Photoelectrons Beam Measurement from a Magnesium Cathode in a RF Electron Gun*

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Abstract

The performance of a magnesium cathode in a one-and-half cell photocathode RF gun was measured at the Brookhaven Accelerator Test Facility (ATF). The frequency quadrupled Nd:YAG laser (266 nm) was used to stimulate the photoelectron emission. For a normal incident laser pulse, the quantum efficiency of the magnesium at 10^{-7} torr was measured to be $5\text{x}10^{-4}$, which is more than 20 times the value for copper under similar conditions.

Introduction

The development of the photocathode RF gun in the last decade [1-2] has made it possible to produce a bright electron beamto satisfy the increasing demands of free electron lasers and other applications. A 1.5 cell, S-band photocathode RF electron gun has been in operation at the ATF for the past few years.

Based on the previous DC studies [3] magnesium (Mg) is a good candidate for RF gun cathode.The work function of Mg is about 3.66 eV, and a good quantum efficiency has been measured under DC conditions. A high field RF cavity presents unique operational conditions, such as RF breakdown, electron bombardment and outgasing. It is essential to study the performance of Mg in the RF gun.

We first present the experimental set-up utilized in the measurements of a Mg cathode in a RF gun, Then experimental results are discussed in the following sections.

Experimental Arrangement

The ATF is a dedicated laser linac users' facility for advanced accelerator and beam physics. The ATF injection system [4] was used for the Mg cathode study.It consists of a photocathode RF gun, laser beam optics and associated laser diagnostics, an electron beam transport line and electron beam diagnostics.

The laser pulse strikes the cathode at normal incidence through the first 90° dipole magnet. The photoelectron beam generated is either injected to the linac through a double bend electron beam transport line, or to a low-energy experiment station (named the Z-line) using just the first dipole magnet. The photoelectron beam was accelerated up to 3.5 MeV in the RF gun. The electron beam was bent to a momentum analysis slit that is located past the first 90° dipole. it can be used for charge measurements and as a beam profile monitor. A stripline position monitor was installed ahead of the first dipole magnet to measure the electron beam intensity and position. A 2856 MHz RF deflection cavity was installed for the electron beam bunch length measurement.

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The laser system consists of a cw mode-locked Nd:YAG oscillator and Nd:Yag amplifier chain, phase-locked to the 81.6 MHz master oscillator of the RF system. The laser pulse is frequency doubled to green, then doubled to 266 nm ultraviolet(UV) light. Prior to the entrance into the RF cavity, a small fraction of the UV beam is split off for on-line monitoring of the laser energy and spot size. In order to increase the accuracy of the laser energy measurement and avoid damage of the Mg cathode, a special optic was installed to split off 90% of the laser energy to on-line monitoring. The laser pulse lengths at IR (1.06 μm) and green (532 nm) were measured using a streak camera.

The ATF RF gun has an interchangable cathode plug. The plug is made of pure Cu with a 6 mm diameter magnesium disk pressed into its center. The cathode plug surface was polished with one micron diamond paste.

Photoelectron beam measurement

The photoelectron current can be described by,

$$J = aI\left(h\nu - \phi + b\sqrt{\beta E}\right)^2. \tag{1}$$

where J is the total electron current density, I is the laser intensity, $h\nu$ is the photon energy, ϕ is the work function, β is the field enhancement factor, and $b = \sqrt{(e/4\pi\epsilon_0)} \approx 3.8 \times 10^{-5}$ in MKS units, a is a constant related to the material properties and surface condition.

1.Mg Quantum efficiency and Schottky effect measurement

The quantum efficiency of the cathode depends critically on its surface conditions and its environment. There were many RF breakdowns during the RF conditioning. The nearest vacuum gauge to monitor the RF gun is about one half meter away. At the gauge, the vacuum with RF power off was about $2\text{x}10^{-8}$ torr. The vacuum with RF power on was $5\text{x}10^{-8}$ torr. We estimate that the vacuum inside the RF gun was about one order of magnitude worse than the vacuum reading, i.e., the vacuum at the Mg cathode was about $5\text{x}10^{-7}$ torr.

We installed a magnesium cathode in the RF gun on two occasions. The initial test demonstrated the feasibility of Mg as the photocathode in a RF gun. At that test the highest measured quantum efficiency was $5\text{x}10^{-4}$. Furthermore, a charge of 4 nC was measured with a laser energy of 70 μJ (normal incidence). This charge, at the known laser spot size and pulse length, corresponds to a peak current density of 10 KA/cm^2. The quantum efficiency under these conditions was $2.9\text{x}10^{-4}$. It is probable that the reduction in measured quantum efficiency at higher charge is due to the losses between the gun exit and the momentum slit. Those losses are probably caused by the effect of space charge on the electron dynamics.

The second Mg cathode was installed for the routine ATF operation. The photoelectron charge, measured at a field of 50 MV/m, is shown in Fig.1 as a function of laser power. The linearity of the curve is as expected, since the low laser energy eliminated space charge and possible depletion effects.

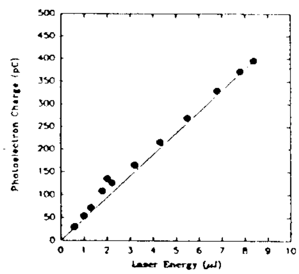

Figure 1: Photoelectron charge vs laser energy at a field of 50 MV/m. The measured quantum efficiency was 2.5×10^{-4}.

The photoemission Schottky effect was studied by varying the RF power to the gun. Fig.2 shows the result of the measurement. The experiment is in agreement with Eq.(1), and shows a factor of two change in the quantum efficiency. The highest measured quantum efficiency is about 5×10^{-4} at a cathode electric field of about 70 MV/m.

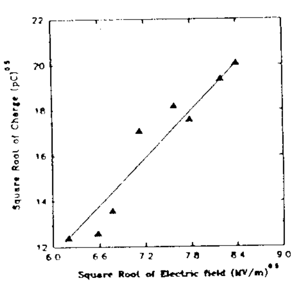

Figure 2: Quantum efficiency vs electric field at the cathode surface. The highest quantum efficiency is 5×10^{-4}.

2.Multipulse response measurement

For FEL oscillator experiment and linear collider applications, bunch trains with a pulse repetition frequency on the order of 100 MHz are required. A lower quantum efficiency for later arriving pulses has been observed in a semiconductor cathode.

The present ATF Nd:YAG laser is capable of producing a six-pulse train with an intra-pulse spacing of 24.5 ns. A fast photodiode with subnanosecond rise time was used to measure the laser pulse train energy. The diode pulse width was determined by the bandwidth of the measuring system. The ATF stripline monitor has a bandwidth of more than 5 GHz. [5] We used it for a direct measurement of the charge of the electron beam pulse train. A 500 MHz bandwidth Tektronix digital scope was connected directly to the fast photodiode and stripline monitor. Fig.3 shows the electron beam pulse train and corresponding laser pulse train. The top trace bi-polar signal is the electron beam signal while the bottom trace is the laser energy signal. The charge for the first electron bunch is about 0.5 nC. We find that the charge of each electron beam pulse is proportional to the energy in the corresponding laser pulse. In other words, for the given total charge there is no observed decrease in quantum efficiency along the bunch train.

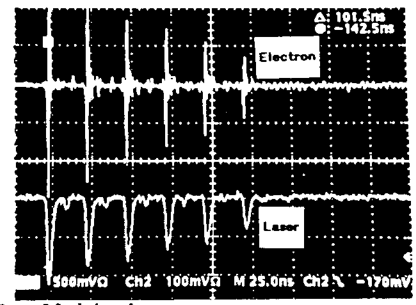

Figure 3: Multipulse response measurement, the top trace is the electron beam charge while the bottom trace is the corresponding laser energy. The time scale is 25 ns/division, the top trace scale is 500 mV/division and the bottom trace scale is 100 mV/division.

3.Electron beam bunch length measurement

The laser pulse length was measured both at IR ($1.06\mu m$) and green (532nm) using a Hamamatsu streak camera. The results were 21 and 15 ps FWHM, respectively, showing the expected reduction of the pulse length by $\sqrt{2}$ following the frequency doubling. The electron pulse length was measure using a TM_{102} mode RF kicker cavity operating at the same frequency as the RF gun cavity.

As electrons pass through the cavity, they were deflected by the x component of the magnetic field H_x. The deflection angle θ is given by,

$$\theta_y = \theta_{max} sin\phi. \qquad (2)$$

where θ_{max} is the maximum deflection and ϕ is the electron phase relative to the RF field. Eq.(2) shows that, the electron's deflection is correlated to the time (or phase) of the electron. This angular deflection translates to the vertical position change,

$$\Delta y \approx \ell \times \theta. \qquad (3)$$

where ℓ is the distance from the RF kicker cavity to the beam profile monitor (i.e., momentum slit).

The RF power for the ATF RF kicker cavity was obtained from a 24 dB directional coupler inserted in the RF gun wave guide. The power level and the phase were adjusted by a motor driven phase shifter and attenuator.

The momentum slit was used as the beam profile monitor. To simplify the measurement, the quadrupole magnet between the RF kicker and the momentum slit was turned off. Fig.4 is the measured electron beam centroid deflection as a function of the RF phase. This well behaved sine function provides the values of maximum deflection. The vertical width (σ) of the image of the electron beam on the slit at zero phase point (no beam centroid deflection) provides a measure of the bunch length. To measure the electron bunch length, we compare the kicker-off beam width (σ_0) to the kicker-on width (σ). The net beam width due to the RF deflection is,

$$\sigma_{RF} = \left(\sigma^2 - \sigma_0^2\right)^{1/2}. \qquad (4)$$

The electron bunch length measured in units of the RF phase is,

$$\Delta\phi = arcsin\frac{\sigma_{RF}}{\sigma_{max}}. \qquad (5)$$

where σ_{max} is the amplitude of the beam centroid deflection. The measured rms electron beam bunch length was 4.7 ps, or 11 ps FWHM. It agreed with the laser pulse length measurement when a further $\sqrt{2}$ reduction is applied to the result of the green (532 nm) laser to allow for frequency doubling to the UV (256 nm).

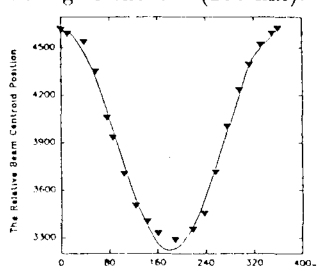

Figure 4: The electron beam centroid displacement vs the RF phase, the solid curve is the best fit of sine function; the measured rms electron beam bunch length was 4.7 ps.

4.Emittance measurement

The quality of the electron beam is characterized by its emittance and brightness. The variable quadrupole method [6] was used to measure the photoelectron beam emittance. A major concern in the emittance measurement is to contain the emittance growth in the post-gun transport. The design of the ATF injection system minimizes vertical emittance growth caused by the nonlinear magnetic fields.[4] Our numerical simulations show that for the experimental conditions considered, the space charge effects are negligible for a bunch charge below 100 pC.

We have used two quadrupoles ZQ1 and ZQ2 in the Z-line to focus the electron beam. The measurement was carried out by varying quadrupole ZQ1 and measuring the beam spot size on the down stream beam profile monitor. The measured electron beam rms size and a best fitted curve for the beam size as a function of quadrupole current are plotted in Fig.5. The measured normalized rms emittance is 2.5 mm-mrad for total charge of 80 pC with a laser rms spot radius of 0.2 mm.

We compared the measured emittance with the emittance calculated using formula given in reference[7]. The calculated thermal emittance is 0.3 mm-mrad,the emittance caused by the RF field is 2.2 mm-mrad while the space charge contributed 1.1 mm-mrad to the emittance. The combined emitance from the calculation aggreed wevy well the the measured value.

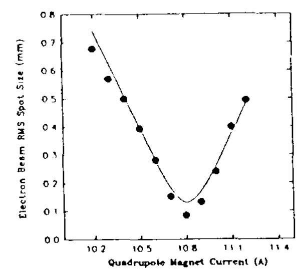

Figure 5: The emittance measurement data at momentum 2.8 MeV/c, and its best fit (solid curve). The measured normalized rms emittance was 2.5 mm-mrad.

Conclusion

We have measured a record high quantum efficiency of a metal cathode in the RF gun using magnesium. Our experimental results established the use of magnesium metal as a very attractive photocathode material for RF gun.

We believe that an even higher quantum efficiency for Mg can be achieved in the future. In an experiment with a Cu cathode RF gun described in reference, [8] we determined that the quantum efficiency of the cathode can be increased by a factor of three if the laser is incident on the cathode at 71 degrees to the normal. Similar result was also observed for Mg cathode under DC field in our laboratory. Furthermore, we expect to operate the RF gun at 100 MV/m, where the Schottky effect will improve the quantum efficiency by another estimated factor of two.

References

1. J.S. Fraser et al, IEEE Trans. Nucl. Sci. NS -32 (1985) 1791.
2. K. Batchelor et al, Proc. of 1988 European Particle Accelerator conf., Rome p. 954.
3. J. Fischer et al, Nucl. Instr. and Meth. A 340 (1994) 190.
4. X.J. Wang et al, Proc. of 1989 Particle Accelerator Conf., Chicago (1989) p 307.
5. J.T. Rogers et al, Brookhaven National Laboratory report BNL - 47145 (1992).
6. X.J. Wang et al, Proc. of 1993 Particle Accelerator Conf., (1993)p2486.
7. K.J. Kim, Nucl. Inst. and Meth. A275(1989) 201.
8. X.J. Wang et al, Proc. of 1993 Particle Accelerator Conf., Washington(1993)3000.