STUDIES ON FACTORS AFFECTING THE LIFE-TIME OF HIGH AVERAGE CURRENT G A PHOTOCATHODE *

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Abstract

The negative electron affinity (NEA) GaAs photocathode has been demonstrated as an important electron source for high average current accelerators, such as the free electron lasers (FELs) based on energy recovery linacs (ERLs). To increase the life-time of NEA-GaAs, some factors are studied in this paper, such as the vacuum pressure around the cathode, the temperature of the cathode surface and the ion back-bombardment inside DC gun. With these studies, some strategies are applied on the photocathode injector of FEL-THz facility. The cathode operation life-time has been improved at least two orders of magnitude.

INTRODUCTION

High average power high-brightness electron source plays a significant role in the path to the realization of the future high repetition short-wave free electron lasers (FELs) and energy recovery linacs (ERLs) [1]–[9]. The negative electron affinity (NEA) GaAs photocathode has been demonstrated as an important electron source in recent years. On the one hand, GaAs has many advantages, such as high Quantum Efficiency (QE), low work function, low thermal emittance, et al [10]. On the other hand, it is sensitive to vacuum, temperature and ion back-bombardment, which are considered as the three most important factors affecting the life-time of the cathode [11]–[14]. Although the DC gun with NEA GaAs photocathode is being developed in many laboratories [15]–[19], little literature mentioned all the three factors and considered them together.

FEL-THz facility is the first high average Tera-Hertz source based on FEL in China [20, 21]. A long operation time (>0.5 h) as well as a high average-current (1∼5 mA) is needed for the FEL-THz injector, which is the Chinese first high-voltage DC injector with NEA GaAs photocathode activated by Cs/O YOYO method [22, 23]. In this paper, based on some previous effects that many laboratories have made [24]–[28], a preliminary physical model is established to consider the vacuum, temperature and ion back-bombardment factors all together. With this model, several problems of the FEL-THz injector have been found. Great efforts in the injector optimization have been made and some strategies have been applied on the injector. With these works, the operation life-time has been improved at least two orders of magnitude.

PHYSICAL MODEL

When the drive laser power is constant, the operation life-time τ is defined as the time during which the injector output current decays to $1/e$ of the maximum value. The QE decays for three reasons, as shown in Fig. 1. Firstly, in a vacuum system, toxic gas molecules like H_2O or CO, will be absorbed on the surface of cathode and poison the activation layer. Secondly, thermal energy through laser power will break the chemical bonds of Cs and O. Thirdly, ions, like H^+ or H_2^+ generated by the collisions between electron beam and gas molecules, will bombard the cathode surface.

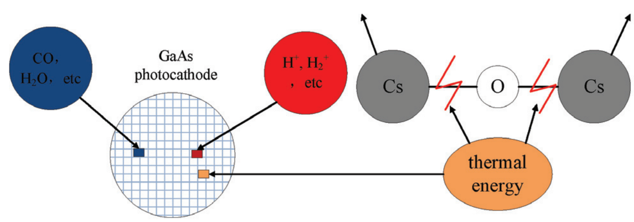

Figure 1: Diagrammatic sketch of factors affecting the life-time of GaAs photocathode.

In order to describe these processes, the GaAs photocathode is divided into many activated regions with a total number m [29]. Each region is much larger than a signal Cs-O dipole. When a region is inactivated by any reason above, it lose its ability to generate electron immediately. $\theta(t)$ is the ratio between the remaining activation region area and the total area.Assuming that the QE has a maximum value η_0 at $t = 0$, then $\theta(0) = 1$, $\eta(t) = \eta_0\theta(t)$, and current $I(t) = I_0\theta(t)$. The three factors will be discussed separately below.

Vacuum

In literature [24], the dark life-time at constant temperature is almost inversely proportional to the pressure p, i.e. $\tau_p \propto p^{-1.01}$, experimentally. Here we assume that kp is the collision times between toxic gas molecules and cathode surface per unit area per unit time, and A is the probability the molecules inactivating one region. Based on these

* Work supported by China National Key Scientific Instrument and Equipment Development Project (2011YQ130018), National Natural Science Foundation of China with grant (11305165) and CAEP development grants (2013B0401073, 2014B0402069, 2014B0402070)

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ISBN 978-3-95450-171-7

assumptions, a differential equation can be written as

$$\frac{\mathrm{d}\theta}{\mathrm{d}t} = -\frac{Akp}{m}\theta. \tag{1}$$

Then QE becomes

$$\eta_p = \eta_0 \exp\left(-Akpt/m\right). \tag{2}$$

And the life-time affected by vacuum pressure is

$$\tau_p = m/(Akp). \tag{3}$$

Temperature

Desorption of Cs atom caused by thermal energy is a Temperature Programmed Desorption (TPD) process. Literatures [26, 27] have proved that the QE would be

$$\eta_T(t) = \eta_0[1-(1-n)k_n t]^{\frac{1}{1-n}}, \tag{4}$$

where $k_n = \nu_n \exp\left[-E_a/(RT)\right]$, E_a is the activation energy, R is gas constant, T is the cathode temperature, n is the order of chemical reaction, and ν_n is the pre-exponential factor.

So the life-time affected by cathode temperature is

$$\tau_T = \left(\frac{e^{n-1}-1}{n-1}\right)\nu_n^{-1}\exp\left(\frac{E_a}{RT}\right). \tag{5}$$

Ion Back-bombardment

When the vacuum and temperature are constant, the colliding gas molecule number per unit time is proportional to current and pressure. We assume that $\beta_0 pI$ is the positive ion generation rate, and i the probability that one ion inactivating one region. So we get

$$\frac{\mathrm{d}\theta}{\mathrm{d}t} = -\frac{i\beta_0 pI\theta}{m}. \tag{6}$$

The current

$$I(t) = \frac{e_0}{h\nu}\eta(t)P = \frac{e_0}{h\nu}\eta_0 P\theta, \tag{7}$$

where $h\nu$ and P are photon energy and average laser power, separately. e_0 is the charge of a single electron.

Frome (6) and (7), the QE would be

$$\eta_B(t) = \frac{\eta_0}{1+\kappa t/m}, \tag{8}$$

where $\kappa = e_0\eta_0 i\beta_0 pP/(h\nu)$. And life-time is

$$\tau_B = \frac{m}{\kappa}(e-1). \tag{9}$$

Operation Life-time

The probabilities of QE decaying caused by the three reasons above are considered as independently. So the operation QE would be

$$\eta(t) = \frac{\eta_0[1-(1-n)k_n t]^{\frac{1}{1-n}}}{1+\kappa t/m}\exp\left(-\frac{Akpt}{m}\right). \tag{10}$$

And life-time

$$\tau = \left(\frac{1}{\tau_p}+\frac{1}{\tau_T}+\frac{1}{\tau_B}\right)^{-1}. \tag{11}$$

In logarithmic coordinate, equation (10) becomes

$$\begin{aligned}\ln\eta(t) = \ln\eta_0 - \tfrac{Akpt}{m} - \ln(1+\kappa t/m)\\ -\tfrac{1}{n-1}\ln\left[1+(n-1)k_n t\right]\end{aligned}. \tag{12}$$

(12) is the main equation that we observe the operation status of DC injector and its GaAs photocathode. It implies that when the current-time curve decline as a straight line in logarithmic coordinate, the vacuum would be the main reason for the QE degradation. And a logarithmic curve means that the temperature and ion back-bombardment are the main reasons.

EXPERIMENTAL PROGRESS

Layout of FEL-THz DC photocathode injector is shown in Fig. 4, and the parameters in Table 1. E_k, f, I, t_o are beam kinetic energy, repetition rate, output current and operation time, separately. λ_l is laser wavelength.

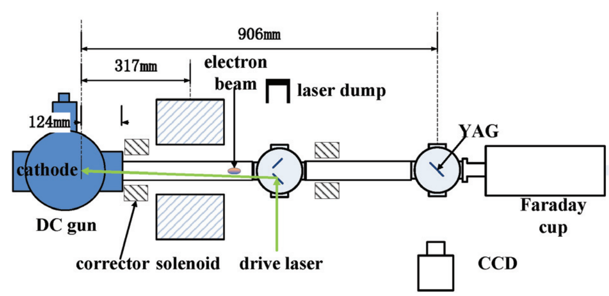

Figure 2: Layout of DC photocathode injector.

Table 1: Main Parameters of FEL-THz CW DC Injector

E_k/keV	f/MHz	I/mA	t_o/h	λ_l/nm
200∼350	54.167	1∼5	>0.5	532

Initial Status

In the first beam output experiment, drive Laser with about 1 W power was used and the lift-time was only about 50 s, as shown in Fig. 3.

At first, the current declined as an approximate logarithmic curve. Then it became a straight line in logarithmic coordinate. This implied that the main reason is the vacuum pressure. The pressure in the first experiment was not measured property. When the current is relatively small the pressure in the DC gun was recorded in Fig. 3(b). The vacuum dramatic declined in only one minute, which means lots of electron lost in the beam tube around cathode. In Fig. 3(a), the life-time declined while the laser power increased, which means the temperature raised a lot.

ISBN 978-3-95450-171-7

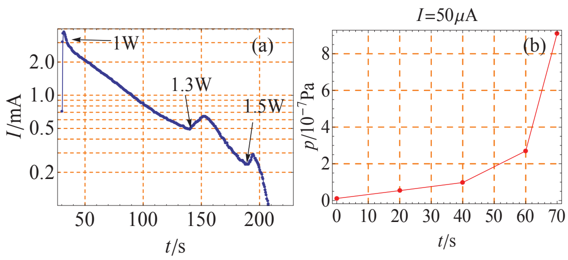

Figure 3: The first beam output experiment: (a) current, (b) vacuum.

Optimization Strategies

Based the phenomena in Fig. 3, some strategies were applied to optimize the injector working status and cathode operation life-time.

Firstly, we degraded the ghost pulses for the diagnostics of macro-pulses. The details can be found in [30].

Secondly, to improve the vacuum condition, dimensions of electron transport tube and the anode hole was enlarged; and more correctors were applied in the beam line. More information is in [31]. After these efforts being made, the current and pressure were improved as in Fig. 4.

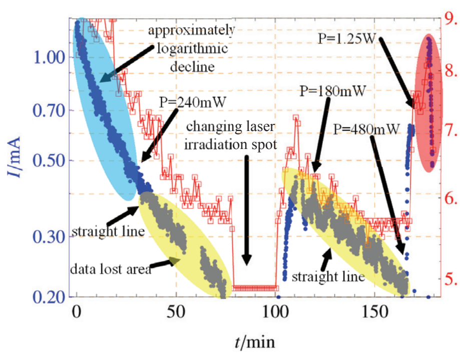

Figure 4: Current and pressure after vacuum condition improved.

In Fig.4, when the laser power was less than 480 mW, $\tau \sim 1$ h. The vacuum was better than 10^{-8} Pa in the gun. When the current is lager than 0.5 mA and vacuum worse than 6×10^{-9} Pa, the curve is like logarithmic (blue area in Fig. 4). When the laser power and current is relatively low, the current curve was almost straight lines (yellow area), which means the vacuum was the main factor then. When the laser power is raised to 1.25 W, the life-time came back to a few seconds. This phenomenon can be explained that the ion back-bombardment was the main factor in the blue area, while the temperature was mainly in the red area.

Thirdly, to reduce the surface temperature, the cathode was welded to the wafer. In a relatively adiabatic environment, the temperature rising with different laser power was measured by an infrared thermal camera. The results implied that the time to reach thermal equilibrium last about 7 times longer when the GaAs cathode was welded with indium. More details can be found in [32]. After the indium welding, one of the current curve is shown in Fig. 5. The green spot in gray circle represent the laser position on the cathode. The experiment implied that the life-time remained lager than 0.5 h when the laser power is lager than 1.25 W.

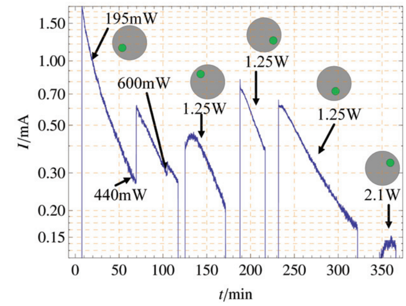

Figure 5: Current output after surface temperature reduced.

Present Status

Present status of FEL-THz DC injector is shown in Fig. 6. With the life-time physical analysis and some optimization strategies, stable high average power electron emission phenomena of 1 mA/3.3 h, 3 mA/1.4 h and 5 mA/0.5 h were achieved, respectively. More research on ion back-bombardment is on the way right now, some of which are posted in [33].

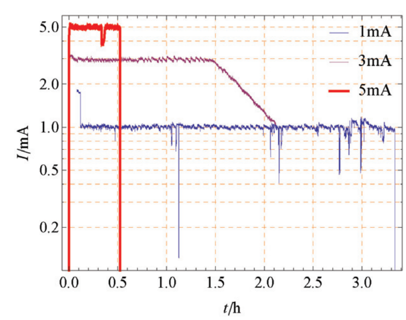

Figure 6: Present status of FEL-THz DC injector.

SUMMARY

In this paper, three factors affecting GaAs photocathode life-time are studied, including vacuum, temperature and ion back-bombardment. A preliminary physical model on the operation life-time of GaAs photo-injector is established. With this model, some efforts to improve the operation life-time of GaAs photocathode in FEL-THz facility are briefly introduced, such as the optimization of electron transport tube's dimensions to improved the vacuum condition and cathode's indium welding to reduce the surface temperature. Though these efforts, a 5 mA over 0.5 h electron emission phenomenon is observed and the preliminary operation condition of FEL-THz facility is achieved.

ISBN 978-3-95450-171-7

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ISBN 978-3-95450-171-7