DEVELOPMENT OF A PHOTOCATHODE DC GUN AT JAEA-ERL

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Abstract

An electron gun producing an e-beam with high-brightness and high-average current is a key component to realize a next-generation X-ray light source based on an energy-recovery linac (ERL). In JAEA, we are developing a photocathode DC gun for a future ERL light source. The DC gun is operated at 250 kV and 50 mA at maximum, and equipped with a load-lock chamber for cathode preparation. In order to keep small emittance at high current operation, we adopt new type of semiconductor photocathode such as AlGaAs and superlattice. In this paper, we present the status of the gun development and future plans towards the ERL test facility to construct in collaboration with KEK and other institutes.

INTRODUCTION

In JAEA (Japan Atomic Energy Agency), we have conducted a research program for a high-power free-electron laser since 1987. As a part of the research program, an energy-recovery linac (ERL) has been commissioned. The design study of the ERL was started in 1999[1]. After one-year construction period we made first demonstration of energy-recovery operation in 2002[2]. The ERL consists of a 250 kV DC gun with thermionic cathode, 2.5 MeV injector, an ERL loop for 17 MeV electrons, and an FEL undulator. The FEL wavelength is around 20 μm [3]. The ERL also generate strong radiation in millimeter wavelength region by coherent synchrotron radiation from a bending magnet[4].

Following the successful demonstration of ERLs at JAEA and Jefferson laboratory[5], several new proposal of ERLs have been suggested. Since the energy-recovery linac provides a versatile technology to generate a high-brightness electron beam of high-average current, it can be applied to various kinds of accelerators. Next-generation X-ray light source is one of the most promising direction for the future ERL development. We can produce X-rays with excellent coherence and/or ultrashort pulse duration, if we employ an energy-recovery linac equipped with a high-brightness injector such as a photocathode gun. In Cornell university, a 5 GeV ERL light source is proposed as a successor of CESR, and an injector for the ERL is under development[6]. Research and development towards next-generation light source based on an 800 MeV ERL is carried out at Daresbury[7].

In Japan, KEK and JAEA had proposed each own 5-6 GeV ERL project for a future light source independently. These two institute, however, agreed to unite their projects into a single form in March 2006. We are now working together to construct an ERL test facility at KEK site to resolve technical and physical challenges[8]. In the joint project, JAEA is mainly responsible for the gun development and KEK has charge of superconducting cavities[9].

In this paper, we present the status of electron gun development for the future ERL light source in Japan.

ELECTRON GUN FOR ERL LIGHT SOURCES

Next-generation light source based on the ERL technology provides an evolutionary path of X-ray science, because the ERL generates coherent X-rays and femtosecond X-rays which are difficult to obtain in existing storage rings. When the divergence of an electron beam is smaller than the intrinsic divergence of an X-ray, a large part of undulator radiation becomes coherent, and this criteria is called “diffraction limit” and given by $\varepsilon < \lambda/4\pi$, where ε is geometrical rms emittance and λ is X-ray wavelength. In order to satisfy the diffraction limit for 1 Å X-rays, emittance should be less than 8 pm-rad, which corresponds to normalized rms emittance of $\sim$0.1 mm-mrad at 5 GeV. Average current of an ERL light source should be as large as 100 mA to obtain X-rays of flux comparable to 3rd-generation light sources. Thus, the requirements of an electron gun for a future ERL light source are average current of 100 mA and normalized rms emittance of 0.1 mm-mrad.

Developing an electron gun to satisfy the above requirement is a serious matter. Photocathode RF guns have been studied for high-brightness electron beams and normalized rms emittance is approaching to a value of 1 mm-mrad [10]. Recently, a DC gun with a thermionic cathode generating an electron beam of 1.1 mm-mrad was built for an XFEL[11]. These guns, however, are designed for pulsed operation with small duty cycle. The gun of JAEA-ERL is compatible with 10-mA CW operation but has rather large emittance, 13 mm-mrad, due to its gridded thermionic cathode[13].

The only candidate for the future ERL light source is the combination of a DC gun and semiconductor cathode with negative electron affinity (NEA) surface. Since GaAs with NEA surface is able to emit photo-electrons by visible lasers, it is an optimum electron source for generating high-average current. An NEA cathode can be installed only at DC guns, because stable operation of an NEA surface requires ultra-high vacuum, typically 10^{-9} Pa. A DC gun with NEA cathode has been employed at the JLAB ERL, where average current of 9 mA and normalized emittance

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of 10 mm-mrad have been obtained[14]. Similar electron guns are also used for generating polarized electrons. In the studies on a polarized electron source, emittance of 0.1 mm-mrad has been demonstrated with small average current, 1 nA$\sim$ 1μA [15][16].

We consider that an electron gun for future ERL light sources can be realized by improving existing technologies of DC guns and NEA photocathodes.

STRATEGY OF GUN DEVELOPMENT

In order to develop an electron gun which fulfills the requirements of future ERL light sources, 100 mA and 0.1 mm-mrad, we have launched two apparatus: a photocathode test bench and a 250-kV DC gun.

Since the performance of electron guns depends much on their photocathode, improvement of semiconductor photocathode is the main task in the gun development. For this purpose, we have assembled the photocathode test bench consisting of an old MBE chamber and a mode-locked Ti:sapphire laser. The chamber reaches ultra-high vacuum $\sim 3 \times 10^{-9}$ Pa, which is enough to activate an NEA surface. Quantum efficiency of a photocathode can be measured as a function of injection laser photon energy by using the Ti:sapphire laser and other auxiliary lasers. In the test bench, beam current is limited at a few μA because of available extraction voltage $\leq$1 kV. This small current and low voltage operation makes it difficult to estimate cathode life time in a practical situation. This is because ionization rate of residual gas by electron beam is a strong function of electron energy and degradation of NEA surface due to ion back-bombardment shows quite different behavior depending on DC voltage and field. However, we can compare performance of various cathodes with respect to their relative life time at the test bench.

We decided to construct a 250-kV, 50-mA DC gun for the demonstration of high-brightness and high-average current beams under more practical conditions than the test bench. Although simulation studies predict normalized emittance of 0.1 mm-mrad is obtained at gun voltage higher than 500 kV[17] [18], we chose a rather low voltage gun, 250 kV, which can be assembled by making best use of spare components available at JAEA-ERL. In the DC gun, we will explore the performance of newly developed photocathode under high-average current and high voltage condition as well as beam diagnosis at the downstream.

PHOTOCATHODE

There are two sources of initial emittance at semiconductor photocathodes. One is thermal motion of electrons which reflects the cathode temperature, and the other is residual energy of photo-excited electrons with respect to the potential of the conduction band. Although the latter is partially compensated during electron diffusion to the surface, the compensation works little for electrons generated near the surface. In previous experiments with polarized electron sources clearly showed the above physics, and initial emittance equivalent to thermal motion at room temperature is only available when the laser photon energy tunes to the band gap energy[15] [16].

Quantum efficiency of NEA semiconductor is proportional to density of state of conduction band and shows a monotonically increasing function of injection photon energy. Operation of high-average current requires electron excitation by photon energy larger than the band gap energy. This behavior of quantum efficiency is incompatible with the criteria for small initial emittance.

We have suggested that the incompatible properties, small emittance and large quantum efficiency, can be obtained concurrently by using a superlattice semiconductor instead of conventional bulk cathodes[19]. In order to promote this strategy, we made a series of experiments with bulk GaAs and bulk AlGaAs, in which quantum efficiency and life time of different cathodes were measured to confirm the predicted relation between the performance of photocathodes and their band structure. From the measurements, it was found that AlGaAs has two times larger quantum efficiency and more than 10 times longer life than GaAs[20]. The large quantum efficiency in AlGaAs is due to its band gap energy 1.79 eV, which is larger than GaAs, 1.42 eV. We can also attribute the improvement of life to the difference of electron affinity, 4.1 eV for AlGaAs and 3.8 eV for GaAs, because the smaller electron affinity results in the lower vacuum potential, i.e. the larger negative electron affinity. As a result of the measurements, we have confirmed that performance of NEA cathode is controllable by tuning the band structure.

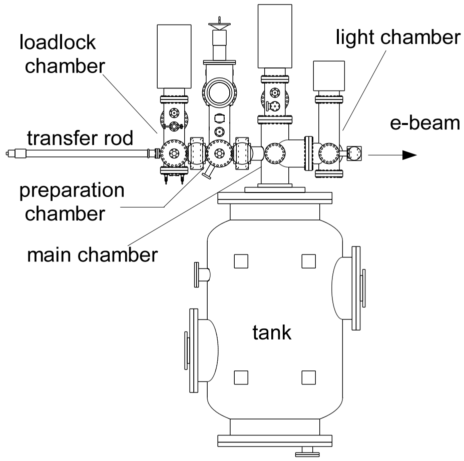

Figure 1: Top-view of the 250-kV, 50-mA gun.

250-KV DC GUN

Figure 1 shows layout of the 250-kV, 50-mA DC gun under construction. A high-voltage generator of Cockcroft-Walton circuit and a ceramic colum are installed in the tank filled with SF_6 gas, and the high-voltage terminal is connecting to a cathode block in the main chamber. In the preparation chamber, a photocathode surface is activated by cesium and oxygen to turn it into the NEA state. A laser light is introduced from the bottom of the light chamber, and an electron beam is extracted to the right side.

A high-voltage test without a beam load was completed [20], and further assembling of vacuum chambers is underway. The first beam extraction is expected around summer of 2007.

We are also designing beam transport and diagnostic systems for the 250-keV beam. A solenoid magnet will be installed at $z = 0.25$ m for emittance compensation and beam focusing at the down stream. The solenoid has a bucking coil to compensate magnetic field at the cathode surface. The beam emittance will be measured by double slit technique. Figure 2 is a result of `PARMELA`[21] simulations for a 250-keV electron beam, where we assume the initial bunch has uniform distribution of 2 mm in diameter for a 77-pC bunch, and 0.6 mm for a 7.7-pC bunch, and Gaussian distribution, $\sigma_t = 14$ ps, in longitudinal direction, electron temperature at the cathode is 30 meV. In fig.2, normalized rms emittance has the minimum value of 0.57 mm-mrad for a 77-pC bunch, and 0.15 mm-mrad for 7.7 pC. The trend of emittance in fig.2 shows somewhat different behavior from well-known emittance dilution by space charge force and its compensation by solenoid magnet, because the electron bunch does not keep its initial temporal profile, rms bunch length at $z = 2.2$ m is 66 ps for 77 pC and 29 ps for 7.7 pC.

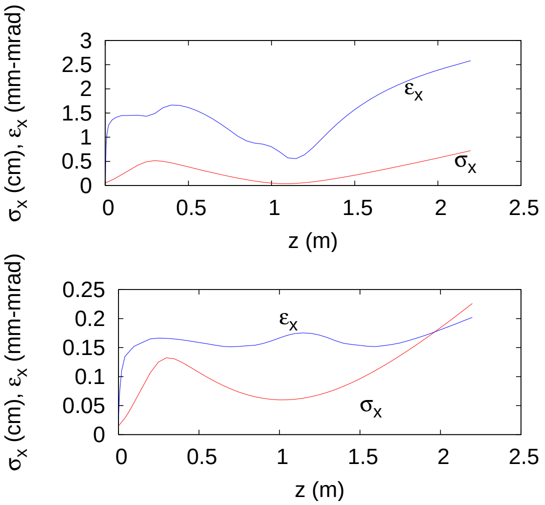

Figure 2: `PARMELA` simulation: Beam envelope and normalized rms emittance of a 250-keV, 77-pC bunch (top) and 7.7-pC (bottom). The cathode is located at $z = 0$ and the solenoid is installed at $z = 0.25$ m.

SUMMARY AND FUTURE PLANS

In JAEA-ERL, we are developing a photocathode DC gun for future ERL light source. Studies at the photocathode test bench have revealed that AlGaAs has higher quantum efficiency and longer life time than GaAs. The better performance of AlGaAs agrees with the theorical prospect that the larger band gap gives the larger quantum efficiency, and the larger electron affinity results in the longer cathode life. We continue further improvement of photocathode including superlattice structure. The 250-kV DC gun is under assembling and the first beam is expected around summer of 2007.

The outcome from the photocathode test bench and the 250-kV gun will be succeeded by a 500-kV gun for the ERL test facility which is to be constructed at KEK site. As for a drive laser for the photocathode gun, we plan to develop a fiber laser system.

The authors would like to acknowledge the contribution of Profs. Y. Takeda, M. Tabuchi for preparing AlGaAs and GaAs photocathodes under a collaboration program between JAEA and Nagoya University. This work was supported in part by MEXT KAKENHI (18740253).

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