# PHOTOTHERMAL CATHODE MEASUREMENTS AT THE ADVANCED PHOTON SOURCE*

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*Abstract*

The Advanced Photon Source (APS) ballistic bunch compression (BBC) gun in the Injector Test Stand (ITS) presently uses an M-type thermionic dispenser cathode as a photocathode. This photothermal cathode offers substantial advantages over conventional metal photocathodes, including easy replacement and easy cleaning via the cathode's built-in heater. We present the results of photoemission measurements as a function of cathode heater power, laser pulse energy, and applied rf field strength.

## INTRODUCTION

The thermionic impregnated dispenser cathode was developed initially by Levi [1] in the 1950s. Known as "B"-type cathode, it consisted of a porous tungsten matrix impregnated with barium calcium aluminate. A disadvantage of the "B"-type cathode was its high working temperature (1030 - 1040 °C). In 1966, a significant improvement occurred when Zalm and Van Stratum [2] showed that coating the cathode surface with metals from the platinum group (osmium, iridium, ruthenium, or rhenium) reduced the work function by about 0.2 eV. In practice this led to a higher current density at the same working temperature, or lower working temperature for the same current density. This type of coated "B" type cathode is referred to as "Magic" or "M"-type cathode. The current density of a dispenser cathode is on the order of A$\cdot$ cm$^{-2}$ [3].

The investigation into using a dispenser cathode as a photoemitter is driven by the need for an efficient yet robust electron source for free-electron lasers [4, 5]. This is attributed to the fact that traditional metallic cathodes have low quantum efficiency, while the highest quantum efficiency semiconductor cathodes available require ultra-high vacuum to avoid poisoning [6].

While a theoretical model for the dispenser cathode has been evolving for decades [7], recent developments compare well with experimental results [8, 9]. The experimental investigation carried out at the University of Maryland showed that the dispenser cathode could be a promising photocathode candidate [10, 11].

In this present paper, we report our experimental results of the photoemission measurements as a function of dispenser cathode heater power, laser pulse energy, and applied rf field strength.

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## EXPERIMENTAL SETUP

The M-type cathode we used is a standard barium-impregnated tungsten cathode with an osmium surface coating provided by the University of Maryland. The cathode is fabricated by Spectra-Mat Inc. An alloy heater wire buried behind the cathode can increase the temperature of the cathode to enhance the photoemission. The heater power can be varied, and the maximum power applied was about 15 W.

The ballistic bunch compression (BBC) gun is composed of 2+1/2 cells, operating at 2856 MHz with 6-Hz repetition rate. The rf power and phase of each cell can be independently adjusted. The dispenser cathode is located at the back plate of the half cell, which is also referred to as the cathode cell. For the measurements reported here, the total rf power is share equally by the cathode cell and the first full cell (i.e., the third cell is off).

Two photocathode drive-laser systems are available for the measurements. One is a picosecond laser, which is based on a diode-pumped Nd:Glass oscillator and a Nd:Glass regenerative amplifier. The laser system outputs UV (263 nm wavelength) pulses of length around 3 - 4 ps, and energy of 30 - 100 $\mu$J as measured by an energy meter inside the laser room. The transport efficiency from the energy meter to the laser injection window on the beamline is measured to be about 72%. The total efficiency from the energy meter to the cathode is about 63%. Unless otherwise mentioned, the measurements reported here were performed using this laser.

The other laser system is a commercial nanosecond Nd:YAG laser, which can deliver UV at 266 nm with about 3 mJ per pulse.

## EXPERIMENTAL RESULTS

### *Charge versus Heater Power Over Time*

Starting from 15 W, the cathode heater power is gradually decreased to zero over time. The bunch charge decays accordingly; see Fig. 1. The laser energy on the cathode is about 30 $\mu$J in this measurement. In practical units, the quantum efficiency $\eta$ is given by

$$\eta = 4.7 \times 10^{-3}\, \frac{Q(\mathrm{nC})}{U(\mu\mathrm{J})} \left(\frac{263\ \mathrm{nm}}{\lambda}\right), \tag{1}$$

where $U$ is the energy of the laser pulse, $Q$ is the electron bunch charge, and $\lambda$ is the wavelength of the laser. Therefore in this measurement, the maximum quantum efficiency is about $1.7 \times 10^{-4}$.

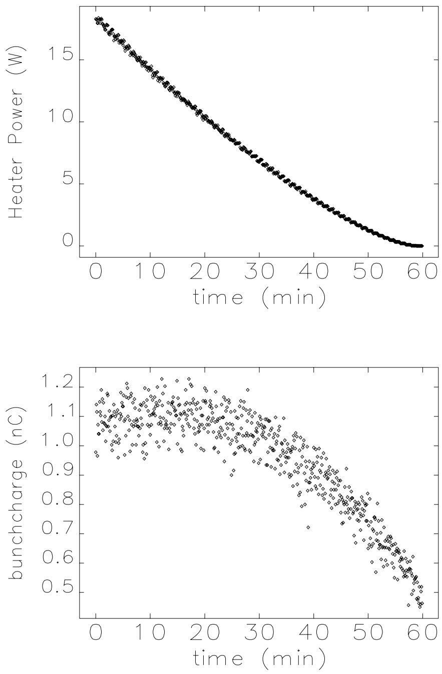


Figure 1: (top) Cathode heater power is varied gradually over time; (bottom) the corresponding bunch charge delivered as a function of time.

The long-pulse laser (nanosecond) is also used to do a similar measurement over a longer period of time; see Fig. 2. At a heater power of around 8 W, the charge settles at about 1.5 nC.

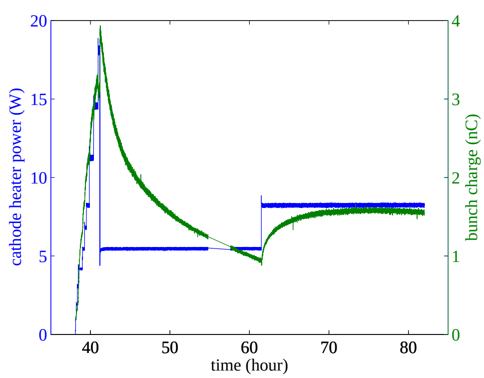


Figure 2: Bunch charge (green) versus time as the cathode heater power (blue) is varied.

## *Charge versus Laser Energy*

The energy of the picosecond laser beam can be easily tuned via remotely controllable laser beam attenuators. At different klystron output power (3 to 9 MW), we measured the emitted bunch charge as a function of the UV laser beam energy; see Fig. 3. At higher UV energy, the enhancement of photoemission from the accelerating electric field on the cathode (i.e., the Schottky effect) is observed. On the other hand, for lower accelerating gradients, the growth of the bunch charge is slower as the UV laser energy increases. This might be due to the space-charge effect — as the cathode becomes positively charged, the attractive Coulomb force it applies on the electrons becomes significant, and the effect is more apparent when the rf accelerating electrical force is smaller.

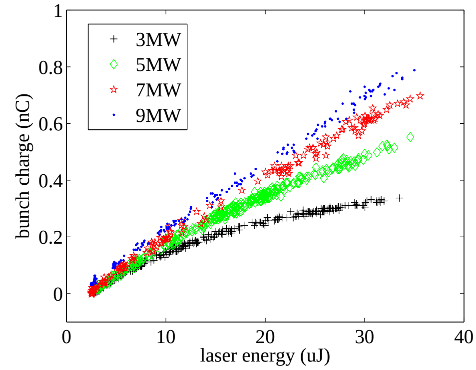


Figure 3: Bunch charge versus UV laser beam energy at different klystron output power.

In Fig. 4, we show a linear fit of bunch charge versus UV laser energy at klystron output around 9 MW (about 130 MV/m on the cathode, see next sections). Taking into account the transport efficiency from the laser energy meter to the cathode using Eq. (1), we conclude that the quantum efficiency is about $1.7 \times 10^{-4}$.

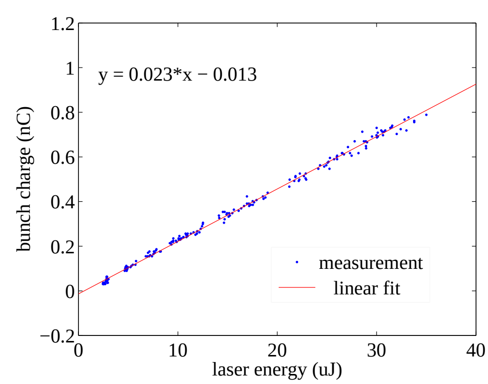


Figure 4: A linear fit of bunch charge versus laser beam energy as measured by the energy meter in the laser room.

## *Charge versus rf Phase*

Since the dispenser cathode is installed in an rf gun, we measured the bunch charge while scanning the rf phase; see Fig. 5. The result shows that the charge delivered is almost constant within about 60 - 70 rf degrees. We also notice a difference of about 5° in the launch phase for the cases with different cathode heater voltages; this is equivalent to about 150 $\mu$m displacement of the cathode, perhaps due to the heat.

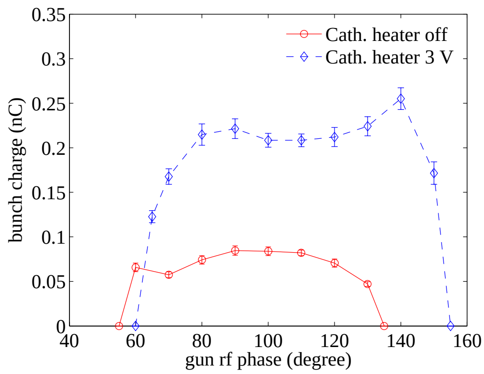


Figure 5: Measured bunch charge versus rf phase at different cathode heater voltages.

### *Charge versus rf Gradient and Heater Power*

In the following measurement, to avoid any influence from the response time of the cathode warming up/cooling down, we vary the klystron output to the gun from 3 MW to 6 MW at each cathode heater voltage setting. A fit of the experimental measurements of beam energies at different klystron outputs combined with General Particle Tracer (GPT) simulation gives the relation between the klystron output $P$ and accelerating gradient on the cathode $E_c$ as: $E_c(\text{MV/m}) = 44.5\sqrt{P(\text{MW})}$. Starting at the gun operating temperature (106 °F), the cathode is gradually warmed up as the heater power is increased from 0 V up to 6 V, which corresponds to about 0 - 15 W power. The results are plotted in Fig. 6. The cathode temperature is estimated to be around 980 °C at 15 W cathode heater power [12].

We see that for zero cathode heater power, the variation of the cathode gradient has little influence on the bunch charge; while for a warmer cathode, the bunch charge extracted increases with the acceleration gradient due to the Schottky effect. Meanwhile, a fast growth of the delivered bunch charge was observed when the cathode heater power starts to increase from zero to about 6 W, above which the charge remained almost constant.

## SUMMARY

The dispenser cathode has been in use for more than a year in the rf gun at ITS/APS. The best measured quantum efficiency is around $1.7 \times 10^{-4}$, and the charge emitted is stable once the cathode reaches its thermal equilibrium. This is one order of magnitude higher than the quantum efficiency of a copper cathode. The dispenser cathode is proven to be suitable for rf photoinjectors.

## ACKNOWLEDGEMENTS

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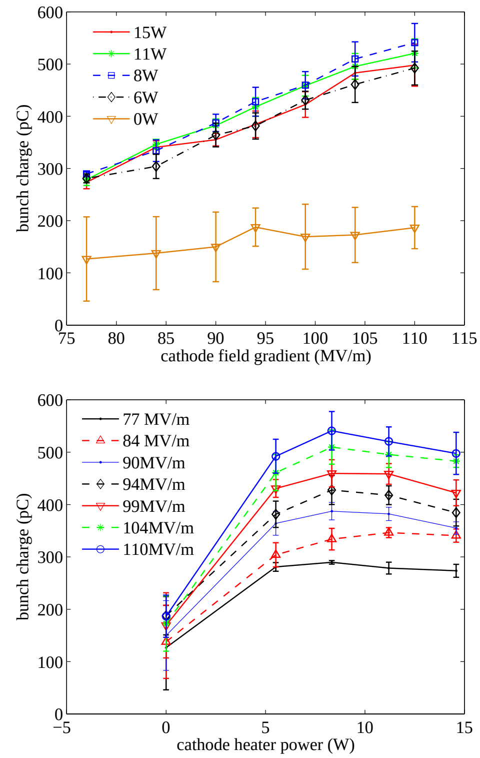


Figure 6: Top: Bunch charge versus the rf field gradient on the cathode at different cathode heater power, cathode started from cold. Bottom: Same data as in the top figure, but different presentation: bunch charge versus the cathode heater power at different gradients.

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