# INVESTIGATION OF NON-RECTANGULAR RF PULSE INFLUENCE IN EMITTED ELECTRON BEAM OF THE THERMIONIC RF-GUN AT THE LINAC-BASED THZ FACILTY IN THAILAND

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*Abstract*

An electron gun of a linac-based THz radiation source at the Plasma and Beam Physics (PBP) Research Facility at Chiang Mai University (CMU) in Thailand is a 1-1/2 cell S-band standing wave RF cavity with an Os/Ru coating tungsten dispenser cathode. The electron current density of a few A/cm$^2$ can be achieved from zero-field thermionic emission using this cathode type at a desired operating temperature. However, non-rectangular RF pulse shape has a significant influence on the acceleration of electrons inside the RF cavity, which leads to the properties of the output electron beam from a thermionic RF-gun. Numerical and experimental studies on the contribution of the effect have been carried out. Results of the investigations are presented and discussed in this contribution.

## INTRODUCTION

A thermionic cathode RF-gun is widely used as a promising electron source for a linac-based accelerator due to its compact, economical and easy operation system. It can produce output electron bunches with higher brightness than DC electron guns with no additional buncher system. It also does not require an expansive high power laser system like in the case of a photo-cathode RF-gun. However, due to the high accelerating gradient at the cathode surface some fraction of electrons emitted late in the RF oscillating cycle feel a decreasing accelerating field and do not exit from the gun before the RF field reverses its direction. These electrons are decelerated back to hit the cathode at high energies leading to a serious disadvantage of the thermionic RF-gun called electron back-bombardment effect.

For an RF-gun of a linac-based THz radiation source at the PBP facility, the electron back-bombardment limits a stable operation with an RF pulse length longer than a few microseconds. The RF pulse length has been shortened in order to reduce the influence of this effect to achieve a more stable beam operation. The drawback of the shortened RF pulse length at our facility is a non-rectangular RF pulse shape. The influence of the non-rectangular RF pulse on the electron beam properties have been investigated in order to improve the performance of the thermionic RF-gun and to accumulate the information for the future upgrade of the RF system.

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## THERMIONIC EMISSION IN RF-GUN

The thermionic cathode of the RF-gun at the PBP-linac facility is a tungsten dispenser cathode with Os/Ru coating model 101207, which is commercially available from the HeatWaves Lab Company [1]. Pure tungsten has a work function of 4.5 eV. After the proper activation by heating the cathode to have a temperature above 1050 °C, the work function of the cathode material lowers from 4.5 eV to 2.1 eV [2]. Applying an Os/Ru coating at the cathode surface leads to the lower work function of 1.9 eV. Specifications of the thermionic RF-gun at the PBP-linac facility are listed in Table 1.

Table 1: Specifications of the Thermionic Cathode

| Parameter | Value | |
|---|---|---|
| Emitting surface diameter | 6 | mm |
| Os/Ru coating thickness | 0.3-0.5 | μ m |
| Cathode work function | 1.9 | eV |
| Emissivity at $\lambda$=0.65 μm | 0.44 | |
| Cold resistance at 20°C | 0.54 | Ω |
| Hot resistance in operation | 2.2-2.3 | Ω |
| Nominal filament power in operation | 13.4-13.8 | W |
| Operating temperature | ~950 | °C |

When the electricity power is provided to the cathode filament the heat is transferred to the cathode. As a result, the cathode temperature increases (Fig. 1) leading to an increasing of the kinetic energy of electrons at the cathode surface to be higher than the Fermi energy and the work function of the cathode material. Then, the electrons escape from the cathode surface to become free electrons in the vacuum chamber of the RF-gun. At zero-field, the kinetic energy ($KE$) of electrons depends on the temperature ($T$) of the heating cathode as $KE = (3/2)kT$, where $k$ is the Boltzmann constant. In experiment, the cathode surface temperature at various filament powers can be measured using a heated-wire comparative type optical Pyrometer. The measured results show that there is a proportional relationship between the filament power and the cathode temperature as showed in Fig. 1. In the measured range of cathode temperature between 770°C to 1065°C, the kinetic energies of the free electrons are 0.22 eV to 0.27 eV.

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The electrons current flows through the cathode surface can be evaluated from Richardson's law, which says that the current density for the thermionic emission relates with the work function (W) and the temperature (T) of the cathode material. This relation has shown in the following equation [3]:

$$j = AT^2 \exp\left(\frac{-e\Phi_W}{kT}\right), \tag{1}$$

where $j$ is the current density of the emission, $A$ is Richardson's constant for the cathode material, $T$ is the temperature in Kelvin unit, $e$ is the electron charge, $\Phi_W$ is the work function of cathode material and $k$ is Boltzmann's constant. The cathode emission characteristics according to Richardson's law and the calibration information provided from the HeatWaves Lab company are shown in Fig. 2. Both emission curves have been evaluated from measured cathode temperatures.

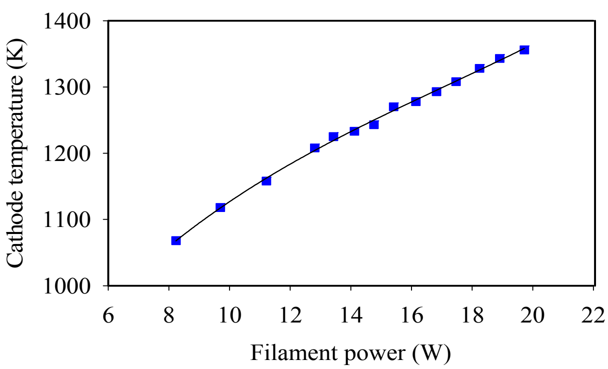


Figure 1: Relationship between the cathode filament power and the measured cathode temperature.

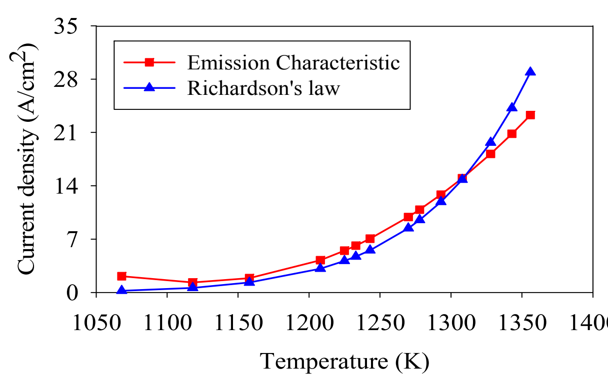


Figure 2: Emission current densities of the thermionic cathode as a function of the cathode temperature.

The electric power (P) is slowly provided to the cathode filament and it can be calculated from the filament voltage (V) and the current (I) according to the relation P=VI. We can evaluate the electron current density at the cathode for any cathode temperature using two calibrations from the two curves in Fig. 2. The first calibration is to evaluate the current density from the measured cathode temperature and the calibration information provided from the HeatWaves Lab [1]. The second calibration is calculating the electron current density from the measured cathode temperature using the ideal thermionic emission formula from Richardson's law in equation (1). Both characteristic curves are comparable.

## METHODOLOGY

### *Setup and Measurements*

To investigate the influence of the RF pulse shape and the power on the electron beam characteristics, we used the measurement set up as shown in Fig. 3. which detailed information of the set up can be found in [4]. The RF pulse is measured using directional couplers and crystal RF detectors on the waveguide section prior the RF-gun. Typical waveforms of the forward and the reflected RF pulses are shown in Fig. 4. The difference of both RF signals defines the cavity wall loss and the beam power. The electron macropulses generating from the RF-gun were observed at the current transformer downstream the gun exit (CT1).

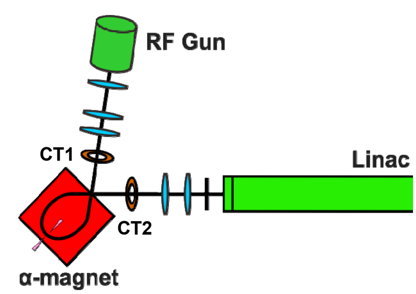


Figure 3: Layout of the injector section of the linac-based THz source facility at Chiang Mai University.

The maximum RF pulse length available at the PBP-linac facility is 6 $\mu s$ (FWHM). However, the longer the RF pulse the more electron back-bombardment. From the experience, the gun operation with an RF pulse longer than 4 $\mu s$ (FWHM) was difficult to maintain the beam stability. To minimize the effect of the electron back-bombardment, the RF pulse width was chosen to be about 3 $\mu s$ (FWHM). Since the RF pulse shape from the existing RF system has been optimized for the RF pulse length of 6 $\mu s$, the rise time of the 3 $\mu s$ RF pulse does not reach the maximum power level. Therefore, the output RF pulse is non-rectangular shape as can be seen in Fig. 4. This leads to the different acceleration of each microbunch in the macropulse and therefore the large variation of electron bunch energies.

In experiment, the electron beam energy is measured using the energy slits inside the vacuum chamber of the alpha magnet ( α-magnet). The electron momentum (cp) is related to the maximum distance of the electron trajectory in x-direction ($X_{max}$) as [5]



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$$X_{max}(cm) = 75.05\sqrt{\frac{cp(MeV)}{mc^2 g\left(\frac{G}{cm}\right)}}\ , \qquad (2)$$

where $mc^2$ is the electron rest mass energy and g is the alpha magnet gradient. Electron current after exiting the alpha magnet is measured with the current transformer CT2 prior the linac section. The electron macro-pulses measured at CT1 and CT2 are shown in Fig. 4 together with the typical forward and reflected RF pulses. This experiment was done at the filament power of 13.6 W corresponding to the cathode temperature of 950°C.

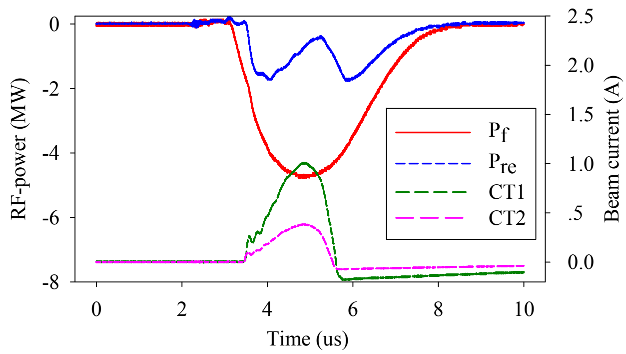


Figure 4: Waveforms of the forward ($P_f$), reflected ($P_{re}$) RF pulses and the typical electron macro-pulses downstream the RF-gun ($I_{CT1}$) and downstream the alpha magnet ($I_{CT2}$).

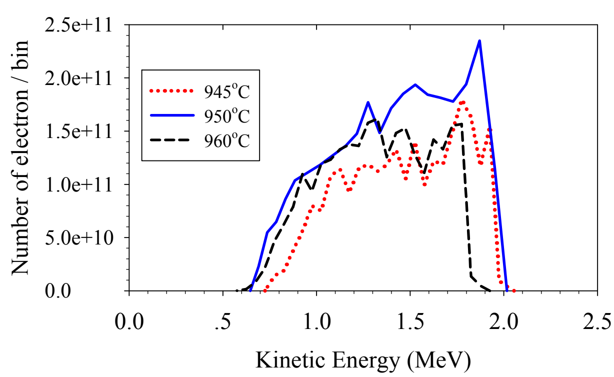


Figure 5: Energy spectrum of electron beam measured at the CT2 for the cathode temperature of 945°C, 950°C and 960°C.

Figure 5 shows the measured time evolution of the electron energy spectrum measured with the energy slits of the alpha magnet. It can be seen that by operating the RF-gun at higher cathode temperature the macro-pulse length of the emitted electron beam is shorter than the electron pulse produced from the RF-gun operation at lower temperature. The maximum kinetic energy of the electron beam is also lower. This phenomenon indicates the back-bombardment and the beam loading effect inside the thermionic RF-gun. To study this phenomenon the beam dynamic simulations have been performed and the results are discussed in the following section.

### *Simulated Kinetic Energy of Electron Beam*

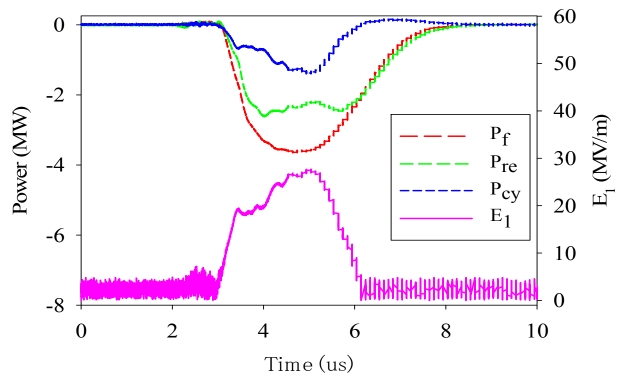


Figure 6: Waveforms of the RF pulses when the cathode heater off and the calculated accelerating gradient at the cathode ($E_1$).

Figure 6 shows the waveforms of forward ($P_f$) and reflected ($P_{re}$) RF pulses when the cathode heater off. The value of $P_f$ and $P_{re}$ are measured directly at the directional coupler of the RF-gun. The difference of $P_f$ and $P_{re}$ is defined the cavity wall loss ($P_{cy}$) and they have a relationship as following:

$$P_f = P_{re} + P_{cy} \quad \text{or} \quad P_{cy} = P_f - P_{re}\ . \qquad (3)$$

Then, we can use the value of $P_{cy}$ to calculate the average accelerating gradient ($E_1$) in the first cell of the RF-gun from

$$P_{cy} = \frac{E_1^2 d_1}{r_{s1}} + \frac{E_2^2 d_2}{r_{s2}}\ , \qquad (4)$$

where $E_1$ is the accelerating gradient at the cathode plane of the half-cell, $E_2$ is the accelerating gradient at the middle of the full-cell ($E_2$=2$E_1$), $d_1$ is the effective length of the half-cell, $d_2$ is the effective length of the full-cell, $r_{s1}$ is the shunt impedance of the half-cell and $r_{s2}$ is the shunt impedance of the full-cell. Specifications of the RF cavity at the PBP-linac facility are listed in Table 2. These parameters are obtained from the numerical study using the code SUPERFISH [6].

Table 2: Specifications of the RF Gun Cavity

| **Parameter** | **Value** |
|---|---|
| Ration of accelerating gradient at the half-cell and the full cell | 1:2 |
| Effective length of the half-cell | 24.9 mm |
| Effective length of the full-cell | 39.2 mm |
| Shunt impedance of the half -cell | 123.71 MΩ /m |
| Shunt impedance of the full-cell | 96.56 MΩ /m |

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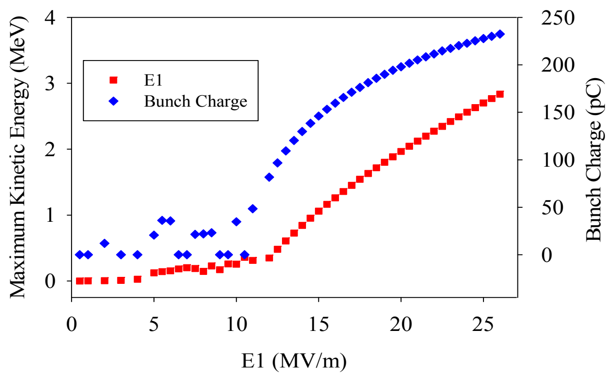


Figure 7: Simulated maximum kinetic energy ($KE_{max}$) and emitted bunch charge of electron as a function of the average accelerating field at the cathode ($E_1$).

PARMELA simulations [7] were performed to investigate electron beam dynamics inside the RF-gun including effects of space-charge force. We assume that the cathode emits a uniform electron beam with a current of 2.9 A represented by 50,000 macroparticle per 2856 MHz cycle of RF field. Each macroparticle represents a charge of 20.3fC which corresponding to $1.27 \times 10^4$ electrons.

In simulations, we used the value of the accelerating gradient ($E_1$) to obtain the maximum kinetic energy of macroparticles that exit the RF-gun. Then, the values of $E_1$ was varied with small step size. From the simulation result in Fig. 7, we found that at low level and high level of $E_1$ the graph have different tend lines. Therefore, we divided the fitting curve of $E_1$ into two ranges and use the resulting kinetic energy to estimate the maximum kinetic energy of electron bunches along the macropulse as shown in Fig. 7.

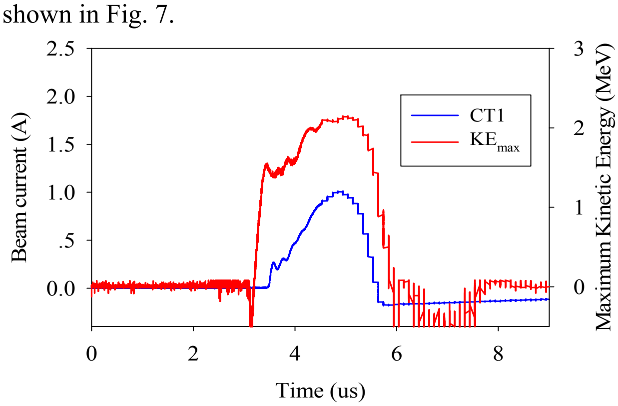


Figure 8: Measured electron macro-pulse downstream the RF-gun ($I_{CT1}$) and the simulated maximum kinetic energy along the macro-pulse.

It is seen in Fig. 8 that the peak of the kinetic energy of electron bunches along the macropulse is about 2-2.1 MeV, which corresponds well to the maximum measured kinetic energy from the measurement of energy spectrum shown in Fig. 5. An example of particle distribution and histogram in energy-time phase space for a single bunch at the RF-gun exit with the maximum kinetic energy of 2 MeV are shown in Fig. 9.

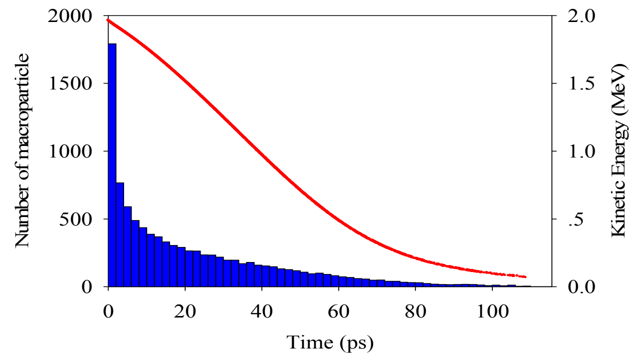


Figure 9: Particle distribution and histogram in energy-time phase space for a simulated single bunch at the RF-gun exit for the maximum beam kinetic energy of 2 MeV.

## CONCLUSION AND OUTLOOKS

The numerical and experimental studies of the influence of a non-rectangular RF-pulse on electron beam properties have been carried out. Results of the investigation are presented and discussed in this contribution. The simulation result of the maximum kinetic energy of electron bunches along the macro-pulse show that the value of a peak kinetic energy in the macro-pulse is close to the value obtained from the experiment. Using the results from PARMELA simulations together with the experimental data of the RF shape and power, we can estimate the maximum kinetic energy of electrons emitting from the RF-gun. Further investigation will be performed in order to accumulate the useful information for improving the RF system for the better performance of the thermionic RF-gun.

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