STUDY OF PHOTO-CATHODE RF GUN FOR A HIGH BRIGHTNESS ELECTRON BEAM

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Abstract

A test bench for multi-bunch photo-cathode RF gun has been developed at KEK-ATF for industrial and medical applications in collaboration among JNC, NIRS, and KEK [1]. Before the test bench study, we examined high peak charge operation by using RF gun on KEK-ATF injector, which is the same as the test bench RF gun. This RF gun has been working in KEK-ATF injector since autumn in 2002. In this report, test results of high charge electron emission from the RF gun are described. Preliminarily a high charge of 4.8nC in the single bunch mode was produced from the RF gun at the maximum field of 100MV/m on the cathode surface.

INTRODUCTION

Since RF guns were invented two decades ago, RF guns have introduced into many applications not only as low emittance electron sources for linear colliders and FELs, but also as injectors for electron storage rings. RF guns are the best selection to produce high charge electron beams of more than 1nC with low emittance less than 10πmm.mrad, because of suppression of the emittance growth due to the space charge effect by the high field gradient acceleration. Now there are two choices of the cathodes for a RF gun: thermionic and photo-emission cathode. A photo-cathode RF gun is very feasible for many applications. It is possible to obtain high peak charge, low emittance, and easily controllable pulse duration by using laser pulse.

In KEK-ATF, since autumn of 2002, the thermionic gun was replaced by a photo-cathode RF gun. The high quality electron beam has been generated by the RF gun, which dramatically decreased the radiation level due to loss of beams during the acceleration, transportation, and injection to the damping ring. This gun is 1.6-cell S-band cavity so-called BNL-IV, which is attached Cs-Te as a photo-cathode with load-lock system [2][3]. This photo-injector can provide up to 20 bunches of 1nC per bunch with 2.8nsec spacing into the ATF damping ring.

On the other hand, the new test bench has been constructing since 2003. It consists of the same as KEK-ATF RF gun, a multi-bunch laser, and diagnostics. Beam specifications are as follows: maximum charge of 5nC per bunch, 100 bunches with 2.8nsec duration, and macro pulse repetition of 12.5pps. We aim at optimisation of beam condition to reduce emittance and energy spread of beam. As the first step for the high-brightness beam generation, we studied the high charge emission from the Cs-Te cathode in the RF gun. We measured charges extracted from the RF gun by using a faraday cup as functions of the laser injection phase and RF input power.

THEORY OF ELECTRON EMISSION FROM THE RF GUN

Kim has made a very important theory about the RF gun [4]. However, this theory is limited within a narrow region. Gao has provided revised formulas to apply it various conditions for the RF gun [5][6]. Briefly the basic formulas are introduced as follows. The electric field on the axis of a standing wave in a BNL-type RF gun is expressed as

$$E_z(z,t) = E_0 \cos(kz)\sin(\omega t + \phi_0) \qquad (1)$$

where $z = 0$ corresponds to the cathode surface, ω is the angler frequency, k is the wave number of $k = 2\pi/\lambda$, λ is the electromagnetic wavelength. E_0 is the maximum field at the cathode surface. If ϕ_0 is the initial phase, which means the injection phase when the laser arrives at the cathode, the final phase ϕ_f at the exit of the gun is

$$\phi_f(\phi_0) = \frac{1}{\alpha \sin(\phi_0 + \frac{\sqrt{2\pi}}{6\sqrt{\alpha}})} + \phi_0 + \frac{2\pi}{15\alpha} \qquad (2)$$

$$\alpha = \frac{eE_0}{m_0 c^2 k} \qquad (3)$$

Fig.1 shows the final phase as a function of the injection phase. Assuming that the asymptotic phase is almost reached near the cathode region, the gamma factor of the energy at the exit of the gun as a function of the initial phase $\gamma(\phi_0)$ is solved as

$$\gamma(\phi_0) = 1 + \frac{\alpha}{2}\left(kL\sin(\phi_f) + \frac{1}{2}\left(\cos(\phi_f) - \cos(\phi_f + 2kL)\right)\right) \qquad (4)$$

where L is the length of the n+1/2 cell RF gun cavity. For example, Fig. 2 shows the output beam energy vs. the initial phase at the maximum field of 100MV/m on the cathode. If a laser pulse length of $\Delta\phi_0$ is measured in the RF phase, one can get the energy spread $\Delta W(\phi_0)$ and the dispersion $\Delta W(\phi_0)/W(\phi_0)$ of the bunch, and the bunch length $\Delta\phi_f(\phi_0)$ at the exit of the gun, respectively as

$$\Delta W(\phi_0) = m_0 c^2 \frac{d\gamma(\phi_0)}{d\phi_0} \Delta\phi_0 \tag{5}$$

$$\frac{\Delta W(\phi_0)}{W(\phi_0)} = \frac{1}{\gamma(\phi_0)} \frac{d\gamma(\phi_0)}{d\phi_0} \Delta\phi_0 \tag{6}$$

$$\Delta\phi_f(\phi_0) = \frac{d\phi_f(\phi_0)}{d\phi_0} \Delta\phi_0 \tag{7}$$

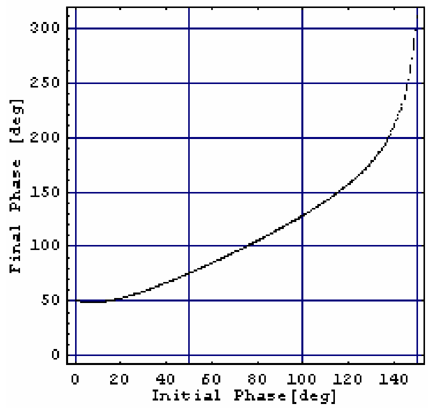

Fig.1: The final phase vs. the injection phase.

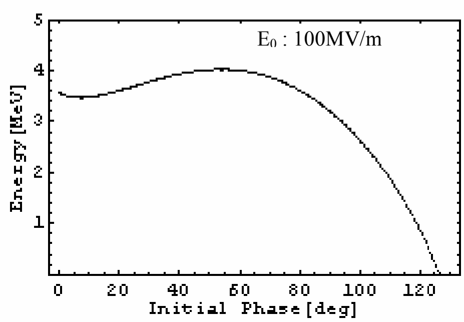

Fig.2: Output energy at the maximum field of 100MV/m vs. the injection phase.

If high field gradient is applied onto the cathode surface, the emission from the cathode is enhanced due to the Schottky effect. The change of the work function $\Delta\Phi$ is

$$-\Delta\Phi = e\sqrt{\frac{eE_C}{4\pi\varepsilon_0}} \tag{8}$$

where E_c is the electric field on the cathode, and ε_0 is the permittivity of vacuum. The ratio of the quantum efficiency including the Schottky effect QE and the one without it QE_0 is

$$\frac{QE}{QE0} = \exp\left(-\frac{\Delta\Phi}{kTe}\right) = \exp\left(\beta\sqrt{E_c}\right) \tag{9}$$

$$\beta = \frac{e}{kT_e}\sqrt{\frac{e}{4\pi\varepsilon_0}} \tag{10}$$

where kT_e is the thermal energy of the electron emitted from the cathode[7]. The electric charge Q_0 produced from the cathode as the function of the laser energy invested onto the cathode W_L and laser photon energy $h\nu$ is as follows : [6]

$$Q_0(\phi_0) = e\frac{W_l}{h\nu} QE_0 \exp\left(\beta\sqrt{E_0 \sin(\phi_0)}\right) \tag{11}$$

EXPERIMENTAL RESULTS AND DISCUSSIONS

Maximum emission charge from the cathode

If the charge density extracted from the cathode is too high to affect longitudinal accelerating field by the space charge force, the extractable charge is saturated. Supposing that the peak charge density near the cathode can be expressed by a gaussian transverse distribution, the maximum extractable charge[8] is

$$Q_{\max}(\phi_0) = 2\pi\sigma_x^2 \varepsilon_0 E_0 \sin\phi_0 \tag{12}$$

where σ_x is the beam size on the cathode corresponding to the laser spot size. By using eq.(12), Fig.3 shows predictions for the maximum extractable charge vs. the initial phase as a function of the beam size.

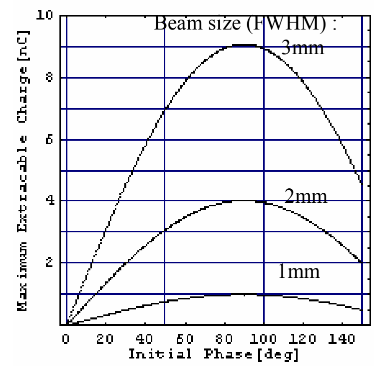

Fig.3: Predictions for the maximum extractable charge vs. the initial phase as the function of the beam size.

We observed saturation for extracted charge from the Cs-Te photo-cathode. In the condition of the maximum electric field of 100MV/m on the cathode, a faraday cup measured charges emitted from the RF gun after the solenoid magnet. The solenoid magnet was adjusted not to escape parts of the electron beam from the faraday cup. The laser wavelength is 266nm and the laser pulse width was about 10psec in FWHM. The laser spot size was about 2mm diameter in FWHM. As shown in Fig.4, it seems that the extracted charge is saturated at the laser power of 2 μ J per bunch, which agrees with the predictions shown in Fig.3.

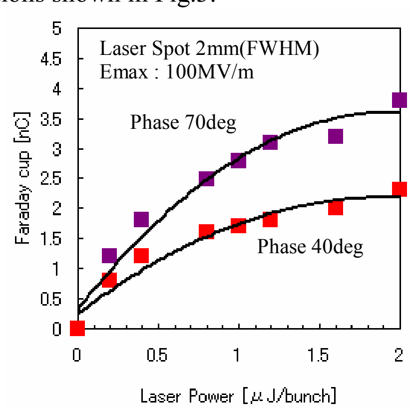

Fig.4: Emitted charge from the RF gun vs. laser power to the cathode with a spot size of 2mm(FWHM).

Estimation of Quantum Efficiency

We measured the emission charge from the photo-injector of KEK-ATF used Cs-Te photo-cathode. Fig. 5 shows an example of measurements for emission charge vs. laser phase. The quantum efficiency measured by UV light of a Xe lamp was kept about 1% for a few months. Therefore, the cathode could use continuously for the operation of the accelerator. As known from eqs.(9) and (10), the quantum efficiency QE_0 without the Schottky effect and the enhancement factor β are obtained by plotting ln(QE) vs. $\sqrt{E_c}$, where QE is calculated by eq.(11). Fig.6 shows the plots of ln(QE) vs. $\sqrt{E_c}$ observed at the plural dates. Each data was normalized to be able to compare with the quantum efficiency. Data points of the region between 20 and 70 degree where slope is almost linear as shown in Fig.5 were used for the analysis, because all electrons in the region can accelerate from the cathode surface to the exit of the gun. We obtained that QE_0 is value between 0.7% and 1.9%. The numerical value of β is between 0.07 and 0.25. Both results were included very large errors by different conditions.

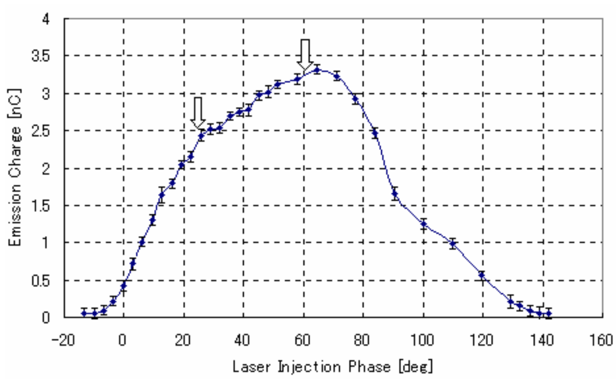

Fig.5: Emission charge vs. laser injection phase at the date of 4/16. Data points between two arrows was used for the Plot of lnQE vs. E^1/2.

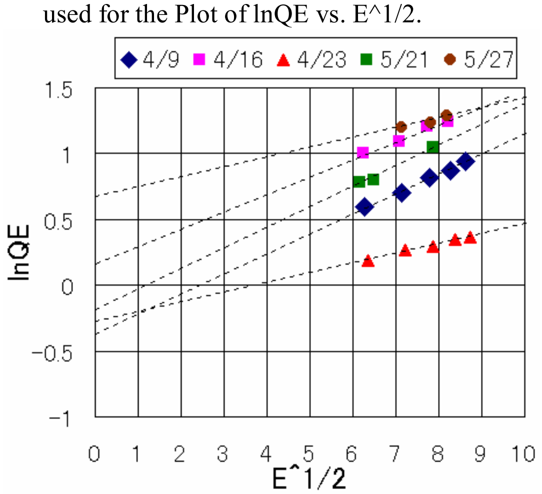

Fig.6: Plot of lnQE vs. E^1/2 to estimate the quantum efficiency QE_0.

Preliminary Test of High Charge Emission

Preliminarily we tried to demonstrate the highest charge generation from the RF gun within the limits of the official approval for radiation. The maximum charge until 4.8nC is allowed to accelerate from the gun. The maximum electric field on the cathode was 100MV/m. The intensity of laser pulse was about 1.6 μ J per bunch with a pulse width of 10psec in FWHM. The conditions of laser, such as spatial size and distribution, influenced the extractable emission. Although we could not get accurate values for the laser parameters, a high charge emission of 4.8nC at maximum, which is almost the aim value in our RF gun test bench, was produced in this test.

SUMMARY

As the first step for the high-brightness beam generation, we demonstrated high charge production from the Cs-Te cathode in the RF gun. We also observed saturation phenomena of the charge emission from the photo-cathode in some laser condition. In the near future, we will complete construction of the exclusive RF gun test bench. We will be able to examine the detail study on RF gun performance. In this test bench, our purpose is to produce high intensity multi-bunch beam with low emittance and small energy spread. We plan to make longitudinal bunch compression by the low phase injection without the emittance growth[1].

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