DETERMINATION OF THE FIELD ENHANCEMENT FACTOR ON PHOTOCATHODE SURFACE VIA THE SCHOTTKY EFFECT

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Abstract

Using photon energy that is less than the work function, we employ the Schotty effect to determine the field-enhancement factor on the surface of a Mg photocathode. The Schottky effect is manifested via a shift in the threshold for photoemission as the amplitude of the RF in the photoinjector gun is varied. From the threshold condition, we can directly determine the field enhancement factor on the cathode surface. This is a viable technique to obtain the field enhancement factor of surfaces of other materials such as Nb and Cu.

INTRODUCTION

The ability to accurately determine the field enhancement factor is crucial in high gradient RF cavities. Such determination will allow for proper fabrication, processing and surface treatment of the cavity walls to reduce breakdowns and field-enhanced effects such as dark currents.

Till now, such determinations have made use of the Fowler-Nordheim model of field emission to extract the field enhancement factor [1]. This model employs a series of assumptions that may no longer be applicable especially in a high-gradient situation [2]. In our work, the field enhancement factor is obtained in a more direct and transparent manner with minimal assumptions. Furthermore, it is obtained under a typical photoinjector operation conditions.

THEORY

For a photoemission process in the presence of an electric field, the kinetic energy of the photoelectrons can be described by $E_k = h\nu - \Phi_{eff}$, where $h\nu$ is the photon energy and Φ_{eff} is the effective work function defined as $\Phi_{eff} = \Phi_0 - b\sqrt{\beta E(\theta)}$. Here, Φ_0 is the material's work function, $b = \sqrt{e/4\pi\varepsilon_0}$, β is the field enhancement factor, and $E(\theta)$ is the applied field on the cathode at the laser injection phase θ. An increase in the applied field lowers the effective potential (Schottky effect). We make use of this effect by using photons with energy *less* than the material's work function, i.e. $h\nu < \Phi_0$. This means that with no applied field, single-photon photoemission is not possible and no photoelectrons are detected. As the applied field increases, the effective work function lowers until a threshold condition is achieved, beyond which photoelectrons are detected. At the threshold condition, the photoelectrons, in principle, have no kinetic energy. This implies that $h\nu - \Phi_0 + b\sqrt{\beta E(\theta)} \approx 0$. Knowing the applied field strength and the material's work function allows for a direct determination of the field enhancement factor. Previous study using this technique has suggested the possibility of generating ultralow intrinsic (thermal) emittance electron beam near or at the threshold condition.[3]

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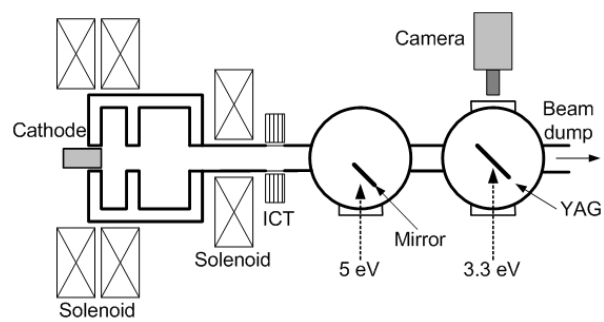

Figure 1: Schematic diagram of rf photoinjector. There are two laser input windows for different photon energies.

EXPERIMENT

The Mg cathode (diameter = 2.8 cm, Φ_0 = 3.7 eV) fabricated from a solid Mg rod, was polished using diamond powder slurry up to 3 µm grit. The cathode was installed in a 1-1/2 cell, 1.3 GHz standing-wave rf gun at the Argonne Wakefield Accelerator facility (Fig. 1)[4]. The gun's operating pressure is ~5 × 10^{-10} Torr. Photons with energy 3.3 eV were generated with 1 mJ per pulse and pulse width of 6 to 8 ps FWHM.

The applied field on the cathode surface comes from the rf field as $E(\theta) = -E_{max}\sin(\theta)$, where E_{max} is the amplitude of the field. At 1.3 GHz, this gives a period of ~770 ps. With a laser pulse width of 6-8 ps and a metallic cathode response time of ~ fs, we can safely assume that all the emitted electrons in a single pulse are in a relatively constant electric field value.

RESULTS

Figure 2 shows the amount of charge emitted per laser pulse at various rf phase angle. For the typical operation shown in Fig. 2a (5 eV photons on Mg cathode, $h\nu > \Phi_0$), the amount of charge varies for different rf amplitude. However, the phase range for detection of photoelectrons remains relatively unchanged, ~120°[5]. The charge is detected over the same phase range for all rf amplitudes. The charge measurements do not yield the expected "flattop" curves and has been attributed to the Schottky effect [6]. While this is plausible, other factors such as space-charge effects and transport issues can affect phase scan charge measurement.

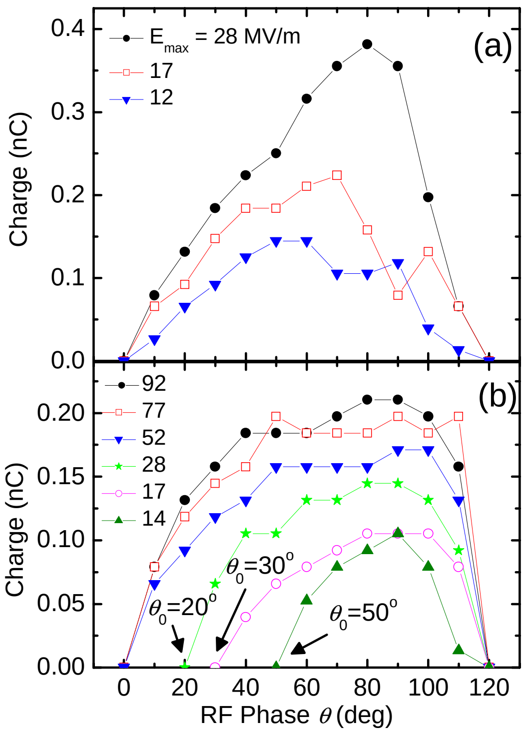

Figure 2: Charge emitted at various rf phase θ from Mg cathode (Φ_0 = 3.7 eV). Electric field on the cathode is $E(\theta) = -E_{max}\sin(\theta)$. (a) Charge produced by 5 eV photons. (b) Charge produced by 3.3 eV photons. θ_0 is the phase angle (±5°) at the threshold of photoemission.

When a photon energy of 3.3 eV is used ($h\nu < \Phi_0$), there is a dramatic change (Fig. 2b). We now observe a variation in the range of phase angle where photoelectrons are detected. There is a clear shift in the angle for the onset of photoemission, shifting to higher values as the rf amplitude lowers. No clear shift is detected for the three highest rf amplitudes. This is due to a combination of detection accuracy and resolution, and the fact that the electric field changes more rapidly over a smaller change in phase angle. This systematic shift in the threshold phase angle with decreasing rf amplitude is the clearest manifestation of the Schottky effect in an rf photoinjector.

We identify the phase angle at the threshold condition for each phase scan and obtain the magnitude of the electric field. From the threshold condition described in the Theory section above, we obtain directly the value of the field enhancement factor as shown in Table 1. The values do not change monotonically with the rf amplitude and hovers approximately around a constant value. We estimate that for our cathode surface, β between 6 and 7.

The value for the field enhancement is obtained with minimal assumptions. The accuracy of this value depends on the accuracy of determining the threshold phase angle θ_0, and how well the material's work function is known.

Table 1: Field enhancement factor obtained from phase scans.

θ_0 (deg)	$E(\theta_0)$ (MV/m)	β
20	9.2	6.8
30	8.5	7.3
50	11	5.8

We make a verification that the detected charges are photoelectrons originating from the Mg cathode and not due to dark currents. Figure 3 shows the amount of charge detected per laser pulse as a function of the laser intensity at a fixed rf amplitude. The linear increase in intensity with increasing total laser energy per pulse indicates that we are measuring photoelectrons and not dark currents in the results of Fig. 2 and Fig. 3.

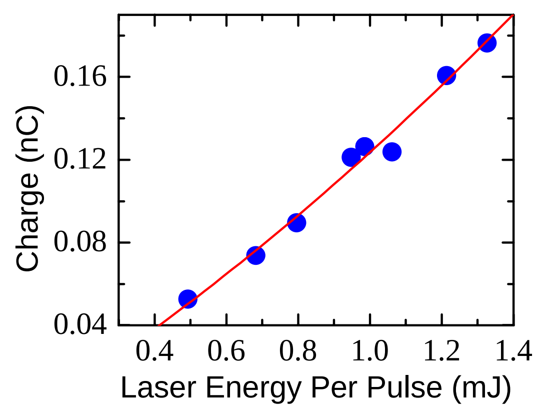

Figure 3: Charge vs. laser energy per pulse (intensity) from 3.3 eV photons. The solid line is approximately a linear fit. The electric field on the cathode is 70 MV/m.

Another issue that we address is the possibility that the shift in the phase angle in Fig. 2 is due to a detection threshold. With decreasing rf amplitude, the overall amount of charge detected also drops. This opens the possibility that the shift in phase angle for the detection of photoelectrons is due to the detection threshold of the integrated charge transformer (ICT) rather than intrinsic to the photoemission process.

Figure 4 shows rf phase scans at the same rf amplitude, but with different laser intensity. The difference in the laser intensity results in different overall amount of charge detected. If we are at the detection threshold limit, the two scans will show a difference in the phase angle for the onset of charge detection. As can be seen from the figure, no such difference is detected. Both phase scans shows the same onset phase angle as expected for the same rf amplitude. This clearly indicates that the shift in the onset phase angle seen in Fig. 2 cannot be attributed to the detection threshold.

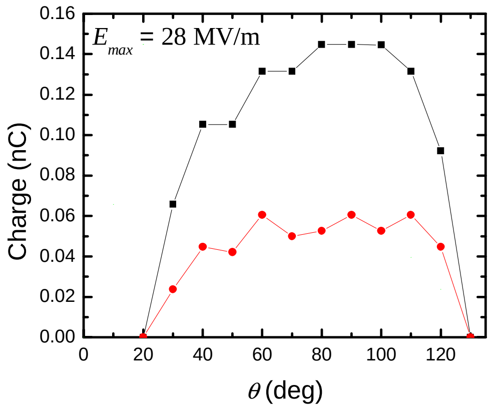

Figure 4: rf scans at E_{max} = 28 MV/m for different laser intensities. No shift in the onset phase angle is detected. This shows that we are not close to the detection threshold.

DISCUSSION

The Schottky-enabled photoemission process described here has produced the most direct way of measuring the field enhancement factor under a realistic photoinjector conditions. The accuracy of the value obtained only depends on how well one knows the value of the material's work function and how well the electric field at the threshold condition can be obtained. This technique should be applicable in finding the field enhancement factor for rf cavity materials such as Cu and Nb, especially in studying the effects of surface processing on such materials.

We note that a potential complication may arise from this technique. Due to the nature of the high powered laser that was used, under certain conditions, we were able to obtain photoelectrons via the two-photon photoemission process. When this occurred, photoelectrons were detected over the full range of the rf scan, very much like those obtained in Fig. 2a. It was only after the photon density per unit area was reduced by expanding the laser spot size from 1 cm to 2 cm were we able to significantly reduce the two-photon process and obtained photoelectrons predominantly from single-photon photoemission. A more detailed discussion of this can be found in Ref. [3].

Future studies using this technique are being planned. This includes the measurement of the field enhancement factor of a number of high QE photocathodes, including Cs_2Te and ultrananocrystalline diamond. There are also plans to measure the emittance of electron beam generated via this method and explore the possibility of producing an ultralow intrinsic emittance electron beam.

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[4] For a more detailed description of the accelerator facility, see M. Conde *et al.*, in *Proc. of 2003 PAC*, Portland, OR (IEEE, Piscataway, NJ, 2003), p. 1036.

[5] Transport issues prevent the detection of photoelectrons over the whole 180° range. A more elaborate explanation has been offered in Ref. [3].

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