Field enhancement coefficient β determination methods: dark current and Schottky enabled photo-emissions

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ANL

CERN RF Breakdown Meeting

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SCHOTTKY-ENABLED PHOTOEMISSION 1

Yusof *et al*., Phys. Rev. Lett. **93**, 114801 (2004)

> ***"… it now appears that the intrinsic cathode emittance will be the dominant quantity that limits our achieving beams of higher brightness from an rf gun."***

ANL Theory Institute Workshop on Production of Bright Electron Beams
Sept. 22-26, 2003

- Study a new regime of electron beam generation that has potential impact on the future Linear Collider and Light sources;
- High brightness electron beam – minimize emittance;
- Scheme: Employ Schottky effect in the RF photocathode gun and with low energy photons;
- This technique also produces a reasonable estimate of the field enhancement factor without employing the Fowler-Nordheim model.

In this presentation, thermal emittance = intrinsic emitance

SCHOTTKY-ENABLED PHOTOEMISSION 2 – Emittance in RF Photoinjector

Emittance from RF photocathode {KJ Kim, NIM **A275**, 1989}

$$\varepsilon^2 = \varepsilon_{thermal}^2 + \varepsilon_{RF}^2 + \varepsilon_{sc}^2 + 2\varepsilon_{RF}\varepsilon_{sc}J_x$$

where ε_{RF} and ε_{sc} are the emittances from RF field in the gun and from space charge effect, respectively. J_x is correlation between ε_{RF} and ε_{sc} and normally is zero.

There are ways to do emittance compensation to handle ε_{RF} and ε_{sc} {B. Carlsten, NIM A285, 313 (1989)}, so in principle, the only limitation left is the thermal emittance $\varepsilon_{thermal}$:

SCHOTTKY-ENABLED PHOTOEMISSION 3 – Thermal Emittance

$$\varepsilon_{thermal} = \frac{1}{m_0 c}\sqrt{< x^2 >< p_x^2 > - < x \cdot p_x >}$$

At the cathode $< x \cdot p_x >= 0$

Therefore, $\varepsilon_{thermal\ ,rms} = x_{rms}\frac{p_{rms}}{m_0 c} = x_{rms}\frac{\sqrt{2 m_0 E_{kin}}}{m_0 c}$

Minimizing E_{kin} will minimize $\varepsilon_{thermal}$.

For a typical cathode: $E_{kin} = h\nu - \Phi$

However, for a cathode in an electric field E: $E_{kin} = h\nu \underbrace{- \Phi + \alpha\sqrt{\beta E(\phi)}}_{-\Phi_{eff}}$

where $h\nu$: photon energy
Φ : material’s bulk work function
α : a constant
β : field enhancement factor
ϕ : RF phase
E : Electric field magnitude

Our scheme is to use $h\nu < \Phi$, and then employ the Schottky effect to lower the effective work function Φ_{eff}, where $\Phi_{eff} = \Phi - \alpha\sqrt{\beta E(\theta)}$

SCHOTTKY-ENABLED PHOTOEMISSION 4 – The Schottky Effect

$$\Delta\Phi = \sqrt{e^3 E / 4\pi\varepsilon_0}$$

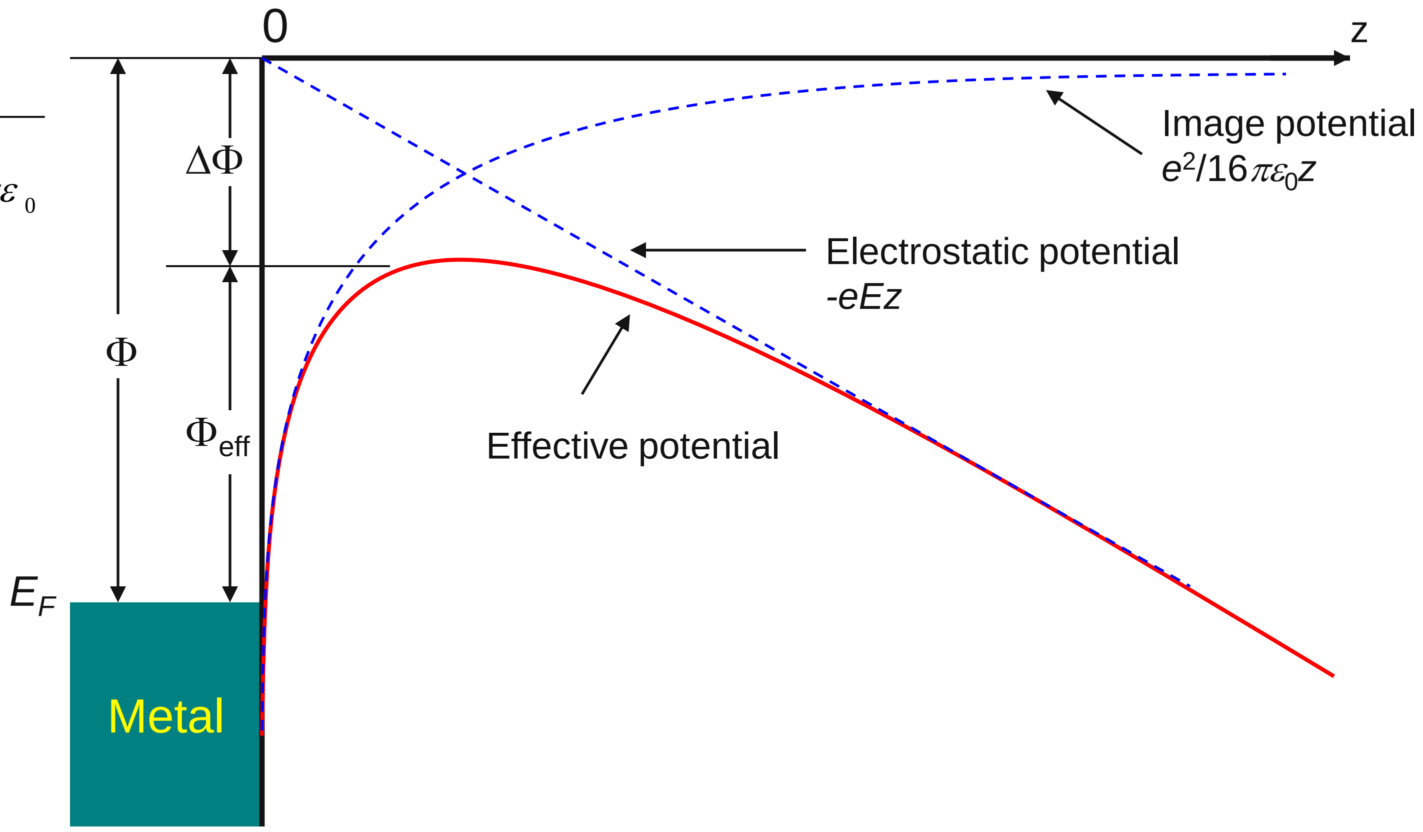


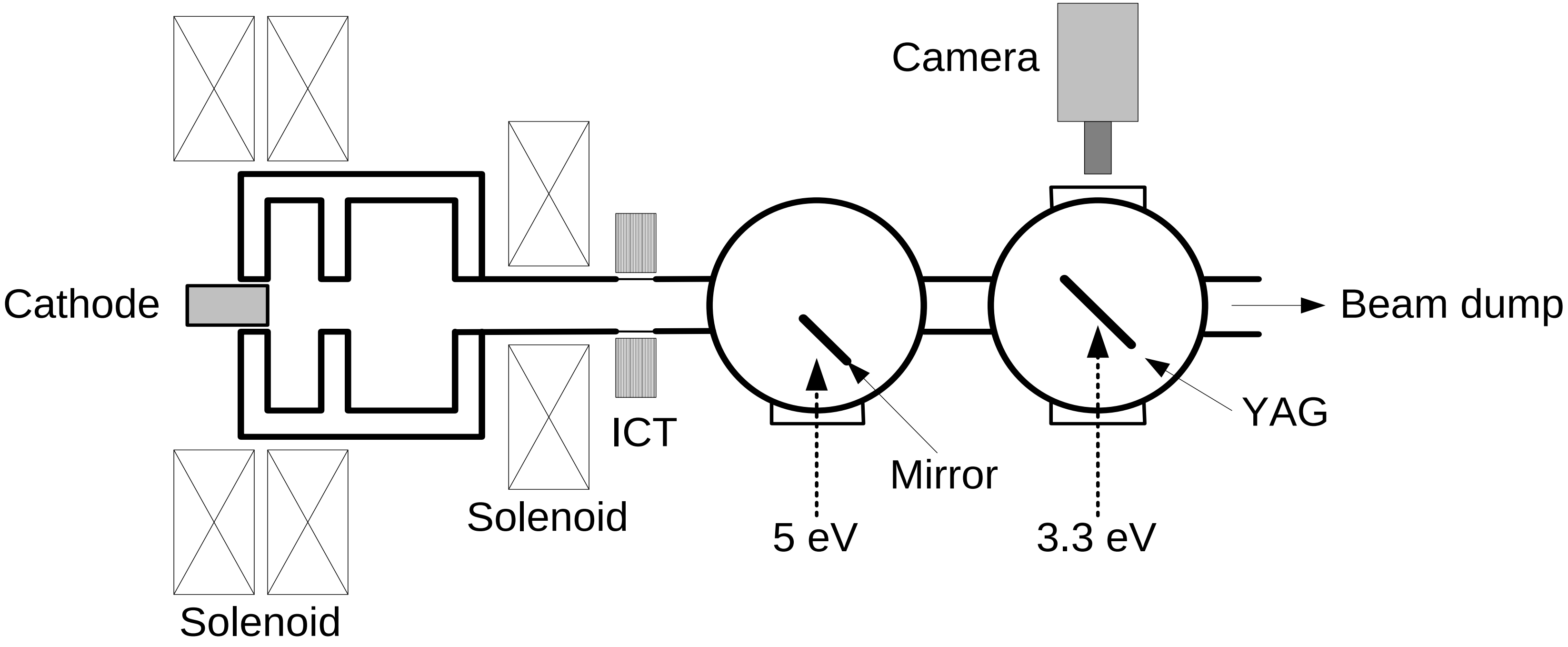
Image potential
$e^2/16\pi\varepsilon_0 z$

Electrostatic potential
$-eEz$

Effective potential

$$\Phi_{eff} = \Phi - \Delta\Phi$$

SCHOTTKY-ENABLED PHOTOEMISSION 5 – Schematic of Beamline

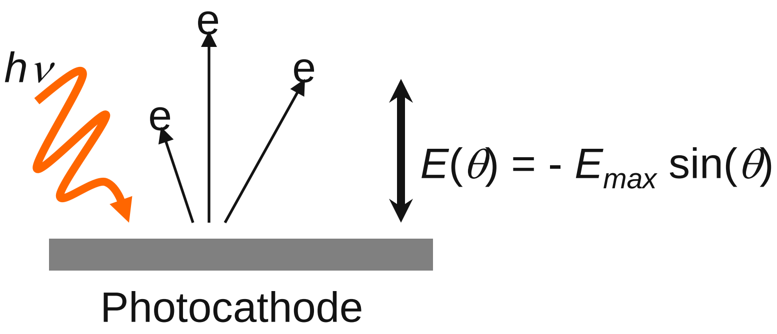


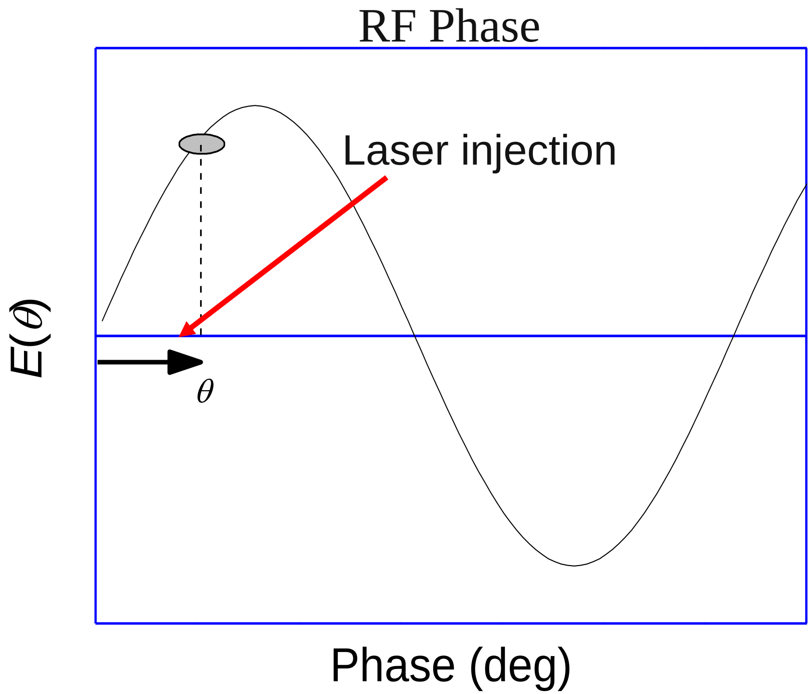
Light source: Frequency-doubled Ti:Sapphire laser 372 nm (3.3 eV), 1 – 4 mJ, 8ps.

Photocathode: Mg, Φ = 3.6 eV.

Example of Schottky effect on the cathode: at $E(\theta)$ = 60 MV/m, $\Delta\Phi$ ~ 0.3 eV

SCHOTTKY-ENABLED PHOTOEMISSION 6 - RF Scans





RF frequency = 1.3 GHz (Period ~ 770 ps)

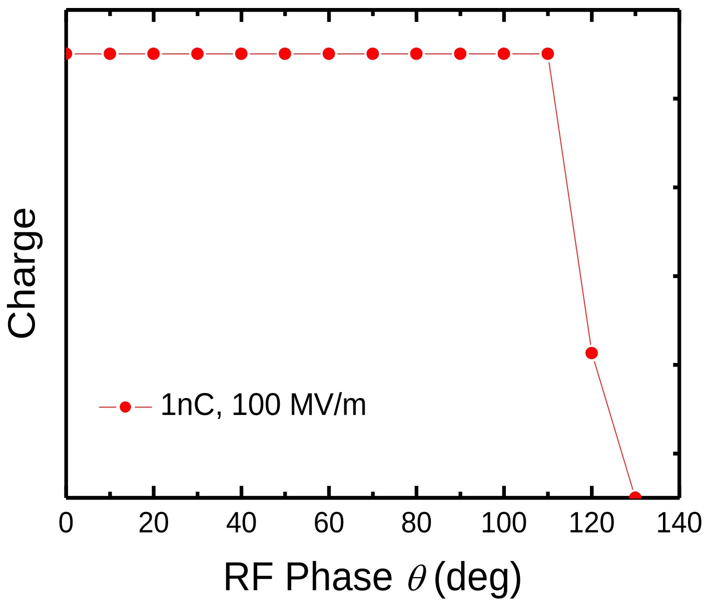
Laser pulse length = 6 – 8 ps

Metallic photocathode response time ~ fs

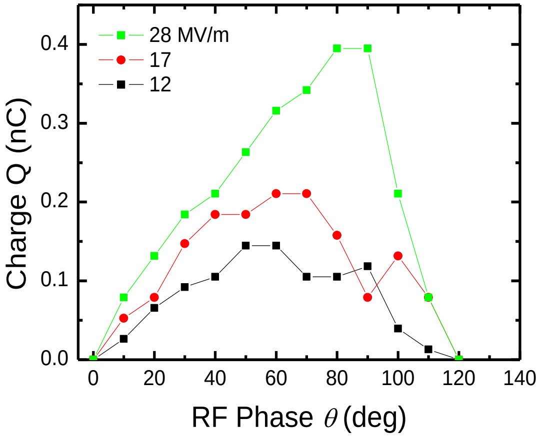
We can safely assume that all the photoelectrons emitted in each pulse see the same *E*-field strength

SCHOTTKY-ENABLED PHOTOEMISSION 7 - Charge Obtained From <u>Typical</u> RF Scans

Theoretical RF Scan



Experimental RF Scan



Our scans

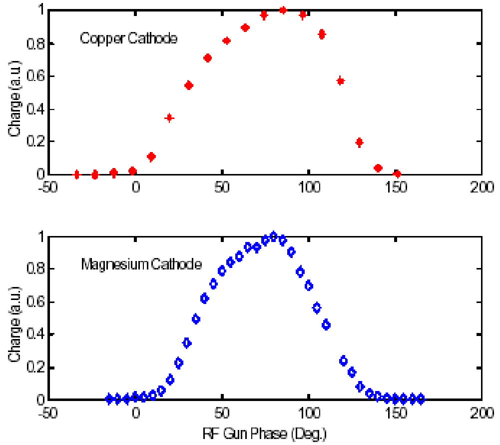


Figure 3: Photoelectron charge as function of RF gun phase for different cathode materials.

X.J. Wang *et al*.
Proc. 1998 LINAC

Theoretical result from PARMELLA simulation of our RF photoinjector (H. Wang)

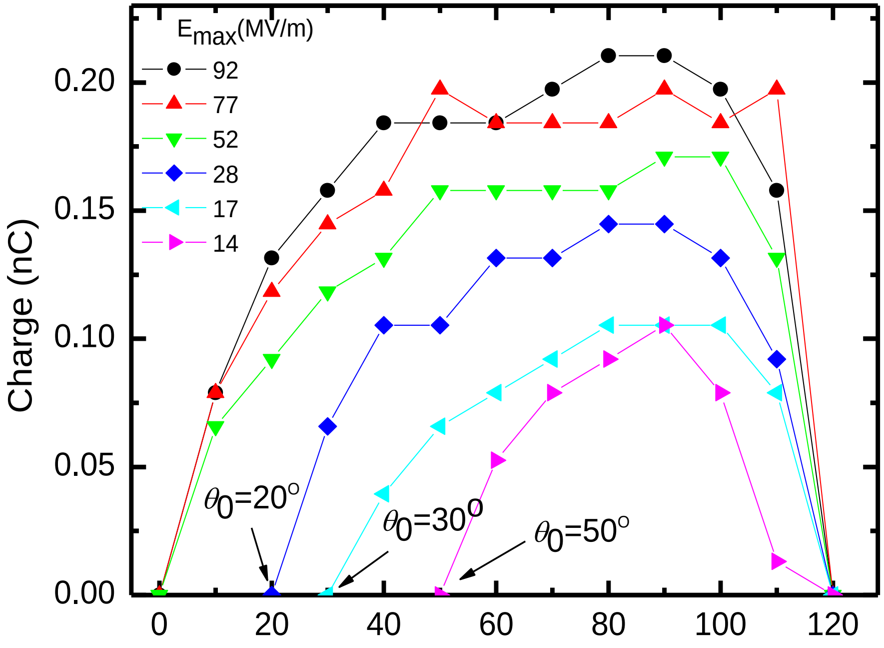
We see the “expected” flat-top profile

Full range of charge detected ~ 130 degrees

SCHOTTKY-ENABLED PHOTOEMISSION 8 – Experimental Result 1: RF Phase Scans

An RF phase scan allows us to impose different electric field magnitude on the cathode at the instant that a laser pulse impinges on the surface, i.e. $E(\theta) = E_{max} \sin(\theta)$.

New observation

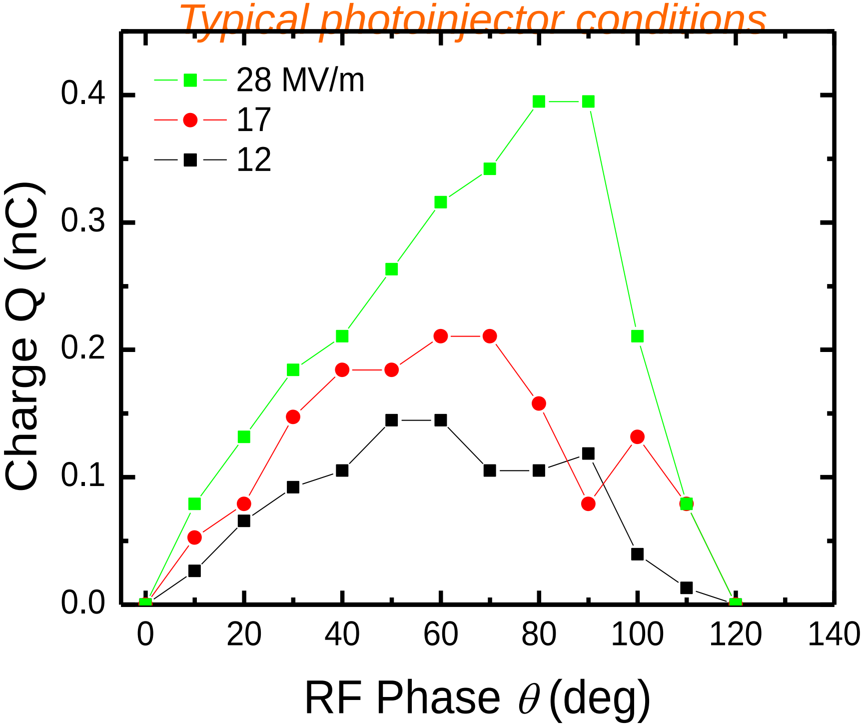


$h\nu$ = 3.3 eV; Φ = 3.6 eV

Laser beam diameter = 2 cm (0.35 mJ/cm^2)

A noticeable shift of the onset of photoelectron production with decreasing RF power.

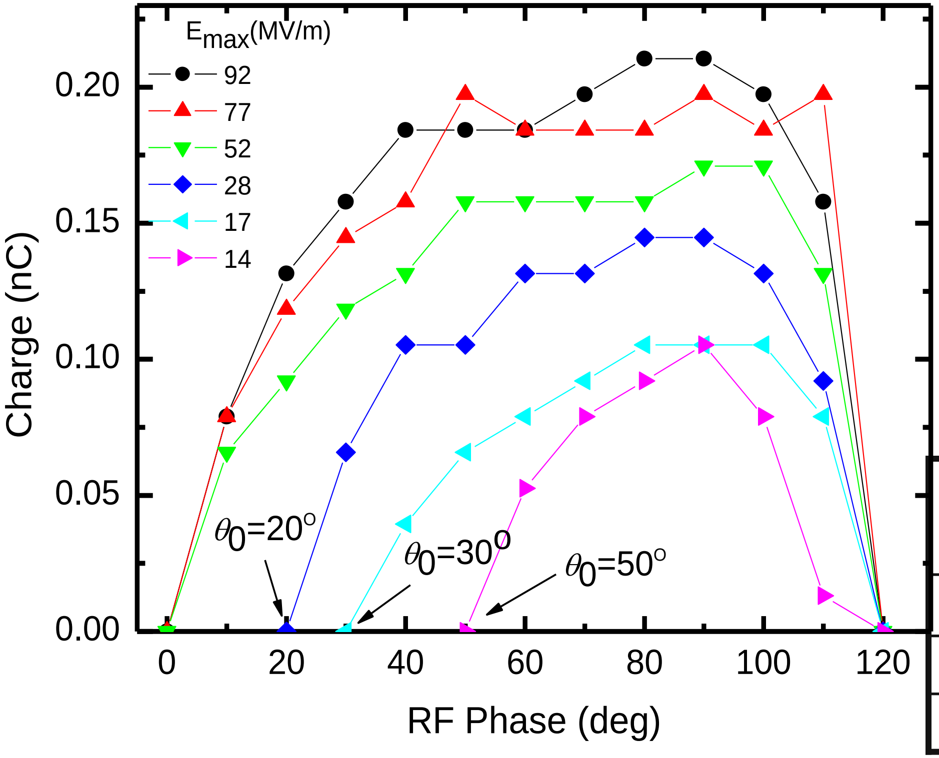
Typical photoinjector conditions



$h\nu$ = 5 eV, Φ = 3.6 eV

No change in the phase range over all RF power.

SCHOTTKY-ENABLED PHOTOEMISSION 9 – Determination of Field-Enhancement Factor



$h\nu = 3.3$ eV; $\Phi = 3.6$ eV

$$Q \propto \left[h\nu - \Phi + \alpha\sqrt{\beta E(\theta)}\right]^2$$

$$E(\theta) = E_{\max}\sin(\theta)$$

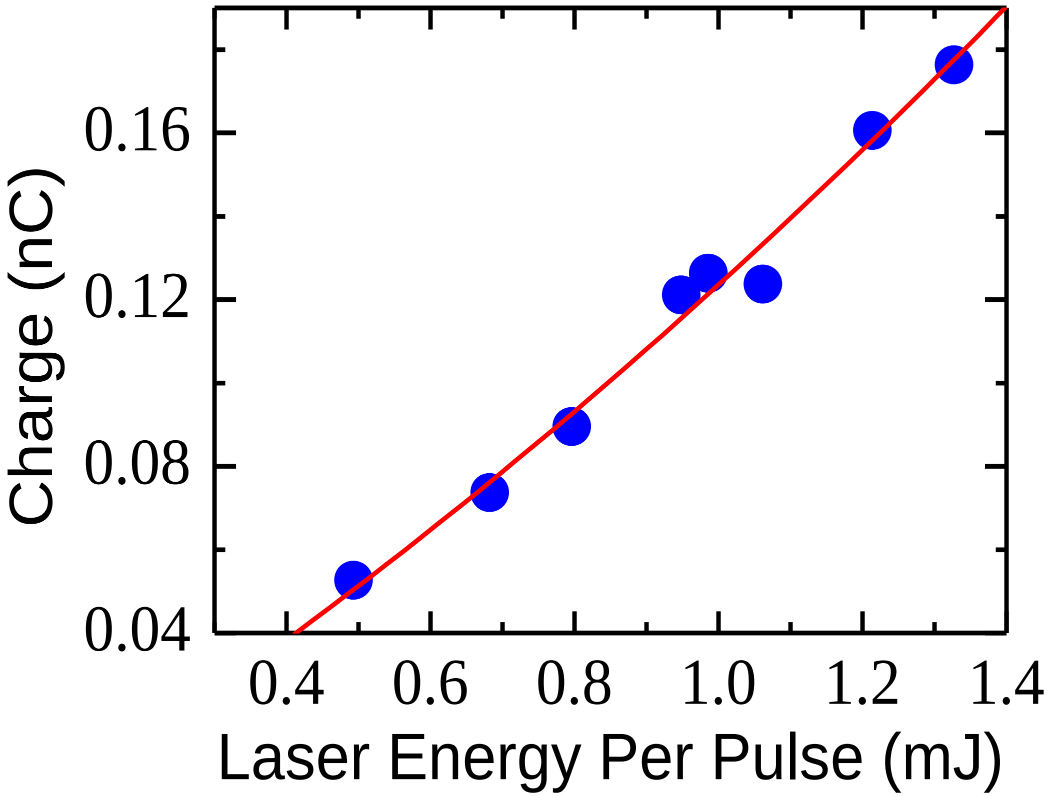
$$\alpha = \sqrt{e/4\pi\varepsilon_0}$$

At threshold, $Q = 0$. This allows us to make a reasonable estimate of the maximum β.

θ_0 (deg)	E_{max} (MV/m)	$E_0 = E_{max}\sin(\theta_0)$ (MV/m)	β
20	28	9.2	6.8
30	17	8.5	7.3
50	14	11	5.8

This is a *new* and viable technique to realistically determine the field enhancement factor of the cathode in a photoinjector

SCHOTTKY-ENABLED PHOTOEMISSION 10 - Experimental Result 2 : Intensity Dependence



Parameters:

$h\nu$ = 3.3 eV

Φ= 3.6 eV

E field on cathode: 80 MV/m

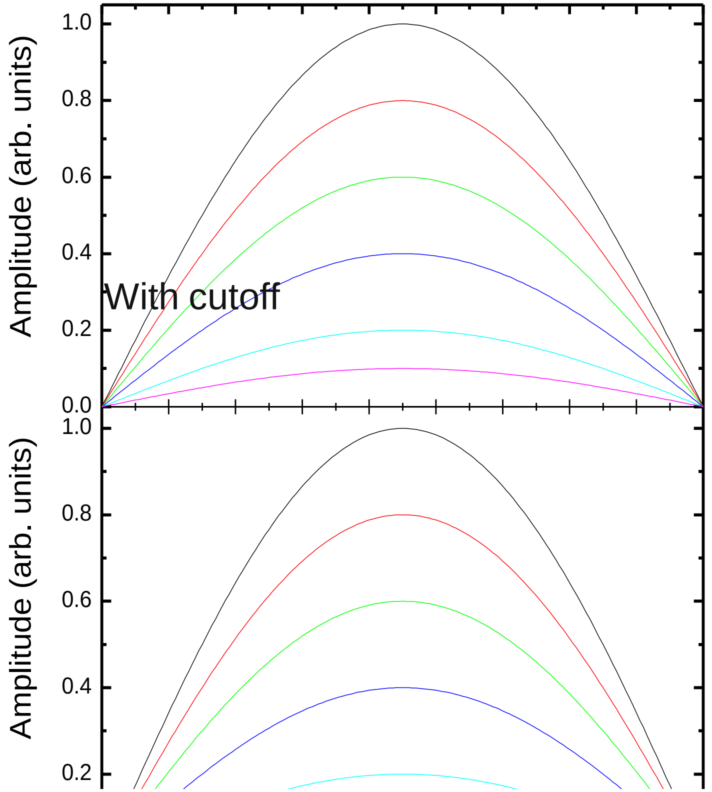
Laser spot diameter: 2 cm

As we increase the laser intensity, we detect more charge. We *definitely* are detecting photoelectrons and not dark currents!

SCHOTTKY-ENABLED PHOTOEMISSION 11- Experimental Results 3 : Detection Threshold?

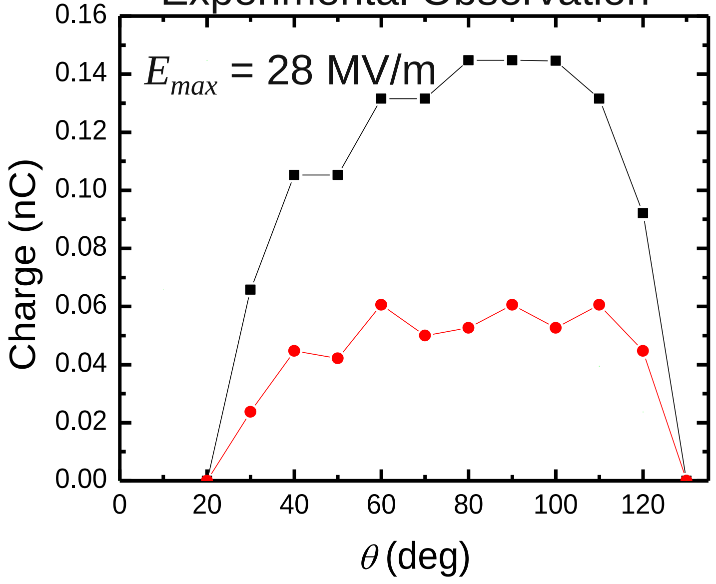
Simulated Detection Threshold
Using A Sine Function

No cutoff



With cutoff

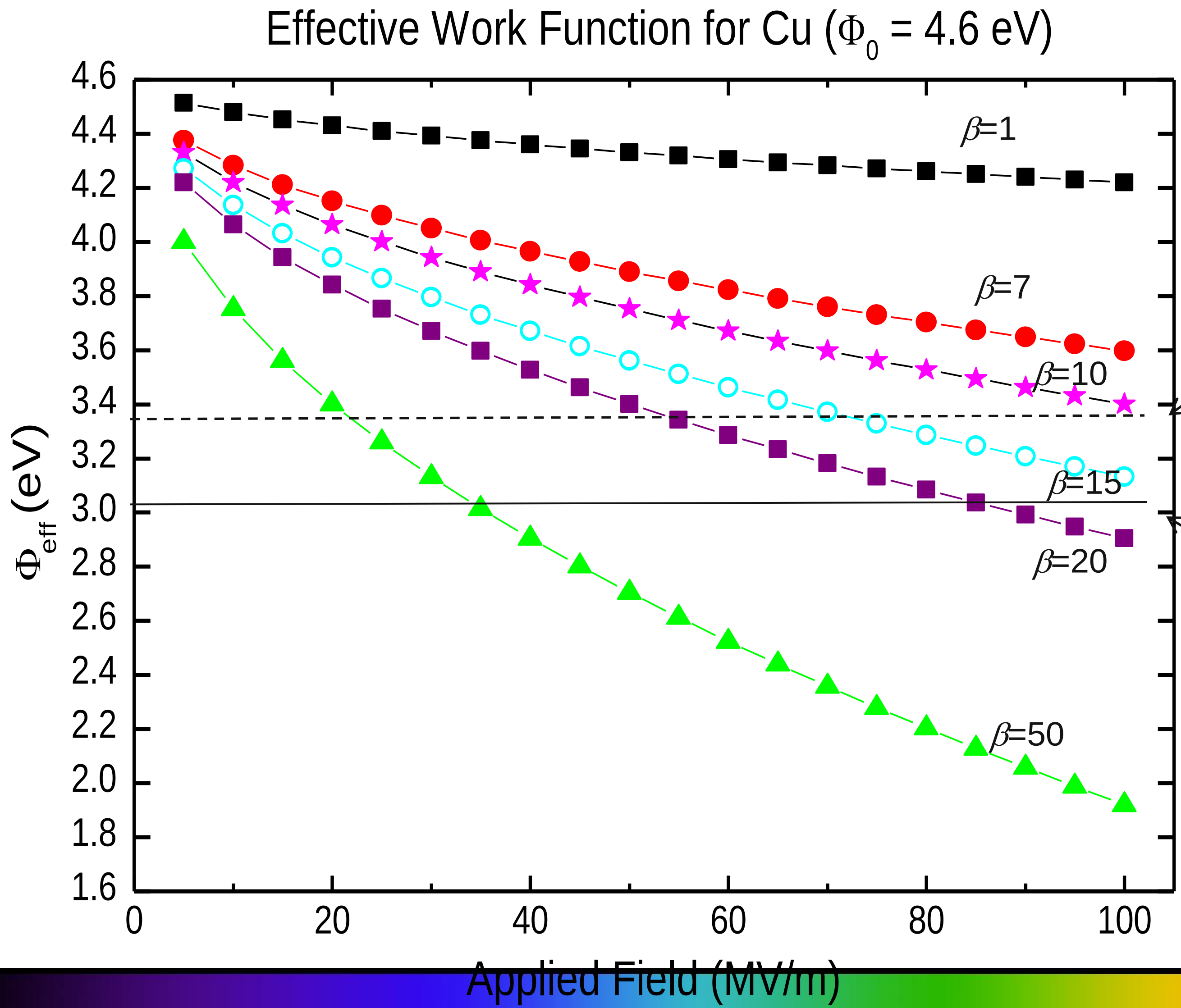
Experimental Observation



Two different scans with different amount of charge produced, but with the same RF amplitude, show the same phase angle for the photoemission threshold.

The shift in the photoemisson threshold is ***not*** due to the detection threshold.

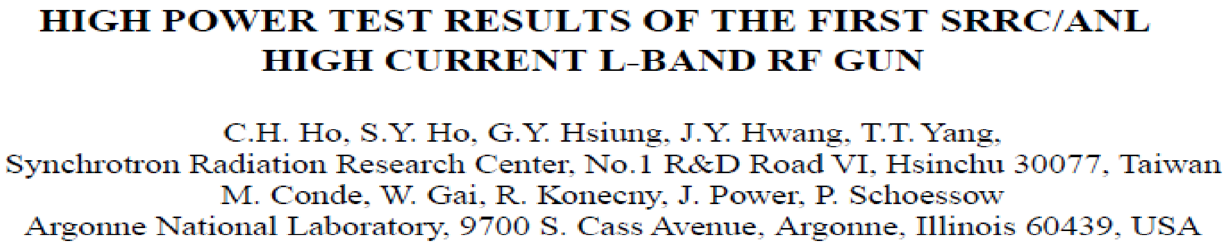
The Effective Work Function for Cu Under External Electric Field



377 nm

400 nm

Estimate of the Field-Enhancement Factor in an RF Photoinjector



HIGH POWER TEST RESULTS OF THE FIRST SRRC/ANL HIGH CURRENT L-BAND RF GUN

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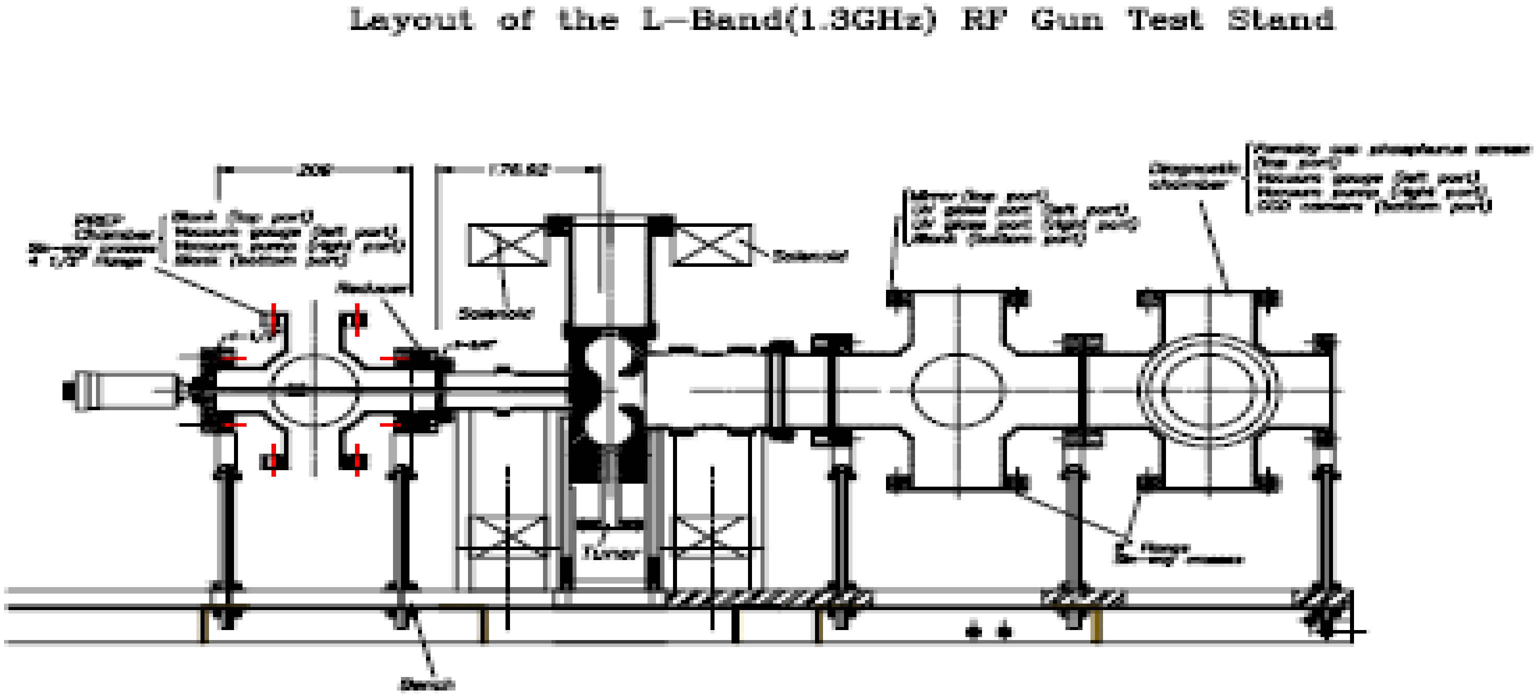
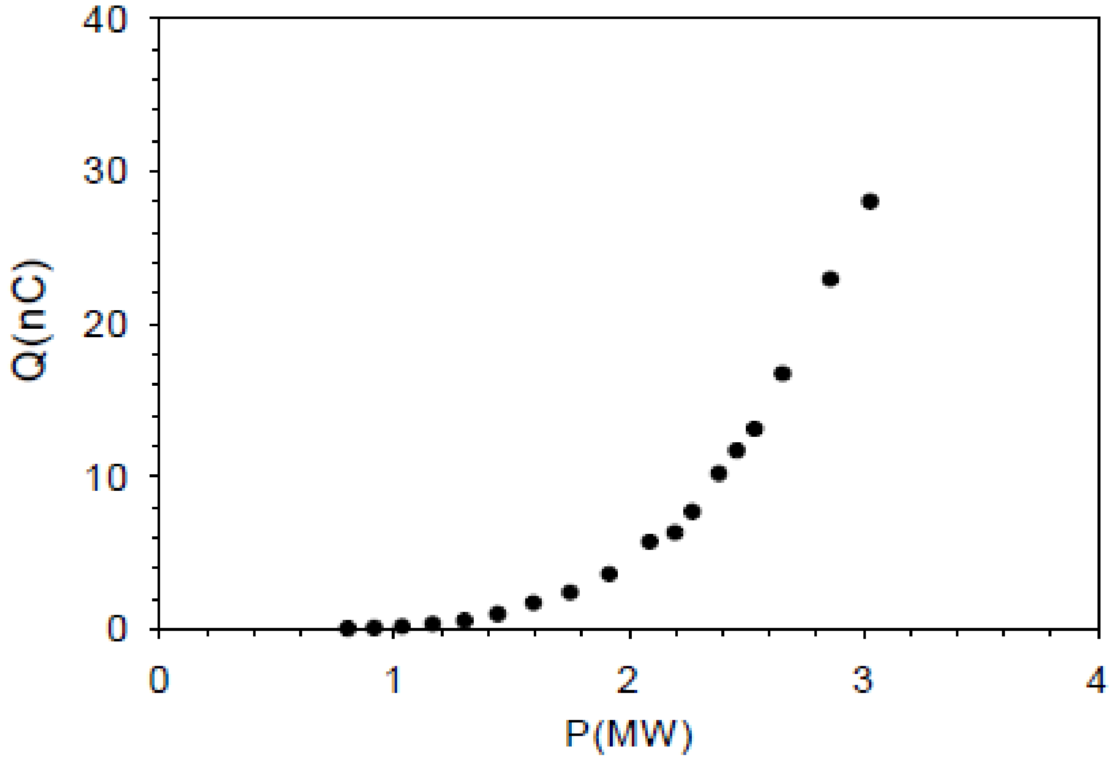


Layout of the L–Band(1.3GHz) RF Gun Test Stand

Figure 5: Layout of the L-band rf gun test stand.

Estimate of the Field-Enhancement Factor in an RF Photoinjector

Measured dark current as a function of forward rf power in the gun (Fig. 8)



To extract the values of (i) current I and (ii) E-field, I used the following:

(i) E-field

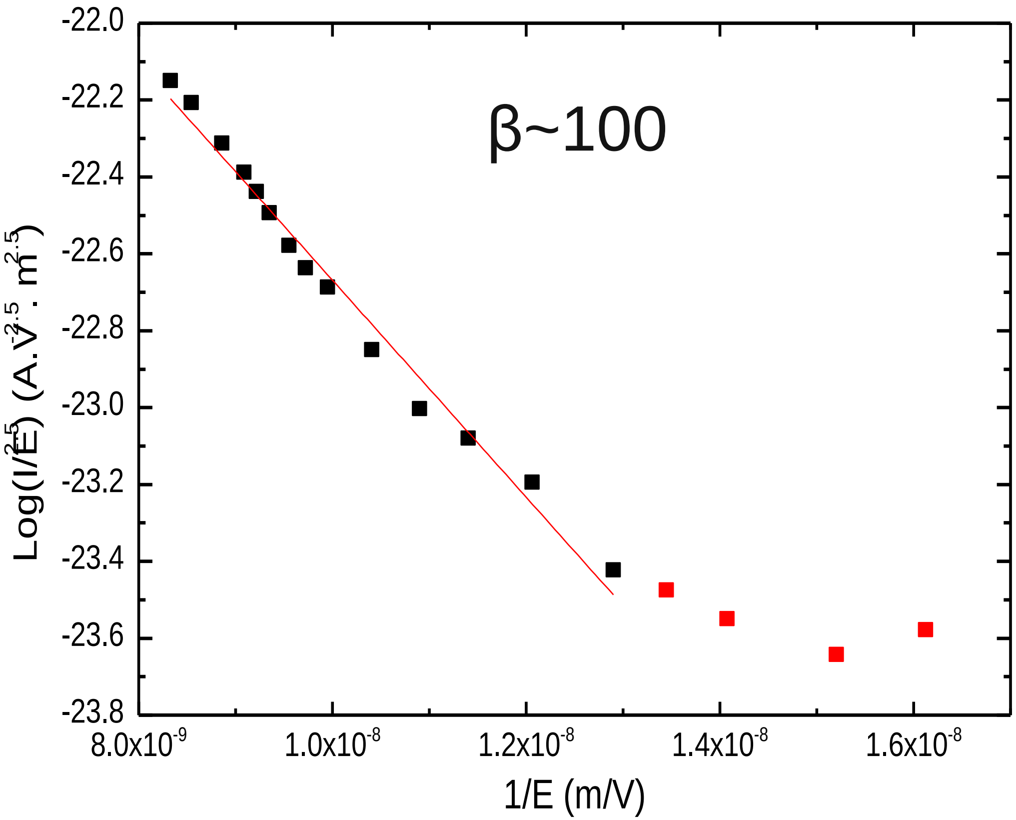
$P = kE^2$.
Since at P=3 MW, E=120 MV/m, we have $k=2.08\times10^{-4}$ MW/(MV/m)^2. From this, E-field can be extracted from the data.

(ii) Current I

Assuming that the dark current pulse length is 2.5 μs, then $I = \Delta Q/\Delta t$. The values of I can then be extracted from Q.

Estimate of the Field-Enhancement Factor in an RF Photoinjector

An estimate of the field-enhancement factor β is made using the Fowler-Nordheim model.



The non-linear data points (red) have been excluded in the fit.

Using Eq. 14 from Wang and Loew (SLAC-Pub-7684), for the case of an RF field, the slope of the graph can be expressed as:

$$\frac{d(\log_{10} I/E^{2.5})}{d(1/E)} = -\frac{2.84\times 10^{9}\phi^{1.5}}{\beta}$$

For Cu, ϕ = 4.6 eV. We then obtain the value of β from the linear fit to be ~100.

Question: Is this the same β as in the Schottky experiments? A: Don’t know, but underline physics should be the same.

What next?

We are planning to perform further experiments with Cu cathodes in both L and S-band guns. (possible setup are at ANL and Tsinghua University)