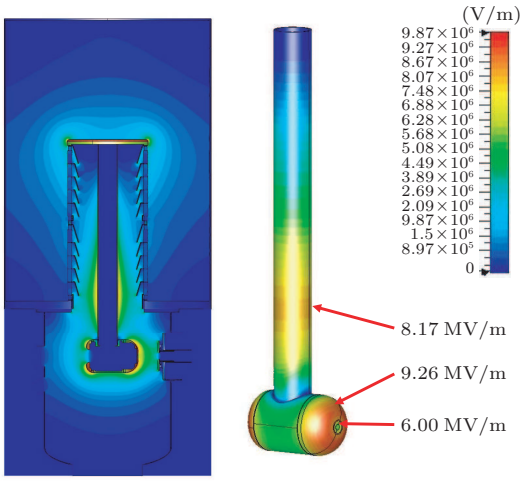

Fig. 6. Simulation of E-field distribution by using CST.

The photoemission beam is accelerated by a static electric field applied between cathode and anode electrodes. Generally, the accelerating voltage should be as high as possible to suppress the emittance growth caused by space charge effect, but field emission electrons generated from the stem electrode and cathode will cause damage to the ceramic insulator and the surface of electrodes, which is a strict limitation to the increase of the accelerating voltage. A simulation about the E-field distribution was carried out using CST (EM Studio)[10] to optimize the configuration of the gun as shown in Fig. 6. A 100 mm acceleration gap between the cathode and anode electrode is simulated under a 500 kV direct current high voltage condition. From the simulation results, it can be found that the maximum electric field on the support rod electrode is 8.17 MV/m and on the cathode electrode is 9.26 MV/m, meanwhile the accelerating field on the cathode surface is 6.0 MV/m. These values are fairly acceptable because the breakdown field for 500 kV at a general vacuum gap is about 10 MV/m.[11]

On the other hand, to reduce the risk of breakdown between the cathode and anode electrode, the support rod electrode, cathode electrode and anode electrode of the IHEP photocathode dc electron gun were fabricated by using titanium material that shows a higher breakdown field between a small gap.[12] The outgassing rate of titanium is 2–3 orders smaller than that of a general SUS,[13] which is helpful to achieve an ultra-high level vacuum in the gun chamber.

The ceramic insulator is the most critical component in the development of a dc photocathode electron gun. It needs to be well insulated and appropriately resistant to avoid any local concentration of the field emission electrons that can damage the ceramic. In the design of the ceramic insulator, the KEK/JAEA option is adopted,[14] in which a segmented ceramic insulator structure with guard rings between every two adjacent segments is employed to effectively avoid the field emission electrons generated from the stem electrode directly hitting the surface of ceramic insulator and hence to protect the ceramic insulator.

Figure 7 shows a cutaway view and a real picture of two sections of ceramic insulators in the IHEP photocathode dc electron gun, which consist of ten segmentations with the length of ceramic ring being 65 mm. The outer diameter of the ceramic insulator is 400 mm with a thickness of 20 mm. The multiple hoops of ceramics and nickel-plated Kovar electrodes were alternately stacked and blazed. The inside electrode rings are used to protect ceramic insulators and the outside electrode rings are used to connect the divide resistors.

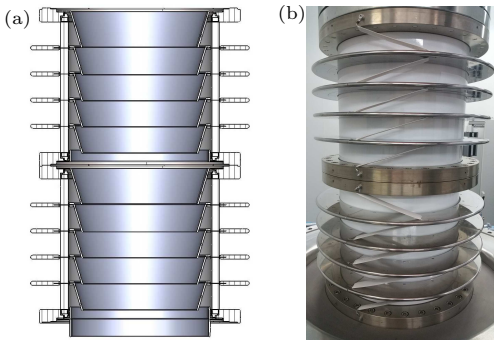

Fig. 7. A cutaway view (left) and a real picture (right) of ceramic insulators.

Figure 8 shows a cutaway view of the IHEP photocathode dc electron gun chamber and ceramic insula-

tors. Considering that QE and lifetime of GaAs photocathode largely depend on the vacuum environment, a kind of low outgassing rate material titanium was also selected for the fabrication of the gun chamber to ensure the inside vacuum environment. The pumping system employed a 600 L/s ion pump and forty-eight 400 L/s NEG pumps. After a sufficient baking of ceramic insulators and gun chamber, the vacuum pressure inside the gun achieved an ultra-high level of 9×10^{-12} mbar.

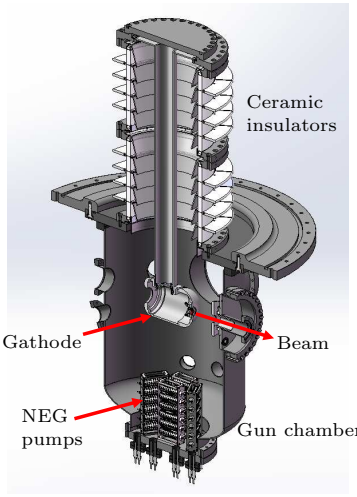

Fig. 8. A cutaway view of gun chamber and ceramic insulators.

Fig. 9. A 500 kV/10 mA HV power supply.

Low-emittance is one of the most important parameters in the design of a photocathode dc gun. The gun voltage must be 500 kV or higher to suppress the emittance growth by the space charge effect.[15,16] As a 500 kV photocathode dc gun, the emittance of a 77 pC bunch charge would be suppressed to 1 mm·mrad. Another key parameter of the power supply system is the voltage ripple, which is one of the major sources of bunch-to-bunch fluctuation such as jitters in emittance, bunch shape, and energy spread after the full acceleration.[17] To fulfill these requirements of dc gun, a product of England company (HiTek) was chosen.[18] Figure 9 shows the structure of the power supply.

The high-voltage circuit used in the dc gun is a conventional Cockcroft–Walton power supply with a capacity of 50 kW (500 kV and 10 mA) and a low voltage ripple (peak to peak is 5×10^{-4}). Two sets of output resistors are applied for the power supply, one is 100 MΩ to avoid damage to the electrodes during high-voltage conditioning, and the other is 50 kΩ to protect the diodes of the power supply during beam operation. For high-voltage operations, the power supply will be installed in a tank filled with pressurized SF_6 gas.

The downstream beam line for beam diagnosis is shown in Fig. 10. A bending magnet with three pairs of solenoid and corrector are used for the beam transport from the gun exit to a beam dump. A light box to deliver a driving laser to the photocathode is placed adjacent to the first solenoid. Three YAG screens distributed on the beam line are used as beam profile monitors. A 1.3 GHz deflecting cavity is utilized to measure the bunch length of photoemission beam, where the RF and laser will be synchronized with a feedback mechanism, which is controlled within 200 fs–300 fs (rms). The beam emittance will be measured by solenoid scan.

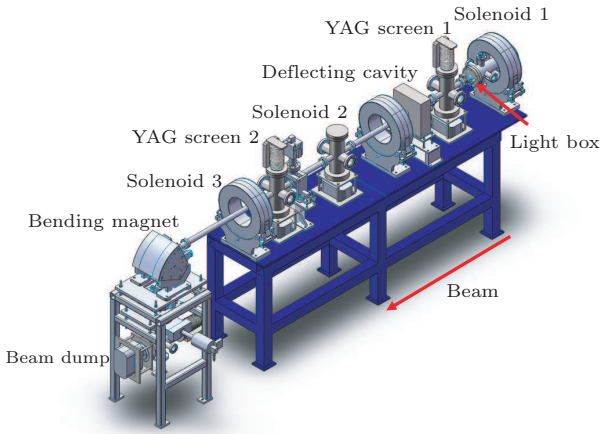

Fig. 10. Scheme of beam line for the IHEP photocathode dc electron gun.

The high-voltage conditioning was carried out by maintaining the base vacuum pressure in the gun chamber lower than 5×10^{-11} mbar and the pressure of SF_6 in the pressurized tank was 0.25 MPa. The C-W power supply was interlocked with the vacuum pressure in the gun chamber to prevent any excessive discharge during the conditioning. The interlock level was a vacuum pressure of 4×10^{-8} mbar. A 100 MΩ output resistor was used to avoid damage to the electrodes during high-voltage conditioning. Ten 500 MΩ resistors and segmentations of ceramic are connected to divide the applied voltage uniformly.

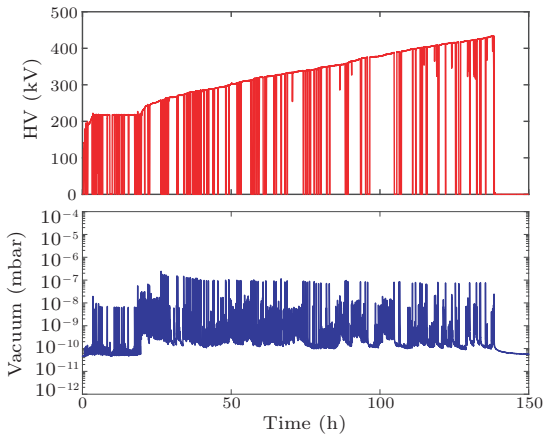

Fig. 11. The results of preliminary high-voltage conditioning.

Figure 11 shows the high voltage (top) and vacuum pressure in the gun chamber (bottom) as a function of time during HV conditioning. After around 140 h conditioning, HV reached up to 440 kV that means an HV between cathode and anode was around 431 kV because a 100MΩ protect resistor divided a voltage by 100 MΩ/5100 MΩ.

During the conditioning at 440 kV, a breakdown happened in the gun chamber and after that a large radiation dose was found at one side of the gun chamber. Unfortunately, this appearance of radiation dose was irreversible, when the HV was dropped to 250 kV there was still a high radiation dose. A hand-held radiation monitor was used to check the region around the gun chamber at 250 kV and it was found that the radiation had a strong directivity. A possibility of this phenomenon was that unpredictable sources of field emissions occurred on the cathode surface. The HV conditioning then was stopped. Before next step HV conditioning, it is necessary to open the gun chamber and check the cathode surface and inside surface of the gun chamber.

In summary, the design and construction of each subsystem is briefly described. To date, the drive laser can transmit a 5 W green light with a 28 ps pulse length, which meets the requirements of beam operation. GaAs photocathodes which can keep the QE higher than 1% for more than 1000 h in a darkroom are obtained. Further experiments are needed to optimize the performance of QE and lifetime with the consideration of the ion back bombardment during beam operation. A preliminary high-voltage conditioning is carried out, and a breakdown in gun chamber at 440 kV introduces some possible sources of field emissions which lead to a high radiation dose at a fixed location of the gun chamber. Opening the gun chamber and checking the surface inside to remove the field emission sources will be a crucial work for the next step. It is expected to recover HV conditioning and start a beam experiment in the near future.

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