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# Electron emission characteristic of CsTe photo-cathode in RF gun

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*Abstract*

As the electron source, CsTe cathode is used in the routine operation of KEK-ATF (Accelerator Test Facility). The stable operation is realized by the good performance of the cathode, i.e. a high quantum efficiency, QE more than 1% and a long life time more than a month, at least. QE is usually measured off line, at low surface electric field with Xe UV-lump flushing, but QE is much influenced by the surface field known as Shotkky effect. Therefore, QE measured off line may be much different from that in operation. We measured QE of CsTe cathode in the real operation by varying the laser power. Variation of QE as function of surface field was also observed by changing the laser injected RF phase. As predicted by several theories, QE in the operation was much higher than that off line.

## INTRODUCTION

KEK-ATF was established for R & D of Global Linear Collider, GLC project. The purpose of ATF is to prove the super-low emittance multi-bunch beam with a damping ring. To generate the multi-bunch electron beam in ATF Linac, the photo-cathode RF gun is employed.

CsTe is originally developed by CERN[1] as the high QE cathode material. KEK-ATF and Nagoya university collaborated to apply this material as the cathode in the photo-cathode RF gun. In ATF, this cathode is routinely used as the primary electron source. The beam property generated by the RF gun meets the requirements as ATF injector. For details, see ref. [2].

QE of the cathode was usually more than 10% initially, but it decreased rapidly and converged around 1%.[3] It was confirmed that this 1% QE was kept more than two months. Therefore, after the initial drop, the cathode life time is not able to be defined, that means it looks infinite.

QE is usually measured off line, at low surface electric field with an Xe-UV lump flushing. QE is, however, much influenced by surface field known as Shotkky effect. Therefore, the off-line QE may be much different from that in the actual operation. The purpose of this article is to extract QE at the operation and connect it to that off line. To do that, the QE behavior have to be understood, especially on the surface field dependence.

Based on a basic formalism, the emission from a photo-cathode material , $J$ is expressed as;[4]

$$J = AT^2 \exp\left(\frac{h\nu - \phi}{kT}\right), \qquad (1)$$

where $A$ is thermionic emission constant, $T$ is temperature, $h\nu$ is energy of a laser photon, $\phi$ is work function, and $k$ is Boltzmann constant. If the Shotkky effect caused by an external field is introduced, the work-function is corrected to be a function of the field as

$$\phi(E) = \phi_0 - \sqrt{\frac{e\beta E \sin\theta}{4\pi\epsilon_0}}, \qquad (2)$$

where $\phi_0$ is the work-function at zero surface field, $\beta$ is the field enhancement factor that is determined by the surface condition, $E$ is amplitude of the surface field, and $\theta$ is the phase of the oscillated field. Assuming these equations, QE as function of the surface field is expressed as,

$$QE(E) = QE_0 \exp\left(\frac{1}{kT}\sqrt{\frac{e\beta E \sin\theta}{4\pi\epsilon_0}}\right), \qquad (3)$$

where $QE_0$ is QE at zero surface field.

If we take logarithm of Eq. 3, it gives

$$\ln QE(E) = \ln QE_0 \frac{1}{kT}\sqrt{\frac{e\beta}{4\pi\epsilon_0}}\sqrt{E\sin\theta}, \qquad (4)$$

that means $\ln QE(E)$ is expressed as a straight line function with respect to root of the effective surface field, $E\sin\theta$.

## THE SYSTEM

The RF gun system of KEK-ATF is schematically shown in Fig. 1. The RF gun cavity is based on the 1.6 cells BNL gun IV. The cavity is modified to set the cathode plug on the end plate. The cathode plug is made from Mo. Cs and Te are evaporated on its surface to form CsTe as the cathode material in a different vacuum chamber. The evaporation chamber and the gun cavity is connected with vacuum

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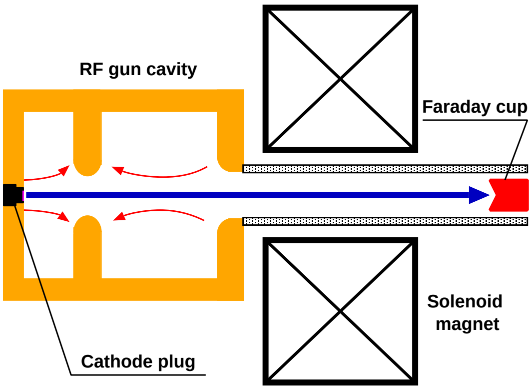


Figure 1: Schematic view of ATF RF gun system. BNL gun IV type cavity was modified to mount the cathode plug on the end plate. The gun is followed by a solenoid magnet to control the beam size and emittance. For the emission measurement from the gun, a Faraday cup is inserted onto the beam line.

pipes so that the cathode plug is transported into the gun cavity without air exposure. It is known that CsTe is affected by air exposure, that is why this system is used. For the evaporation and transported system called by Load-lock chamber, see ref [3].

The multi-bunch beam is produced by illuminating multi-pulse laser with 2.8 ns spacing. The laser wave length is 266nm in UV. Each pulse has typically power of 2-3 $\mu J$ , 10 ps pulse width. Number of pulses is determined by timing of the pulse clipping by Pockels cell. The number of bunches is then varied by changing the clipping timing from 1 to 20. The maximum bunch number, 20 is limited by the radiation safety regulation. The laser power is controlled by the laser power regulator that is composed from a rotational $\lambda/4$ plate and a polarized splitter. The transmission efficiency of the splitter is varied by the laser polarization determined with the plate angle.

The phase and power of input RF to the gun cavity is controlled by a mechanical phase shifter and attenuator. The power is usually 7 - 8 MW that corresponds to 90 MV/m surface field at the maximum phase.

The emission current is measured by the Faraday cup, FC inserted onto the beam line at need. The solenoid focusing is originally employed to correct and optimize the beam emittance, but it is used to control the beam size to catch all of the beam in this study.

## QE MEASUREMENTS AND ANALYSIS

QE is defined as ratio of numbers of emitted electrons and injected laser photons. QE in % is expressed with the conventional parameters as[4];

$$QE[\%] = \frac{128.3 I[nA]}{\lambda[nm] P[\mu J]}, \qquad (5)$$

where $I$ is emitted current of the electron beam in nA, $\lambda$ is wave length of the laser light in nm, $P$ is power of the laser light in $\mu J$. This expression assumes a linear response of the photo-electron effect. Empirically, it is known that QE is generally a function of the emitted current. In that case, it would be better to use a alternative definition of QE in derivative as;

$$QE(I) = \frac{123.8}{\lambda}\frac{\partial I}{\partial P}, \qquad (6)$$

where the units are same as in Eq. 5 In this article, QE at zero emission, i.e. $QE(I = 0)$ is employed as the reference.

To extract Q.E, the laser power and the emission current have to be measured. The laser power is initially calibrated by a laser power meter at the position of the laser beam line closest to the cathode with 100% transmission of the laser power regulator. The actual laser power is estimated to be $P_f \times T_r$ where $P_f$ is the calibrated laser power and $T_r$ is the laser transmission that is determined by the angle of the $\lambda/4$ plate in the laser power regulator. The $T_r$ can be controlled and monitored in our integrated system.

The emission beam current is measured by FC. To measure the emission current correctly, all of the electrons have to be captured. Because the optimized strength of the solenoid focusing depends on the beam energy, the optimized solenoid current is functions of the input RF power and its phase because the beam energy depends on not only the input RF power, but also the RF phase when the laser is illuminated. The signal from FC is sent to ADC to digitize its charge. The data is then corrected and recorded.

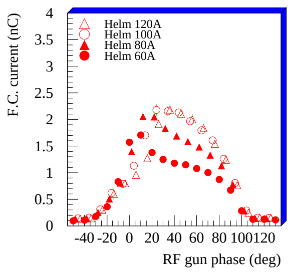


Figure 2: Emission current as function of the laser injection RF phase with different focusing strengths. The laser power was $0.45 \mu J/bunch$.

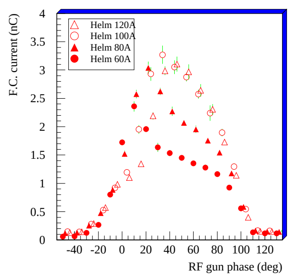


Figure 3: Emission current as function of the laser injection RF phase with different focusing strengths. The laser power was $0.75 \mu J/bunch$.

Fig. 2 and 3 show the emission current with 0.45 and 0.75 $\mu j/bunch$ laser power as function of RF phase with respect to the laser injection timing. Data sets with various focusing strength of the solenoid magnet are drawn together. The error bars are statistics only. From these figures, the emission depends on not only the laser power, but also the RF phase. This phase dependence can be explained as several effects as discussed later .

On the same RF phase, the measured current also depends on the focusing strength as expected. Since with the optimized strength the total current is supposedly captured by FC, the maximum data point among those by variety of focusing strengths is taken as its representative on that phase. Fig 4 shows these representative data as function of RF phase with three different laser power, 0.75, 0.45, and 0.15 $\mu J/bunch$.

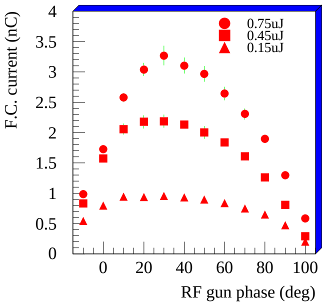


Figure 4: The emission current as function of the RF phase. Among those by the various solenoid currents the maximum current is plotted as the representative on that phase.

From these data QE was extracted. Fig 5 and 6 show examples the emission as function of the laser power at 10 and 70 degree laser injection phase respectively. The fit curve is evaluated by assuming a second order polynomial function with a constraint on zero emission at zero laser power. According to Eq. 6, the QE at zero emission is obtained as its derivative, i.e. the coefficient of the first order of the fit curve.

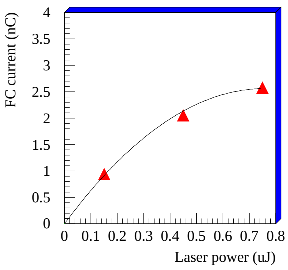


Figure 5: The emission at 10 deg. laser injection RF phase as function of the laser power.

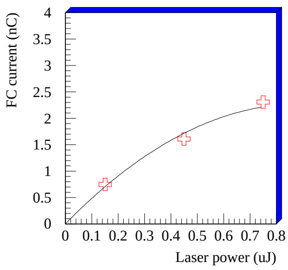


Figure 6: The emission at 70 degree laser injection RF phase as function of the laser power.

Fig. 7 shows QE as function of the laser injection RF phase. The error bars show the ambibuity on the QE evalution with the fitting. The curve is obtained by fitting the data to Eq. 3. The maximum QE of 3.0% was recoreded

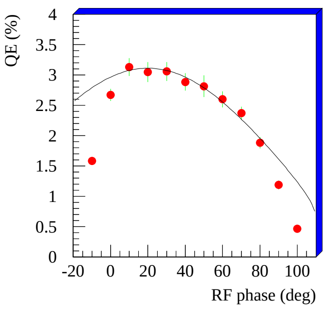


Figure 7: QE as function of the laser injection RF phase. The maximum QE was obtained as 3.0% around 20 degree.

around 20 degree. This is much higher than that measured under the low surface field environment, 1.0% as expected. One can also see easily on this figure that the data are not consistent to the theoretical curve at the lower and higher phase region.

Basically, QE may be influenced by the surface field, surface charge limit effect, space charge limit effect, dynamics in RF field, etc. In the theory used in this fitting, only the effect of the surface field known as Shotkky effect is assumed. The surface charge limit will be appeared as a saturation of the emission current with an increase of the emission. Most of this effect could be removed by taking QE at zero emission. It is also true for the space charge limit, in addition, this effect is expected to be very small at such high electric field.

The last candidate is the dynamics in RF field. This effect is that a part of the beam could not reach to the exit of the gun. As long as the surface field is in the ordinal direction, the electron can be escaped from the inside of the material to the outer space. Even though, if the beam is emitted on some phase, the RF field is reversed before all of the beam is transmitted into the second cell. In that case a part of the beam is decelerated and will be lost resulting a lower emission.

This effect is dominant in phase where the surface field is small. The region where the data are not fit well, can be considered as such region. To suppress this effect onto the fitting, the fit is actually performed with the data points from 10 to 80 degree.

QE at the zero surface field limit, $QE_0$ was evaluated from this fit to be $0.64 \pm 0.16(\%)$. As a biproduct, the absolute RF phase origin giving $\sin\theta = 0$ was determined to be $110 \pm 5 \circ$ in the current phase scale.

The obtained $QE_0$ was inconsistent to that measured under the low surface field. This inconsistency is not understood yet. It may be related to some inner structure of CsTe because a simple metal like structure is assumed in our study. Anyway, It is one of the future issues.

## SUMMARY

QE of CsTe cathode in RF gun at the operation condition was evaluated as the derivative of the emission current with respect to the laser power. For the QE at the zero emission limit, the results are much higher than that measured under the low surface field as expected. The surface field dependence of QE can be explained with the simple model including the Shotkky effect where the surface field is high, but some inconsistency was observed where the surface field was relatively low.

QE at the zero surface field limit was evaluated to be $0.64 \pm 0.16(\%)$ that was not consistent to 1.0%, measured off line with Xe lump. It is a future issue to understand this inconsistency.

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