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LOW EMITTANCE THERMIONIC ELECTRON GUN AT SLRI

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Abstract

The Synchrotron Light Research Institute (SLRI) has developed a new thermionic electron gun producing low emittance electron beam for the future upgrade of the existing one. The thermionic cathode made of a CeB_6 single crystal is selected due to its properties providing high electron beam current, uniform current density, and high resistance to contamination. In addition, the CeB_6 cathode of 3 mm in diameter can produce up to a few Amperes of electron beam current. The electron gun is pulsed at 500 kV with a few microseconds wide to avoid high voltage breakdown as well as to reduce space charge effect resulting in the emittance growth of the extracted electron beam. The preliminary simulation and design of the electron gun together with the high voltage system are described in the paper.

INTRODUCTION

Development of a new electron gun at the Synchrotron Light Research Institute (SLRI) has been started as a part for an upgrade of the current injector and a study for the future light source [1]. A new electron gun with high stability should be capable of producing high-quality electron beam with desired properties for the injector. Two types of the electron guns: a photocathode RF and a thermionic electron guns, are widely used to produce electrons for the light source. The photocathode RF electron gun that is well known for producing electron beam with high peak current, short bunch length, and low emittance, has been employed in several light source facilities while the themionic electron gun with a simple setup and high realiability has been used in many 3 GeV light sources as well as the SACLA FEL facility [2]. Considering cost, sophistication of setup and operation, and experience of our staff, the thermionic electron gun is chosen. However, several modifications must be made so that the quality of the electron beam meets the requirement for the injector.

TECHNICAL MODIFICATION

In order to achieve building a high performance electron gun with small emittance and short bunch length, several changes are needed:

- Small cathode that is capable of producing large beam current.
- High bias voltage to overcome effect of the space-charge effect at low energy.
- Removal of pulsed grid in the traditional setup that significantly enlarges the beam emittance at the initial stage.
- Fast beam deflector allowing nanosecond-pulsed electron beam to transport to the bunching section and to deflect undesired electrons to the collimator.
- Pre-buncher and buncher to adiabatically bunch and accelerate electrons to higher energy and minimize the effect from the Radio-Frequency (RF) field that potentially causes the emittance growth.

ELECTRON GUN

Three main parts that have to be carefully considered for building the high-performance thermionic electron guns are an electron gun cathode, extraction of high-current electron beam, and a high-voltage system.

Electron Gun Cathode

As mentioned earlier, the required cathode as a source of electrons must be small while producing large electron beam current of a few Amperes. According to the normalized rms emittance from a hot cathode given by $\epsilon_{n,rms} = r_c/2\sqrt{k_B T/m_e c^2}$, where r_c is a cathode radius, k_B is the Boltzmann's constant, and $m_e c^2$ is the electron rest mass energy; the emittance of 0.4 πmmmrad can be obtained from the cathode of 3 mm in diameter at $T = 1400$ °C. Moreover, the cathode should be able to produce electron beam current at least one Ampere equivalent to electron current density of 14 A cm^{-2}. It has been shown from previous study that the cathode made of rare-earth hexaborides, for example, LaB_6 and CeB_6, can produce such current density with operational long lifetime.

The hexaboride cathode is widely used in the application requiring low beam spot size such as a scanning microscope, a tunneling microscope etc. and high electron current such as lithography, X-rays source, etc. Due to the lower work function of 2.65 eV, the hexaboride crystals produce the higher electron beam current and brighter beam than that of tungsten. With the flat crystal surface, the uniform electron beam density can be generated at high electron beam current. Since the hexaboride cathode is resistant to the chemical poisoning, requirement of the vacuum can be flexible. Compared with LaB_6, CeB_6 has less work function at 2.65 eV and lower evaporation rate at 1800 K leading to longer lifetime. It is also more resistant to the negative impact of carbon contamination. It has been shown at SACLA that the electron gun with the CeB_6 cathode can produce electron beam current of up to 1 A with long lifetime and stable operation [3].

Electron Cathode Assembly

Figure 1 illustrates an assembly of the electron gun and an electron gun test chamber. The CeB_6 cathode is fixed

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to the graphite sleeve to avoid production of beam halo. Since the graphite is mechanically and chemically stable, the graphite sleeve is radiatively heated by the surrounded graphite heater. Before installing the CeB_6 cathode to the electron gun, its surface roughness has to be measured with a scanning electron microscope in order to investigate the evaporation rate of the cathode surface. Then, the cathode that is mounted on the electron gun assembly will be tested in the test chamber for measuring extracted current and current density as a function of cathode temperature.

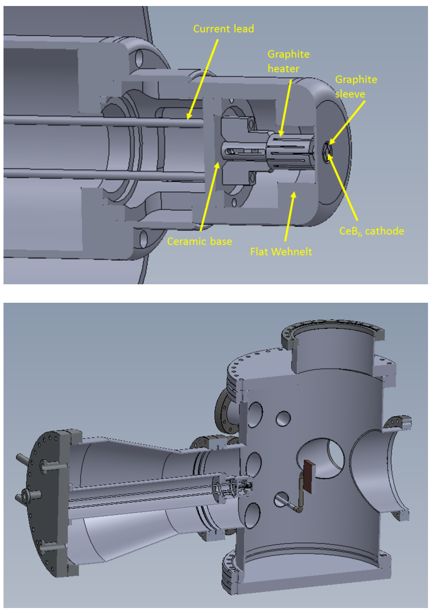

Figure 1: Assembly of an electron gun (top) and an electron gun test chamber (bottom).

Extraction of High-Current Electron Beam

In order to minimize space charge effect at low electron beam energy and emittance growth due to misalignment, the flat Wehnelt cathode is more suitable than the Pierce-type. Although the Pierce-type cathode is designed to produce parallel beam that the space-charge effect is balanced with the focusing field, the installation of cathode must be precise. Slight misalignment that causes the asymmetric focusing field can introduce emittance growth. In addition, the Pierce-type cathode must be operated at the fixed potential to produce parallel beam at proper focusing strength since the electron beam can be over/under-focused at low/high electron-beam current. On the other hand, the Wehnelt type provides more flexibility during the commissioning as the optimization will be obtained by tuning from low to high electron current.

Figure 2 depicts the electric field calculated by Tricomp [4] between cathode and the anode and the electron beam trajectory extracted from the CeB_6 cathode of 1.5-mm radius. Assuming the electrons generated from the cathode have zero thermal energy, the simulated emittance of the electron beam at the exit gap is around 0.1 πmmmrad. Since the field gradient around the Wehnelt electrode is 9.7 MV, the preparation of the electrode is crucial to avoid discharge that could destroy the electrode surface. Chemical-etching method together with rinsing parts in the ultra-pure water will be employed to remove hydrocarbon contamination on the surface. In addition, the pressure inside the electron gun chamber must be maintained around 10^{-9} Torr or less.

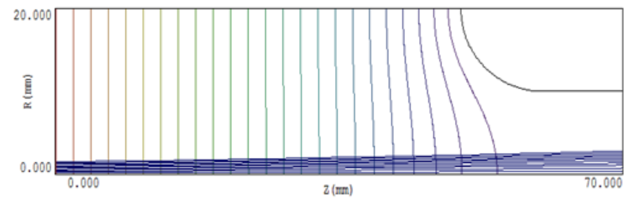

Figure 2: Calculated electric field and extraction of electrons from the electron gun cathode.

ELECTRON GUN TEST BENCH

Once the electron gun is already tested in the electron gun test chamber, it will be installed to the 500 kV high voltage system and the electron gun test bench. Figure 3 illustrates an electron gun test bench. Electrons are produced from a cathode which is biased at −500 kV with a few microsecond pulse width. Extracted electron pulse of 500-keV energy is then shorten by a fast beam deflector to a few nano-second range and the undesired electrons are absorbed to the collimator. A two-slit method, which is simple and straightforward, is used as a diagnostic system to measure emittance of the short-pulsed electron beam. This method requires three current transformers and two pairs of x-y slits. A beam profile monitor used to confirm the electron beam size is installed in front of the beam dump at the end of the transport line. One magnetic lens are mounted to focus the electron beam extracted from the anode, while the other focuses the short pulse electron beam traversing the fast deflector to the diagnostic system.

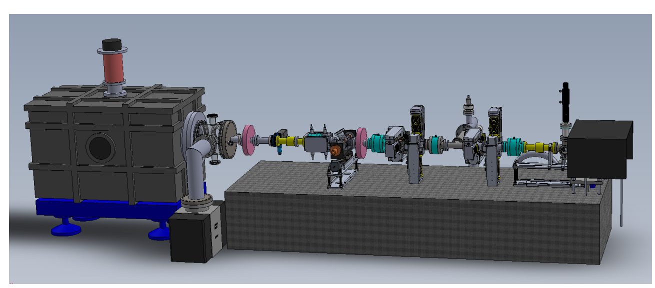

Figure 3: Electron gun test bench.

HIGH-VOLTAGE PULSE SYSTEM

The main components of the High-Voltage (HV) pulse system for the 500-keV electron gun are a high power DC power supply, a pulse modulator, and a HV pulse transformer, as illustrated in Figure 4. Due to the large size of the whole system, the device is separately designed to avoid trouble

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during transportation and each component is connected via coaxial cables.

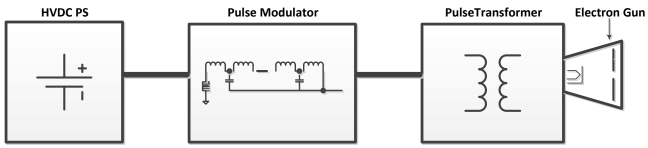

Figure 4: Main components of the electron gun high voltage system.

High Voltage Pulse Transformer Unit

Since the cathode is biased at −500 kV, the pulse transformer has to step up the pulsed voltage from the pulse modulator to −500 kV. In addition, at −500 kV the cathode must be able to supply an electron beam of 1 A. The electron gun can be considered as a resistance of 500 kΩ. Table 1 lists technical properties of this unit. In order to prevent electrical breakdown due to high voltage and make this unit more compact, the HV pulse transformer and its accessories are installed in a stainless steel tank filled with insulating oil. Not only is the insulating oil used as insulator, but it is also coolant fluid for all HV components inside the tank.

Table 1: Technical Properties of the HV Pulsed Transformer

Winding structure	Tapered winding, bifilar secondary winding
Winding ratio	1:21
Max primary voltage	30 kV
Max primary voltage	650 kV
Max pulse width	4 µs
Max primary current	7 kA
Max secondary current	350 A

Pulse Modulator Unit

A pulse modulator is the main part of the 500-kV pulse system as it is the first unit of the HV pulse system that produces desired pulse for the electron gun. The design and specification of this pulse modulator is based on the pulse modulator of the C-band klystron at SACLA. The output pulse of −24 kV is 3.8 µs wide at 70% of the peak. A pulse forming network (PFN), a core circuit, consists of a network of 18 inductor-capacitor cells. Each cell is made of one 490-nh inductor and one 22.3-nF capacitor. The required number of cell is 3.8 µs. Assuming all cells of PFN are identical, the characteristic impedance of the pulse modulation is 4.69 Ω. This characteristic impedance will be used to calculate the dummy load that is connected in parallel with the electron gun for impedance matching purpose.

Dummy Load

The dummy load of 1.9 kΩ connected in parallel to the electron gun is used for impedance matching purpose and technical properties of a dummy load are listed in Table 2.

Table 2: Technical Properties of a Dummy Load for Impedance Matching

Type	Vacuum diode tube
Max input voltage	1000 kV
Operating voltage	500 kV
Resistance	1.9 kΩ, ±5% adjustable
Cooling	30 °C de-ionized water

High-Voltage DC Power Supply (HVDC-PS)

HVDC-PS is used to charge the capacitor of PFN for producing voltage of 50 kV. The technical properties of HVDV-PS is listed in Table 3.

Table 3: Technical Properties of a High-Voltage DC Power Supply

Input Voltage	3 phase, 400 Vac ±5%, 50 Hz
Output voltage	0-50 kV adjustable
Output voltage polarity	Positive
Output voltage stability	10 ppm (rms)
Peak Charging	20 kJ s^{-1}
Rate Charging current	0-800 mA adjustable
Power factor	≥ 0.85

CONCLUSION AND OUTLOOK

The high performance low emittance electron gun has been developed at SLRI as the first step toward the future facility upgrade. The thermionic electron gun with major changes has been selected with the target emittance of less than 1 πmmmrad and the current of 1 A. The high voltage system has been designed to ensure the desired energy of the electron beam. By the end of this year, the electron gun assembly will be complete and tested to confirm results of the design and simulation.

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