Photocathode Studies for the Argonne Wakefield Accelerator RF Photoinjector

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OUTLINE

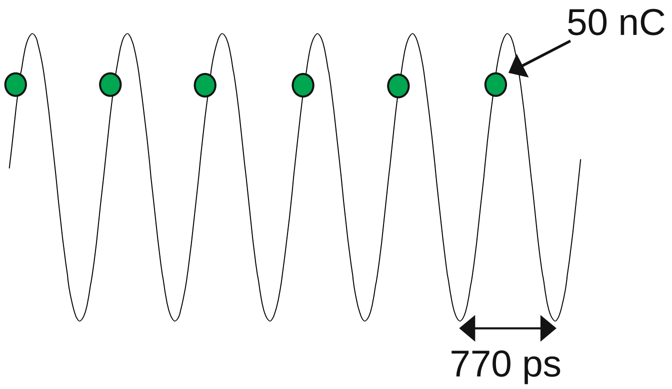
- Overview of photocathodes for photoinjectors;
- Photocathode requirement for the AWA;
- Status of high QE photocathode fabrication at the AWA;
- Schottky-enabled photoemission in photoinjectors;
- High-gradient/breakdown studies.

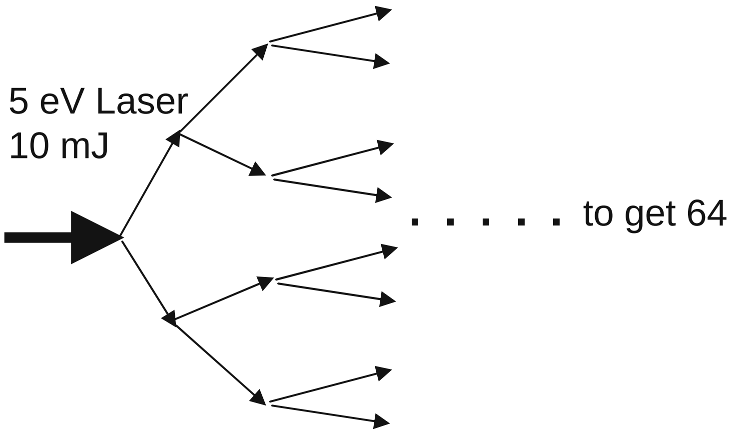
OVERVIEW OF PHOTOCATHODES FOR PHOTOINJECTORS

PHOTOCATHODE	GOOD	BAD
Metallic (*Cu*, *Mg*, *Ag*, etc.)	■Easy to obtain/handle ■Still widely-used ■Does not require UHV ■QE remains constant for long period of time ■Fast response time (~10^{-15}s) ■Low dark currents	■Low QE (~10^{-4}-10^{-6})
Semiconductor (*Cs$_2$Te*, *K$_2$Te*, *GaN*, etc.)	■High QE (0.05 – 0.3) ■Photoelectrons have lower energy spread (in principle) than metallic	■Requires UHV ■Surface deteriorates with O_2 ■Longer response time than metallic (~10^{-13}s) ■Initial QE has short lifetime
Negative Electron Affinity (*GaAs family*, *GaP*, etc.)	■Even higher QE than semiconductor (0.1 – 0.6) ■Widely used in PMT ■Possible source of polarized electrons (GaAs family)	■Requires UHV ■Even longer response time than semiconductor (~10^{-9}s) ■May have higher dark currents
Liquid Metal, Superconducting compatible (*Nb*, *NbN*, etc.)	■Possible use in superconducting RF photoinjector	■Very little is known in accelerator situation ■QE yet to be determined – probably same as metallic?

PHOTOCATHODE REQUIREMENT FOR THE AWA

Creation of charge bunch train up to a maximum of 64 bunches in a single RF pulse





Want 50 nC in each charge microbunch. This is equal to ~ 3×10^{11} electrons.

- 10 mJ of laser energy per pulse;
- Estimate 80% loss due to beam splitter, mirrors, etc.;
- Beam is split into 64 micro pulses;
- Number of photons in each micro pulse is ~4×10^{13}.

QE of photocathode to be able to supply that amount of charge:

$$QE = \frac{3 \times 10^{11}}{4 \times 10^{13}} \approx 0.007 \approx 1\%$$

Need high QE photocathode – choose Cs_2Te

DEVELOPMENT OF Cs_2Te PHOTOCATHODE 1

- High QE photocathode (maximum ~0.1-0.3 and lasts for ~1-2 days). QE then hovers around 0.01 for ~ 1 month;
- A semiconductor with band gap of 3.3 eV and electron affinity of ~0.2 eV. This translates to a “work function” of ~3.5 eV;
- Requires vacuum at or better than 10^{-9} Torr;
- Studies are continuing on (i) possible rejuvenation of QE and (ii) possible coating on surface to improve lifetime.

DEVELOPMENT OF Cs_2Te PHOTOCATHODE 2 – The Recipe

- Deposit 10-20 nm of Te on Mo substrate;
- Then deposit Cs and monitor QE using light source (typically $h\nu$~5 eV);
- Stop when QE reaches a peak.

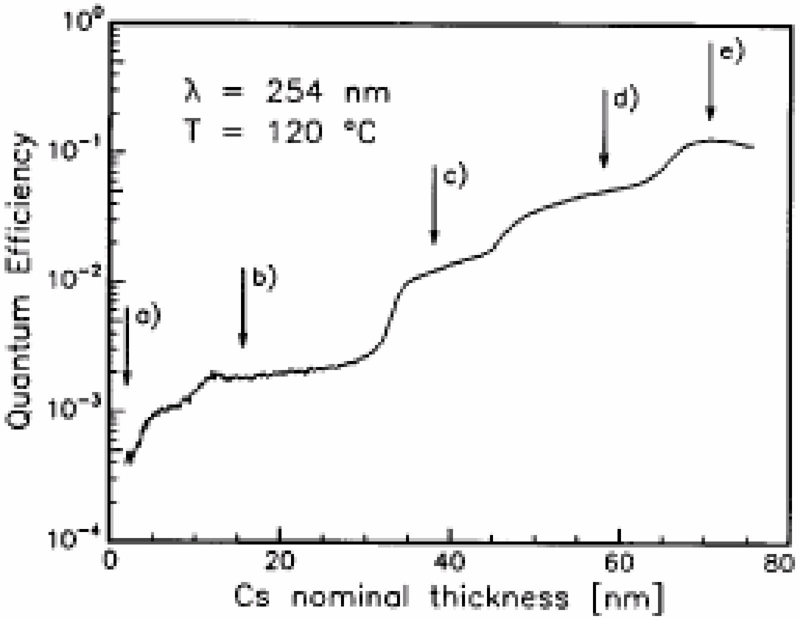
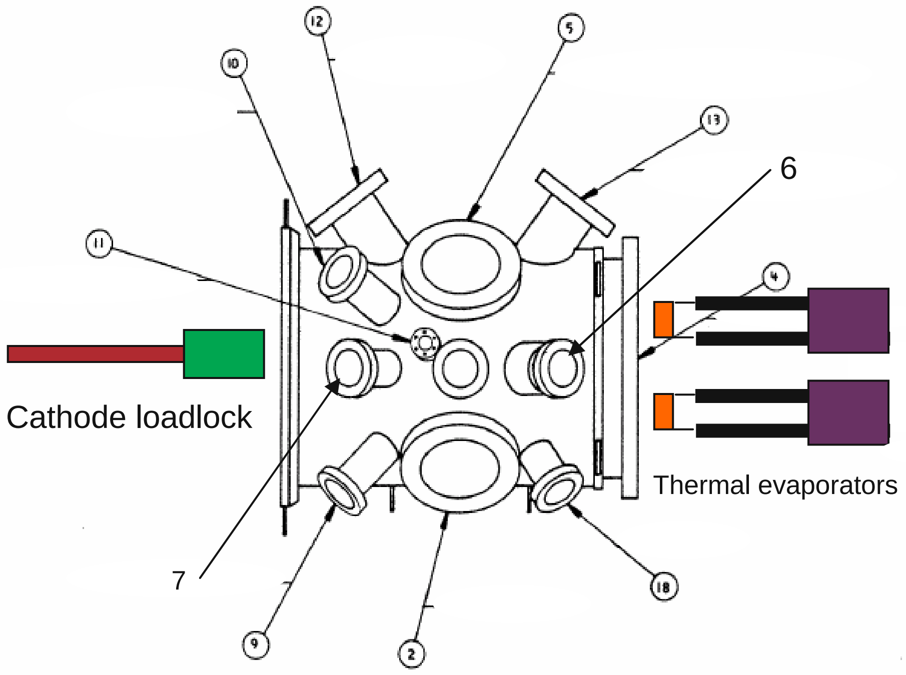


FIG. 1. Quantum efficiency as a function of the Cs nominal thickness during the fabrication of the photocathode. The substrate temperature is held at 120 °C. The arrows indicate the fabrication steps at which XPS experiments have been performed.

di Bona *et al*. J. Appl. Phys. **80**, 3024 (1996)

DEVELOPMENT OF Cs_2Te PHOTOCATHODE 3 – Deposition Facility

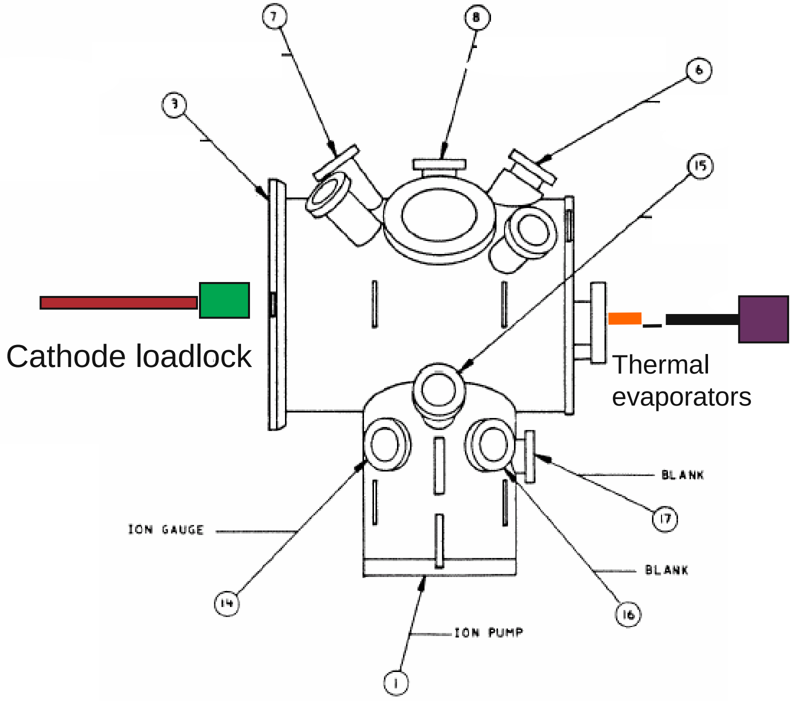
SYSTEM TOP VIEW



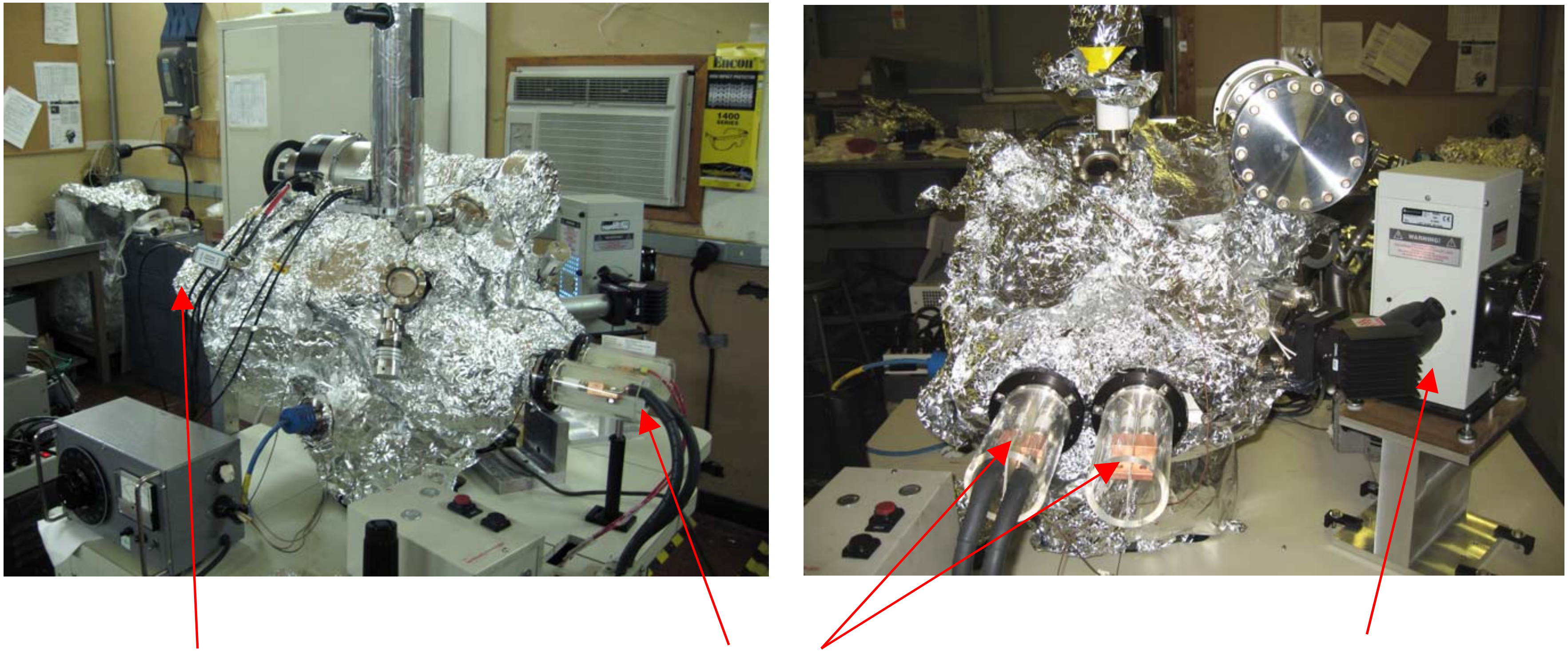
7. Heater/Temp sensor
8. Anode
9. Thickness monitor
13. Hg light source

SYSTEM SIDE VIEW

7. Heater/Temp sensor
8. Anode
9. Thickness monitor
13. Hg light source



DEVELOPMENT OF Cs_2Te PHOTOCATHODE 4 – Deposition Facility (cont)

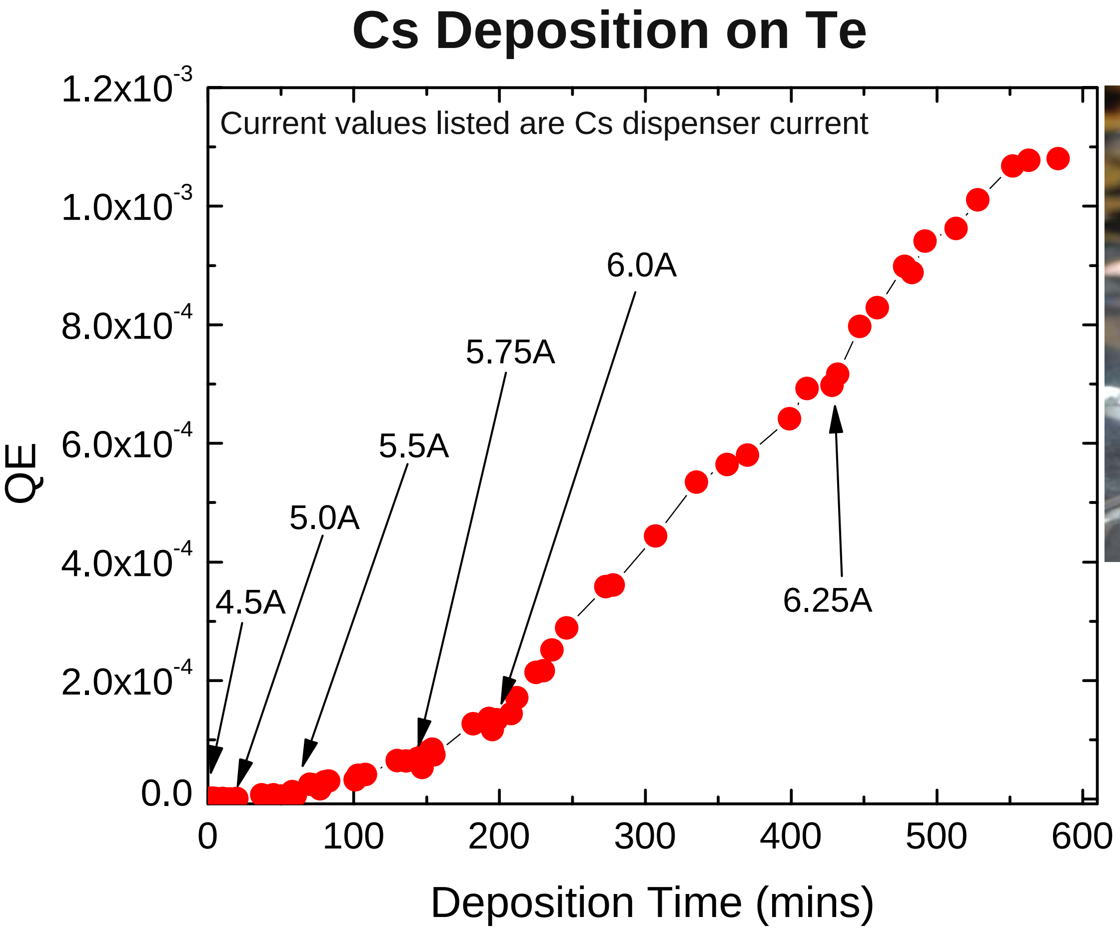


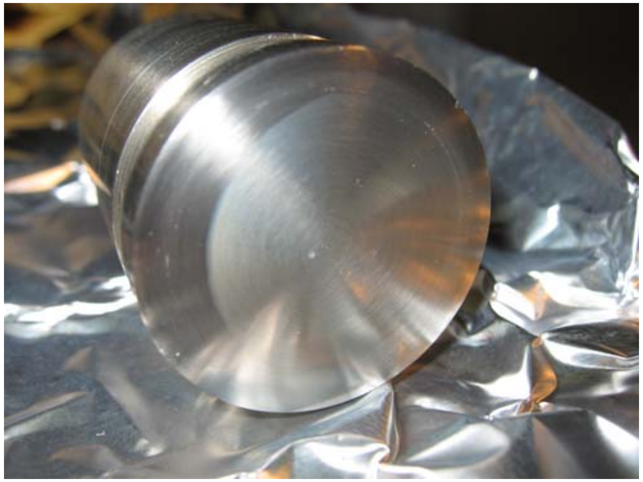
Cathode load-lock transfer will be connected at this end

Thermal evaporators

Hg lamp

DEVELOPMENT OF Cs_2Te PHOTOCATHODE 5 – Our Progress So Far





We are ~2 orders of magnitude lower than expected. A few modifications will be made to the deposition chamber configurations.

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

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

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

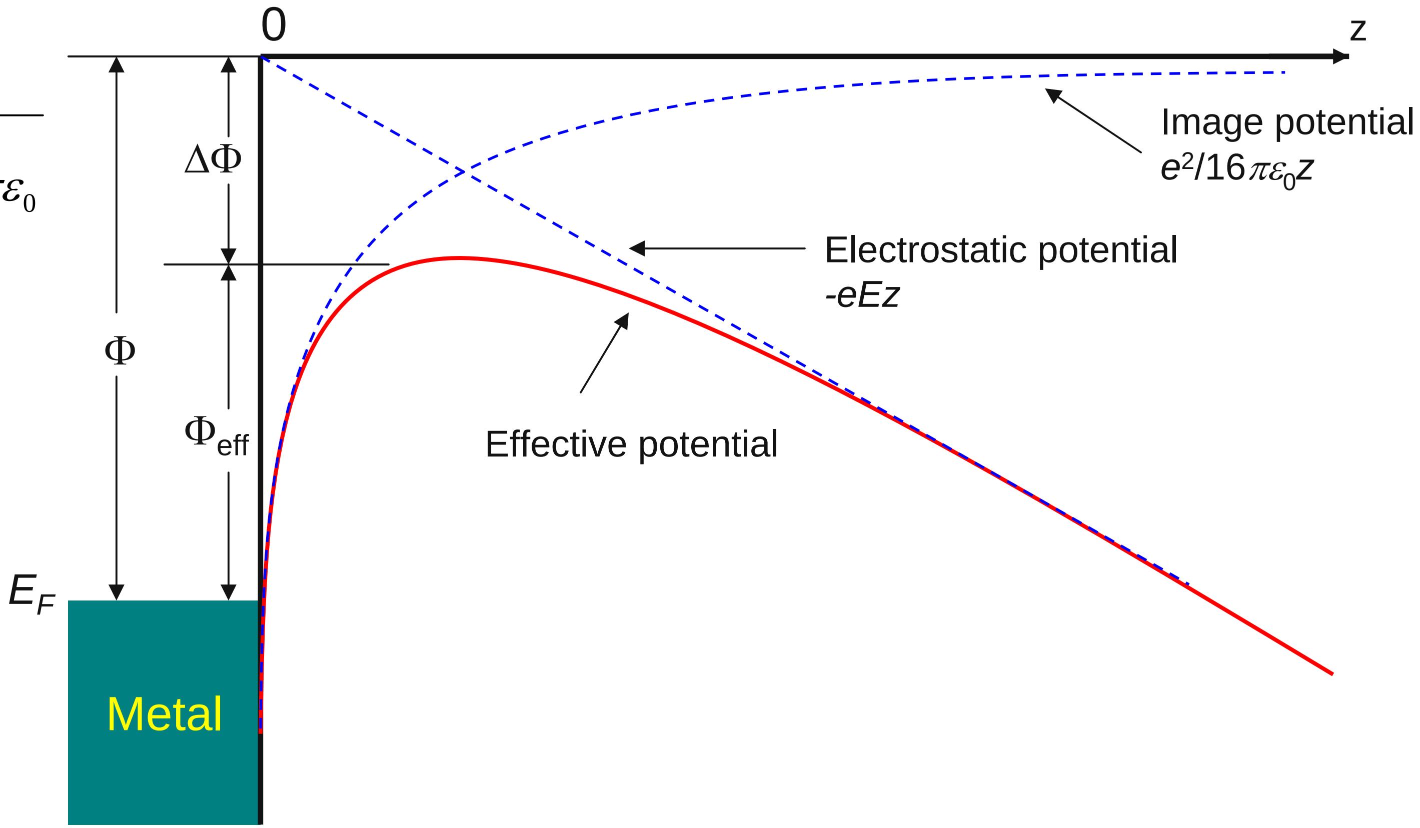
However, for a cathode in an electric field E: $E_{kin} = h\nu \underbrace{- \Phi + \alpha\sqrt{\beta E(\phi)}}_{-\Phi_{eff}}$

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 $\Phi_{eff} = \Phi - \alpha\sqrt{\beta E(\theta)}$

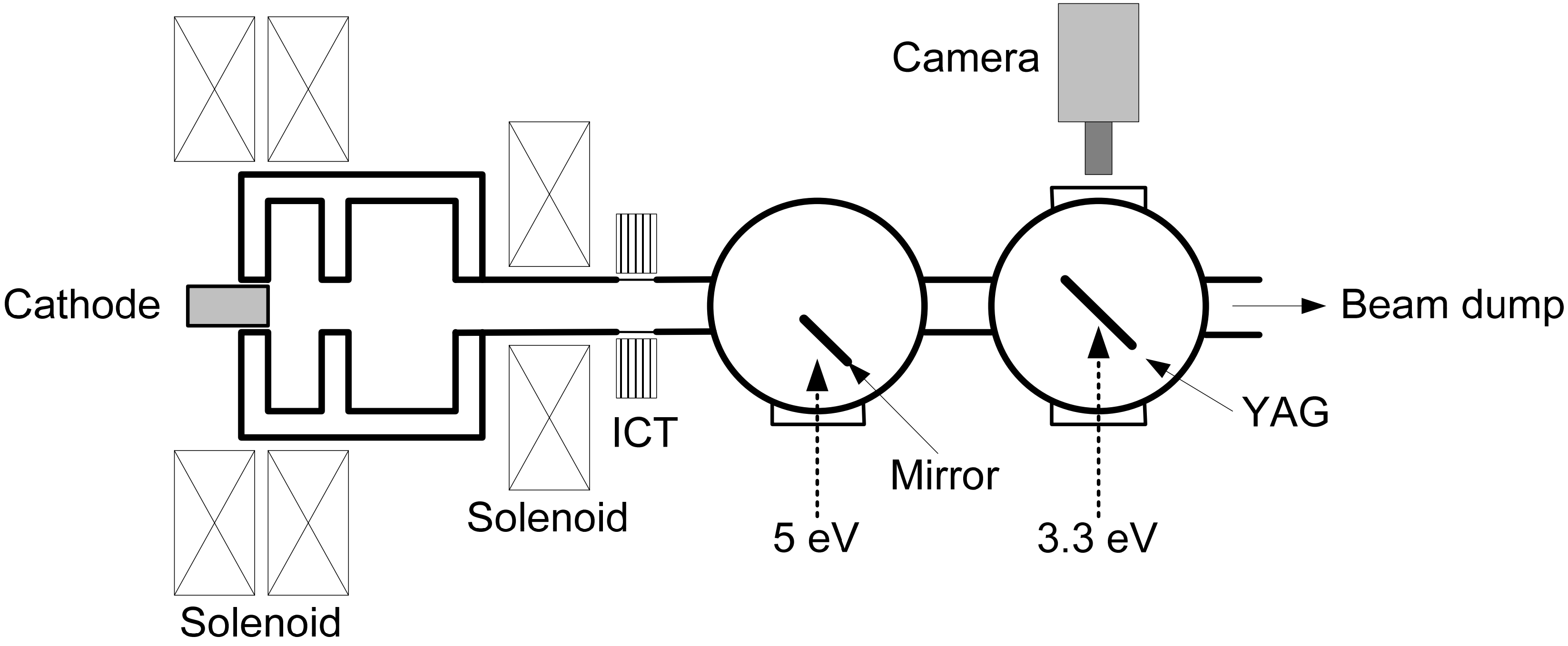
SCHOTTKY-ENABLED PHOTOEMISSION 4 – The Schottky Effect

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



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

SCHOTTKY-ENABLED PHOTOEMISSION 5 – Schematic of Beamline

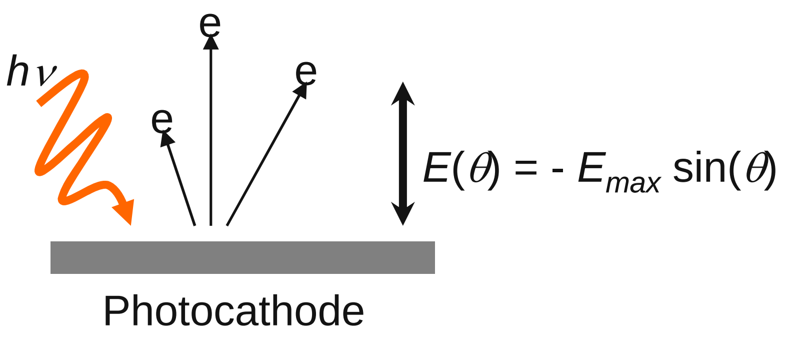


Light source: Frequency-doubled Ti:Sapphire laser 372 nm (3.3 eV), 1 – 4 mJ, 8ps.

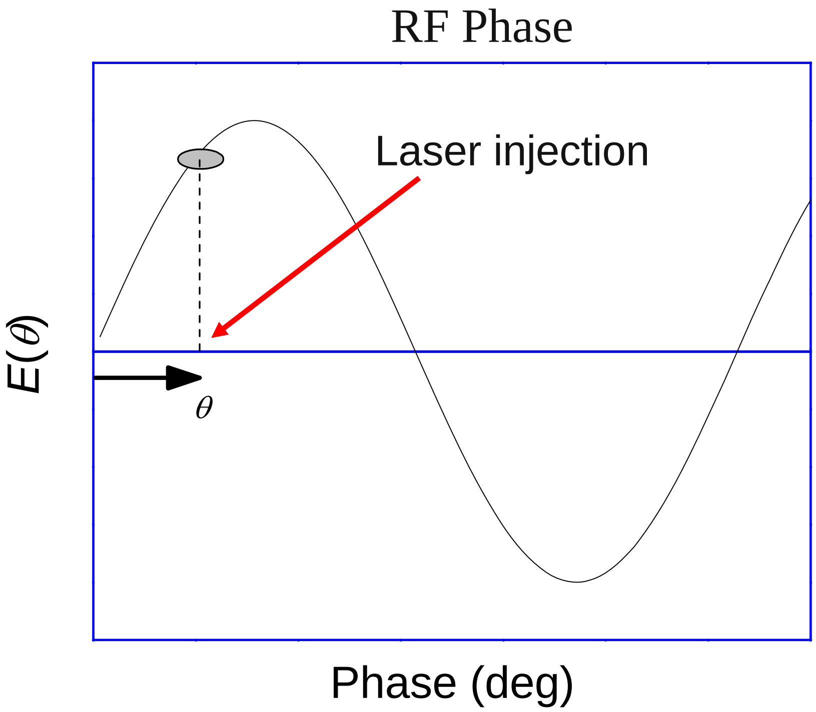
Photocathode: Mg, Φ = 3.6 eV.

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

SCHOTTKY-ENABLED PHOTOEMISSION 6 - RF Scans



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



RF frequency = 1.3 GHz (Period ~ 770 ps)

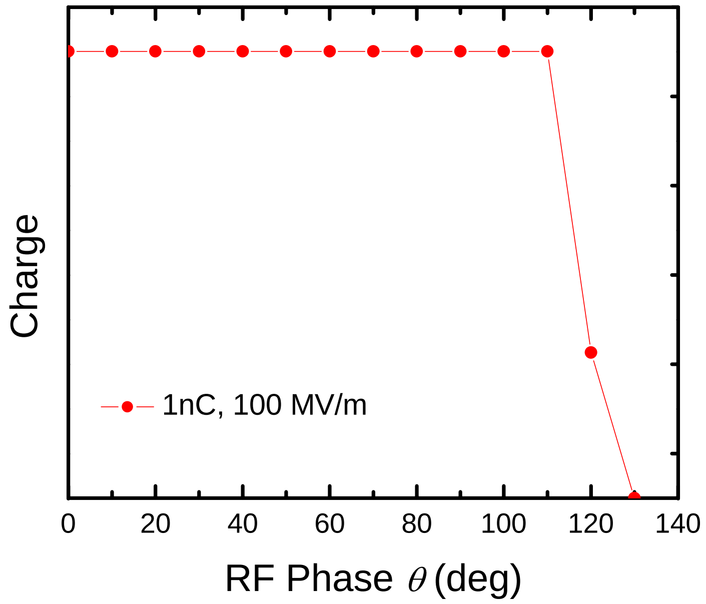
Laser pulse length = 6 – 8 ps

Metallic photocathode response time ~ fs

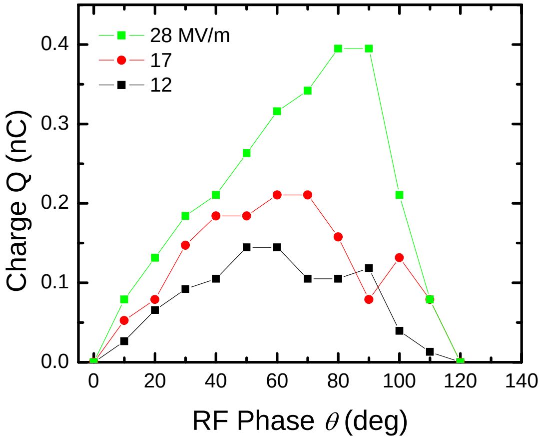
We can safely assume that all the photoelectrons emitted in each pulse see the same *E*-field strength

SCHOTTKY-ENABLED PHOTOEMISSION 7 - Charge Obtained From Typical RF Scans

Theoretical RF Scan



Experimental RF Scan



Our scans

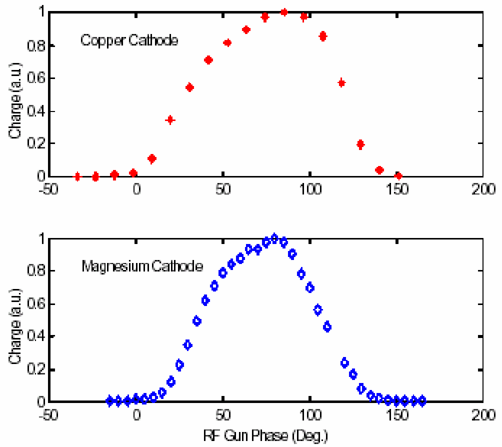


Figure 3: Photoelectron charge as function of RF gun phase for different cathode materials.

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

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

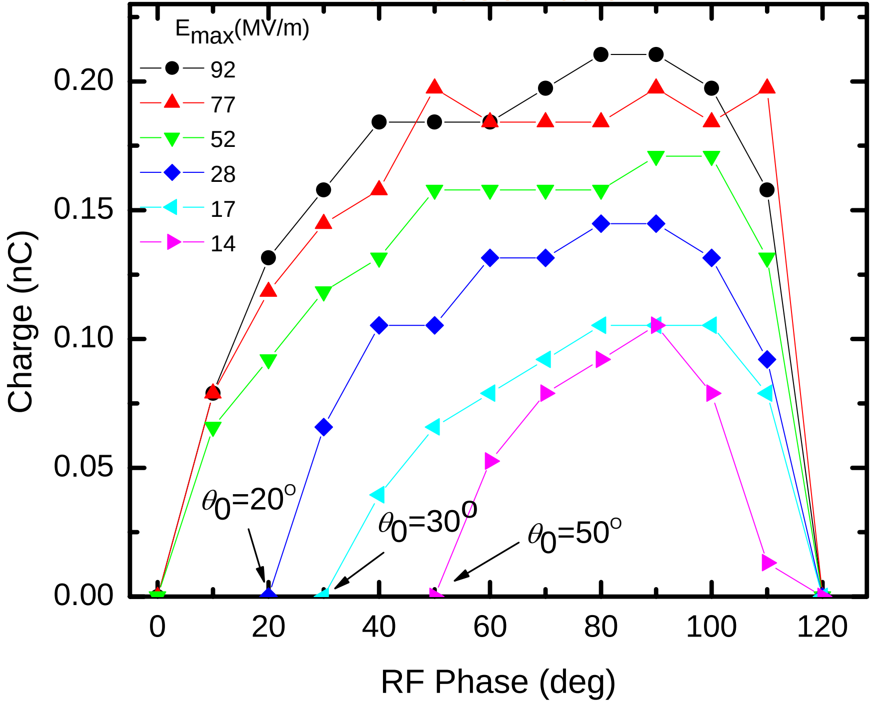
We see the “expected” flat-top profile

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

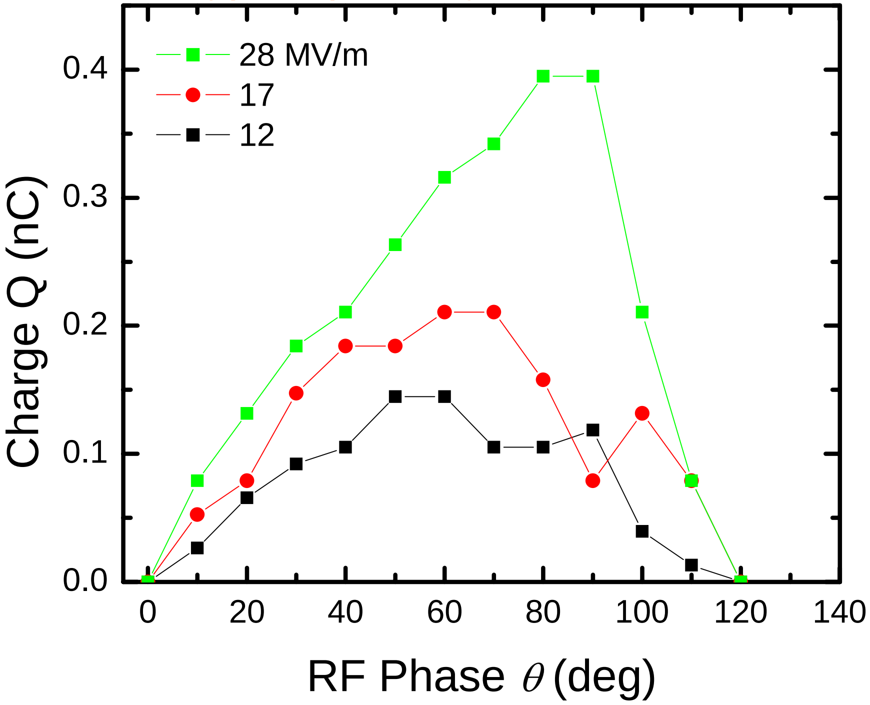


$h\nu$ = 3.3 eV; Φ = 3.6 eV

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

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

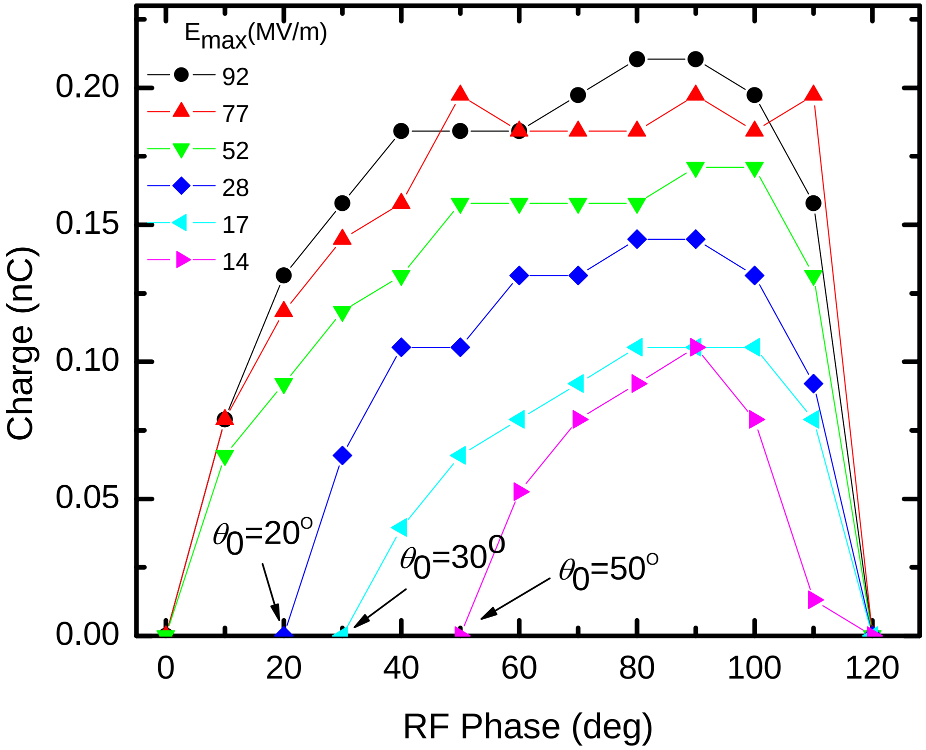
Typical photoinjector conditions



$h\nu$ = 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; Φ = 3.6 eV

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

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

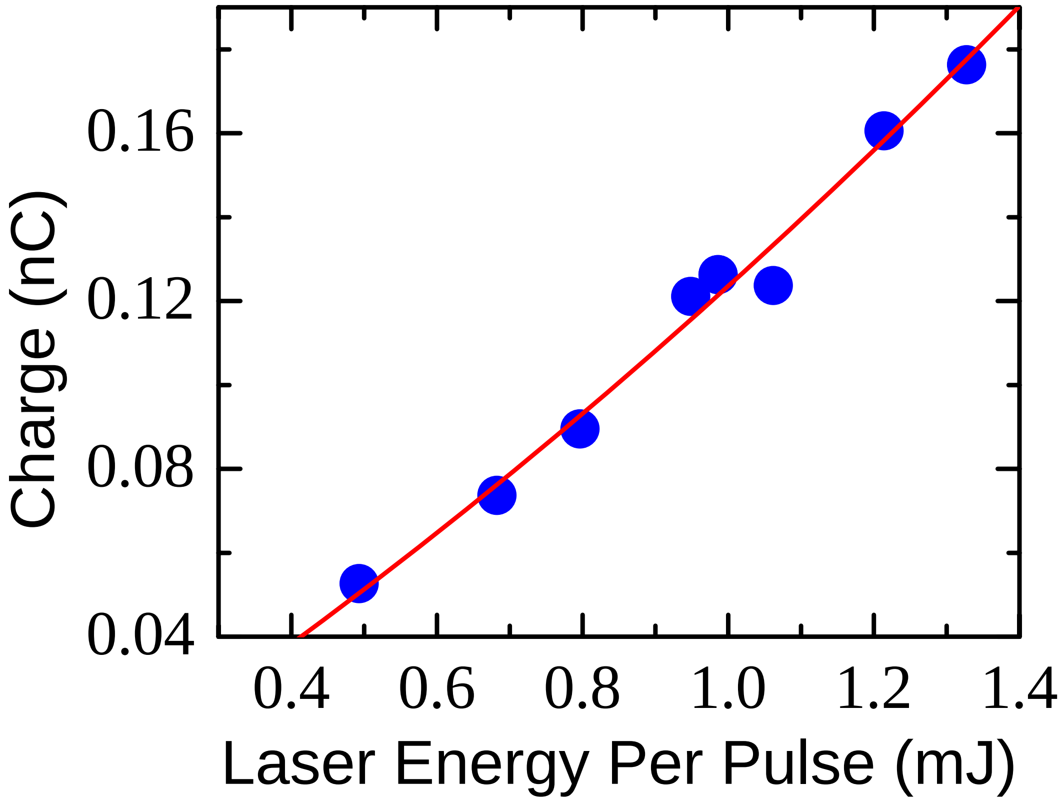
$$\alpha = \sqrt{e/4\pi\varepsilon_0}$$

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

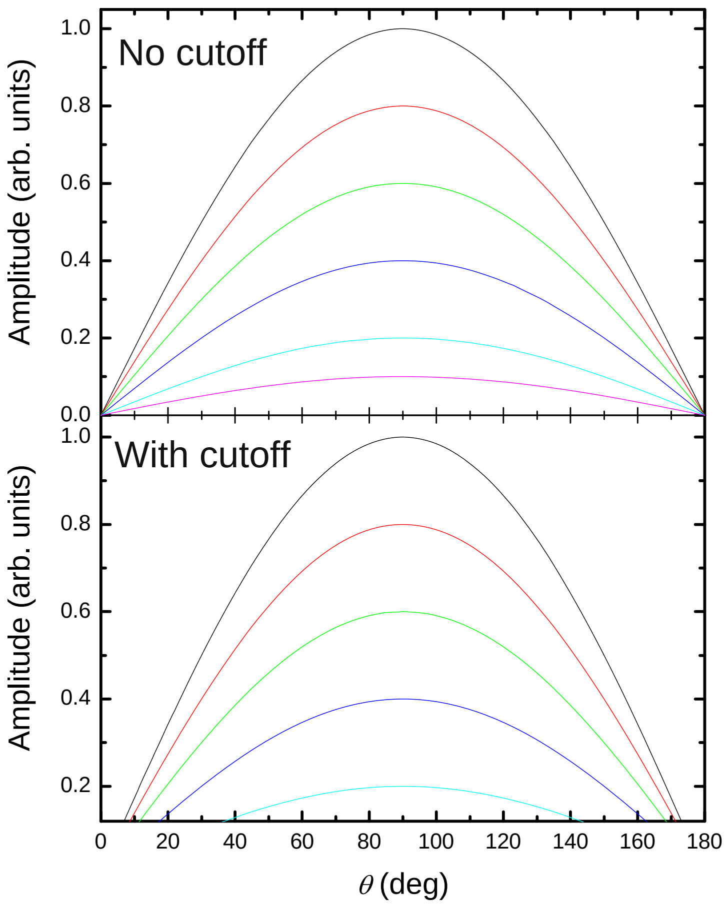
E field on cathode: 80 MV/m

Laser spot diameter: 2 cm

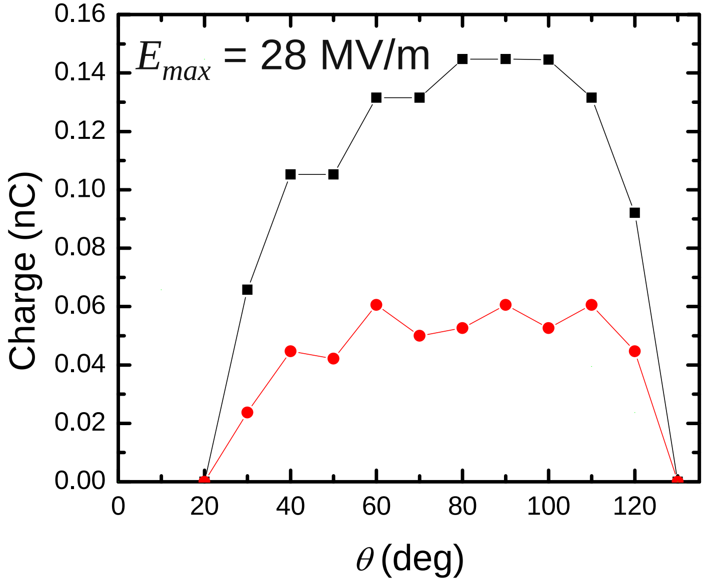
As we increase the laser intensity, we detect more charge. We *definitely* are detecting photoelectrons and not dark currents!

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

Simulated Detection Threshold Using A Sine Function



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.

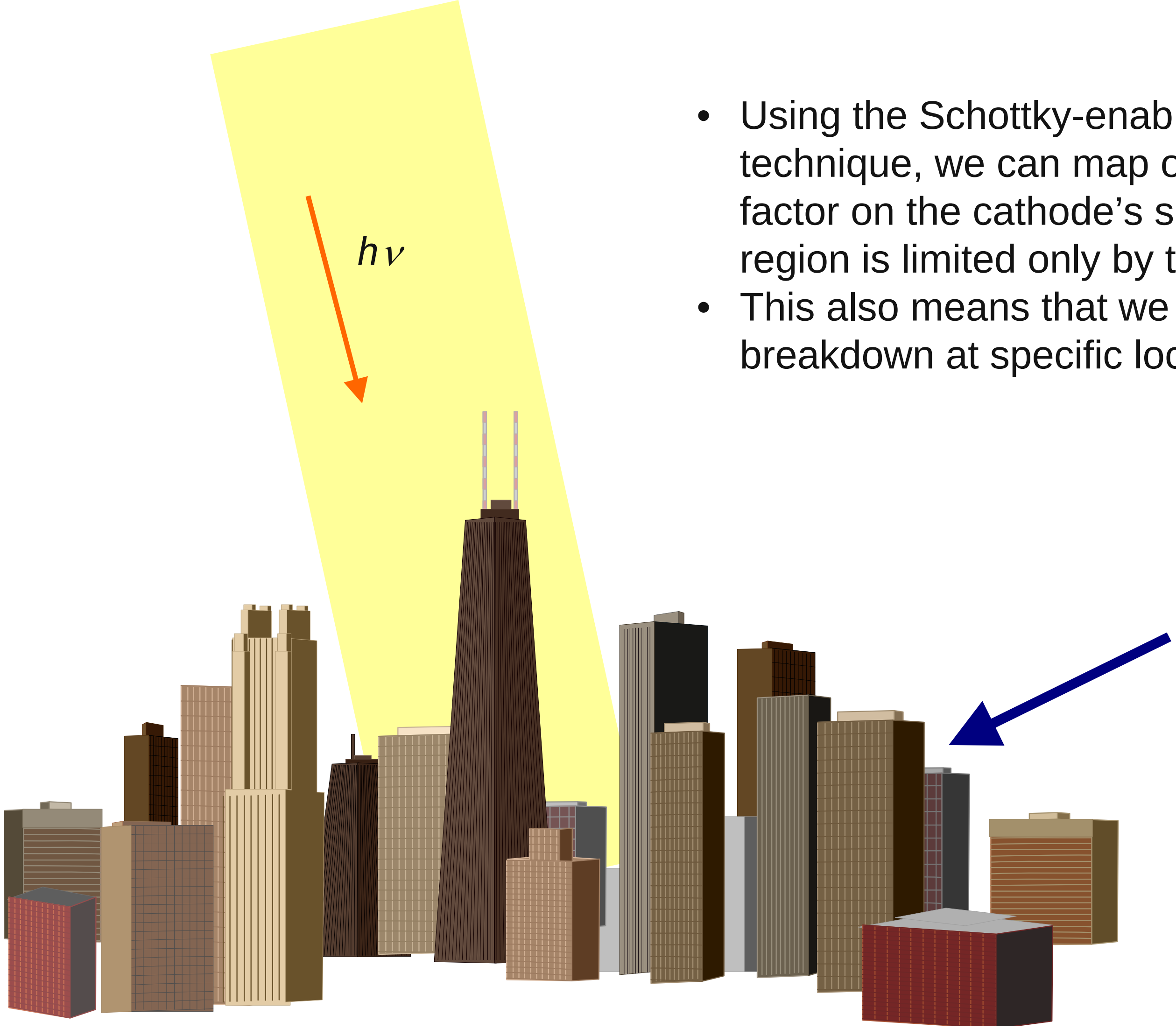
The shift in the photoemisson threshold is ***not*** due to the detection threshold.

HIGH GRADIENT/BREAKDOWN STUDIES 1

- Several different mechanisms have been proposed that triggers a breakdown event in high-gradient environment;
- All of them start with regions on the surface with high field-enhancement factor;
- Can we address/answer some of the nagging issues surrounding the breakdown mechanism?
- We would like to (i) map out the field-enhancement factor on the surface of a cathode, (ii) map out the dark current produced by the cathode, and (iii) try to trigger a breakdown event at a particular location using a combination of high fields and high-power laser.

HIGH GRADIENT/BREAKDOWN STUDIES 2 – Mapping Out The Field-Enhancement Factor

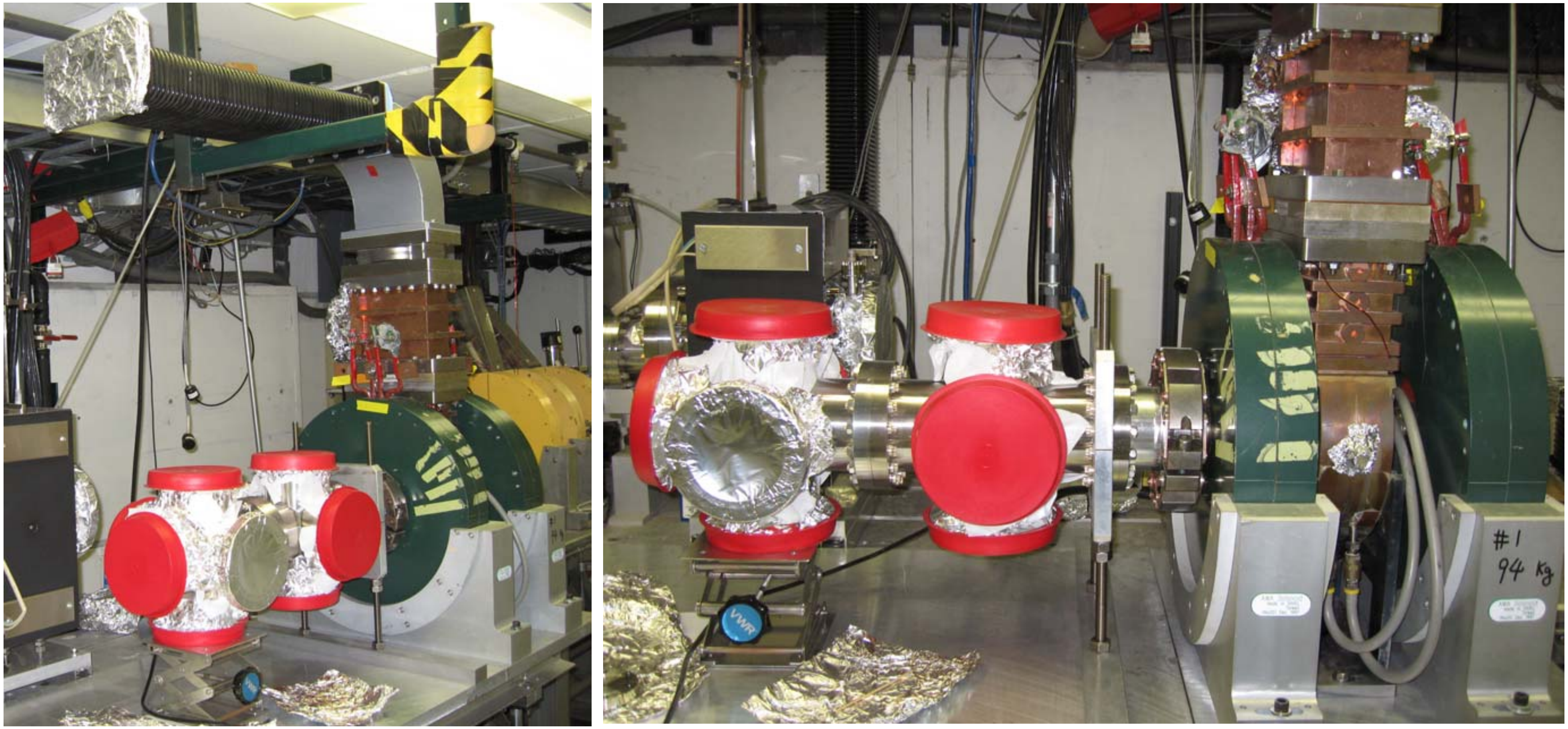
- Using the Schottky-enabled photoemission technique, we can map out the field-enhancement factor on the cathode’s surface. The size of each region is limited only by the size of the laser spot.
- This also means that we can try to trigger breakdown at specific locations on the cathode.



Surface of cathode with various field enhancement factor.

HIGH GRADIENT/BREAKDOWN STUDIES 3 – Dedicated Facility

- ½ cell gun, Maximum gradient ~120 MV/m
- Diagnostics to be installed: ICT, Faraday cup, gated camera, etc.



SUMMARY

- AWA needs high QE photocathode. Cs_2Te seems to be the best candidate at the moment;
- The Schottky-enabled photoemission technique can, in principle, produce electron beam with low intrinsic emittance;
- The same technique can realistically determine the field enhancement factor of a cathode's surface *in situ*, independent of the Fowler-Nordheim model;
- The ability to determine the local field enhancement factor is the starting point for the high-gradient/breakdown studies.