Development of an electron gun for the ERL light source in Japan

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Abstract

A DC photocathode electron gun has been developed at Japan Atomic Energy Agency (JAEA) for the ERL light source project jointly launched by JAEA, KEK, and the Institute for Solid State Physics of the University of Tokyo. The electron bunch is generated from a NEA photocathode upon illumination of a drive laser pulse and is accelerated to 250 keV by the DC high voltage applied between the cathode and anode. A load lock and a photocathode preparation chambers are under assembly. We have measured life time and quantum efficiency (QE) of bulk AlGaAs to find a photocathode having longer life time and higher QE than bulk GaAs. In our preliminary test, AlGaAs has shown twice higher QE and 10 times longer life time than GaAs.

INTRODUCTION

Next generation ERL light sources (LS) require an electron gun capable of producing a high average current of 100 mA with extremely low emittance of 1 mm mrad. The Jefferson Lab (JLab) 10 kW IR Upgrade FEL DC GaAs photocathode gun provides a high average current electron beam of 9.1 mA CW with normalized emittance lower than 8 mm mrad [1]. Generation of 1 nC bunch charge with low emittance approaching 1 mm mrad has been demonstrated in many X-ray FEL facilities at low average current [3, 4]. However, there still remains a huge gap between the demand of ERL LS and existing gun technologies, making the gun development one of the top issues in ERL communities.

Recently, a Japanese ERL light source project has been jointly launched by JAEA, KEK and the Institute for Solid State Physics of the University of Tokyo [2]. As the first step of the collaboration, we started to develop key technologies for the ERL, and are planning to construct together an ERL test facility at KEK site. The tentative parameters for the test facility are the beam current 100 mA, the injection energy 5 MeV, normalized emittance 1 mm mrad, beam energy at main linac 60 MeV, and the bunch length 100 fs. We JAEA group are in charge of the gun development and chose a DC NEA photocathode gun among the existing technologies, since an extension of the JLab Upgrade FEL gun seems to be most straightforward and promising for us to reach our final goal of producing 100 mA beam at extremely low emittance.

We have also proposed to use this gun technology to develop an ERL SASE FEL at extreme ultraviolet wavelength, which may be a promising candidate for future generation semiconductor lithography [5]. Many other different applications will be inspired by gun development for ERLs.

In the present paper, we describe our current status of 250 kV 50 mA gun development and planned diagnostics. Our photocathode test bench to find a cathode material having higher quantum efficiency (QE) and longer life is also shown.

GUN DEVELOPMENT

We have developed a 250 keV 50 mA DC gun equipped with an NEA photocahode shown in Fig. 1 as the first phase of our development toward 500 kV 100 mA gun [6]. A Cockcroft Walton power supply is used to apply high voltage to a ceramic tube. A high voltage test has been successfully done [7] and the photocathode preparation chambers are under assembly [8], as shown in Fig. 2.

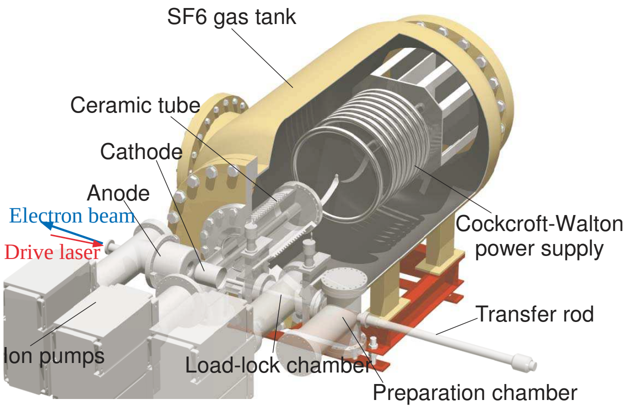

Figure 1: JAEA photocathode electron gun.

The DC gun consists of a load lock chamber where a photocathode sample is introduced and heat cleaned. The cathode sample is then transferred via load lock into the preparation chamber where cesium and oxygen are applied on the cathode. The activated cathode is finally transferred to the main chamber for acceleration of photo-emitted electrons. There are two reasons why the load lock chamber is installed between the preparation and main chambers. One is that the load lock chamber is responsible for roughly evacuating both the load lock and main chambers, whenever they are exposed to air for modifications which we

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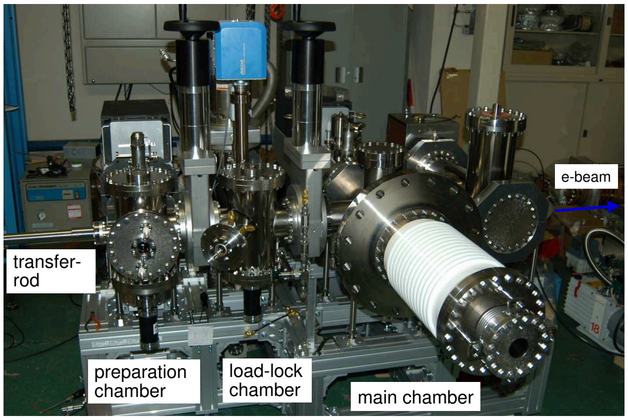

Figure 2: Load lock, preparation, and main chambers.

have to perform in the early stage of the development. The other is that the transfer rod always needs to be evacuated for its poor vacuum conductance.

All the gun chambers are made of Titanium, because it has three orders of magnitude lower outgassing rate than stainless steel [9]. A 300 l/s turbo pump and a 1,700 l/s cryopump are installed in the load lock chamber for rough evacuation, a 500 l/s ion pump and a 2,000 l/s NEG pump are used in the preparation chamber, and two pairs of 500 l/s ion pump and 2,000 l/s NEG pump are installed upstream and downstream the cathode holder. The ultimate vacuum is calculated to be 3 $\times 10^{-10}$ Pa at the main chamber from the pump parameters, chamber configuration and the outgassing rate of ceramic tube.

The gun electrode is shown in Fig. 3. The cathode sit 1 mm back from the cathode holder surface. The cathode area is 8 mm in diameter defined by the cathode holder. The gap distance between the cathode and anode is 40 mm and the anode hole is 40 mm in diameter. The configuration of this electrode assures that the electric field is uniform over the transverse beam size. This configuration is however very similar to that of early version of CEBAF gun where significant beam loss and accompanying x-ray generation due to transverse kick at the junction between the cathode and the electrode were observed [10]. We may switch the cathode configuration to the current version of CEBAF gun where the cathode area is large enough to avoid the transverse kick at the junction and the anodization is used to suppress the beam halo [11].

A solenoid magnet for emittance compensation will be installed 25 cm downstream of the anode. The solenoid has a bucking coil to compensate the field at the cathode surface. We have performed PARMELA simulations as a function of the solenoid field and found that minimum emittance is 0.6 mm mrad for 77 pC bunch charge and that the bunch length is 60 ps rms. The initial bunch shape used in the simulation is Gaussian in longitudinal and uniform in transverse.

The transverse emittance will be measured with a slit placed at 1.1 m downstream of the anode. In order to measure the beam emittance with the slit scan technique, the beam passing through the slit has to be emittance dominant. The beam envelope equation for a relativistic beam in drift space is given by [12]

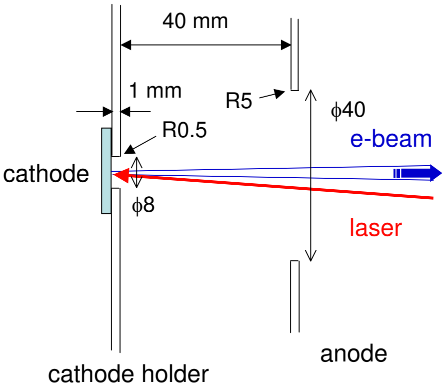

Figure 3: Configuration of gun electrode.

$$\sigma_x'' = \frac{\varepsilon_n^2}{\gamma^2\beta^2\sigma_x^3} + \frac{I}{\gamma^3\beta^3 I_0(\sigma_x+\sigma_y)}, \qquad (1)$$

where $\gamma = 1/\sqrt{1-\beta^2}$ is Lorentz factor, I peak current, $I_0 = ec/r_e$ = 17,000 A the characteristic current and ε_n normalized rms emittance. The first term in the right hand side represents emittance dominant beam and the second term shows space charge dominant beam. The beam is emittance dominant when the first term is greater than the second term. The ratio of the two terms is given by [13]

$$R_b = \sqrt{\frac{2}{3\pi}\frac{Id^2}{\gamma\beta I_0\varepsilon_n^2}}, \qquad (2)$$

where d is the slit width. Substituting beam energy ($\gamma = 1.49$, $\beta = 0.74$), peak current (I = 3 A), and transverse emittance (ε_n = 0.3 mm mrad) into the equation, the ratio is smaller than unity when the slit width is as narrow as 20 μm. Such a narrow slit will be in reach using the existing technology, since 25 μm slit is available at SPring8 Compact SASE Source [4].

We plan to measure electron bunch length using a kicker cavity. The $\lambda/2$ type cavity was originally designed and made for measurement of longitudinal phase space distribution of 2 MeV electron beam. The shunt impedance is 2.5 MΩ and transit time factor is 0.93 for 250 keV beam. In order to apply transverse energy of ±20 keV to the 100 ps length electron bunch, 3.7 kW RF power will be required. We can afford this power using our 6 kW RF power supply.

PHOTOCATHODE DEVELOPMENT

The drive laser energy should be close to the band gap energy for generation of low emittance beam [14, 15]. We have developed a photocathode test bench to find a cathode material having higher QE and longer life at wavelength as close as band gap energy [6]. The test bench consists of a

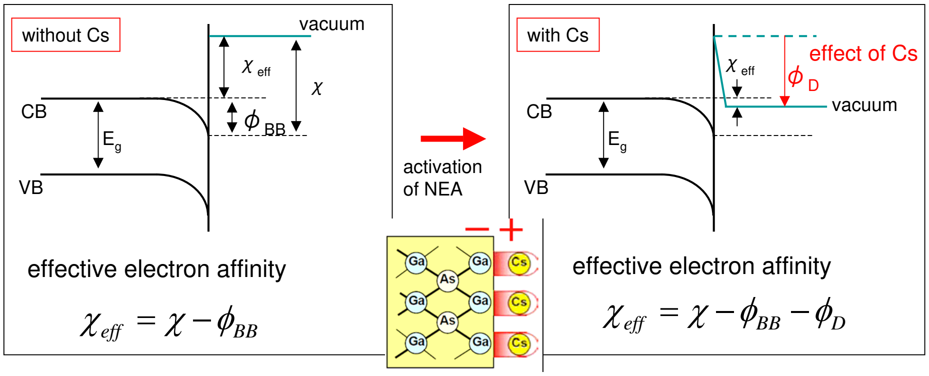

Figure 4: Vacuum potential of GaAs cathode without cesium (left) and with cesium (right). The electron affinity (χ) of bulk GaAs is 4.1 eV and that of bulk $\mathrm{Al_{0.28}Ga_{0.72}As}$ = 3.8 eV. The effective electron affinity (χ_{eff}) of $\mathrm{Al_xGa_{1-x}As}$ is lower than that of GaAs.

cathode holder equipped with a heater and Cs evaporation tool, ultra high vacuum chamber and Ti:sapphire laser. The main chamber keeps high vacuum of 3×10^{-9} Pa. The surface of samples is cleaned by radiation heating using a tungsten heater. The NEA surface is activated by alternative adsorption of cesium and oxygen (yo-yo method). A Ti:Sapphire laser (720-870 nm), a He-Ne laser (633 nm) and a laser diode (690 nm and 670 nm) are used as an excitation laser.

The vacuum potential of a semiconductor cathode is determined by conduction band minus band bending potential ϕ_{BB} plus electron affinity χ (see the left of Fig. 4). The electron affinity minus band bending yields the effective electron affinity χ_{eff}, which is positive when the cesium is not applied on the cathode surface as shown in the left of Fig. 4. Application of cesium on the GaAs cathode creates a fragile surface consisting of thin layer of cesium-atoms attached to gallium-atoms, which forms electric dipole field to pull down the vacuum potential barrier (see the right of Fig. 4). This yields the negative effective electron affinity. Damage on the cesium layer due to ion back bombardment causes a rise of the vacuum potential. The cathode material with smaller electron affinity is therefore preferable for keeping the NEA state for a longer time.

In order to confirm the effect of band-gap energy and electron affinity on the photocathode performance, we have measured QE and lifetime of different materials: bulk GaAs and bulk AlGaAs which has larger band-gap energy and smaller electron affinity than bulk GaAs [16]. The cathode samples with various aluminium fractions (=0.00, 0.10, 0.17, 0.28) have been fabricated with molecular beam epitaxy by a team lead by Profs. Tabuchi and Takeda at Nagoya university. These samples have the same active-layer thickness for the photo-electron generation.

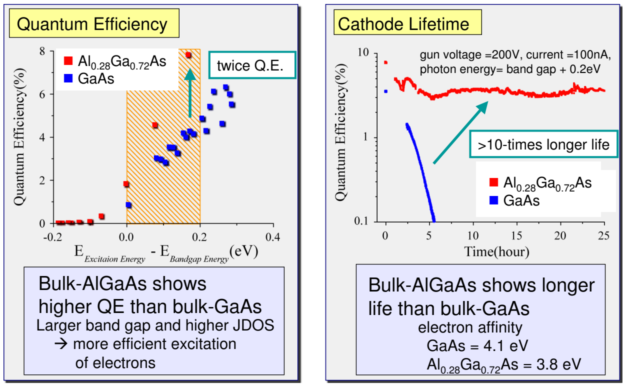

Figure 5: Quantum efficiency as a function of laser energy minus band-gap energy (left) and clock hours life time (right) of bulk GaAs (blue squares) and bulk AlGaAs (red squares).

The left of Fig. 5 shows the quantum efficiency of the GaAs and AlGaAs cathodes as a function of the laser excitation energy minus band-gap energy. The AlGaAs cathode shows twice higher QE than that of GaAs. This is because the larger band gap energy and higher joint electron density of state lead to more efficient excitation of electrons in AlGaAs. The right of Fig. 5 shows cathode life time where the laser photon energy is tuned to the band gap energy plus 0.2 eV. AlGaAs shows longer life time than GaAs as predicted by semiconductor theory. One possible reason why the life time of GaAs is too short is the ion back-bombardment. This is because the applied voltage during the life time measurement was as low as 200 V while the ionization cross section of hydrogen molecule is maximum around 50 V. We should perform the same measurement at much higher voltage to reduce the ion back-bombardment effect. The photo-current during the measurement was 100 nA.

Since the band gap energy of AlGaAs is larger than that of GaAs, the drive laser energy for AlGaAs cathode should be greater than 1.7 eV. We need to use an optical parametric amplifier pumped by the second harmonic frequency of Yb fiber laser instead of the fundamental of Ti:sapphire laser.

SUMMARY

We have initiated R & D studies for a photocathode DC gun and developed a 250 keV 50 mA DC gun. This gun is anticipated to produce electron beam with normalized emittance of 0.6 mm mrad for 77 pC bunch charge. We hope to have the first beam summer in 2007. We have measured life time and QE of bulk AlGaAs and bulk GaAs and found that AlGaAs have twice higher QE and 10 times longer life time than GaAs.

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