# Photocathode Surface Roughness: A Systematic Study

Benjamin L. Rickman, Louis Angeloni, and W. Andreas Schroeder

*University of Illinois at Chicago, Department of Physics (m/c 273), 845 W. Taylor Street, Chicago, IL 60607-7059*

## Introduction

- A detailed systematic study of the effect of surface roughness on the transverse emittance; specifically, the RMS transverse momentum, $\Delta p_T$, of electron pulses generated in a 'low-field' laser driven DC gun.
- Agreement between theoretical analyses and experiment confirms that the total $\Delta p_T$ is dependent upon three factors:
  - (i) The intrinsic RMS transverse momentum of the photocathode, $\Delta p_{T,0}$ – dependent upon $\Delta E = \hbar\omega - \phi$, band structure, etc.
  - (ii) The RMS photocathode surface roughness, $R_q$ – introduces local transverse surface fields that increase $\Delta p_T$
  - (iii) The RMS slope of the photocathode surface, $\Delta_q$ – influences electron emission direction through $\mathbf{p}_T$ conservation

## Approach

Two key components:

1. Solenoid scan determination of $\Delta p_T$(roughness) with 'low-field' DC gun
   - $\Rightarrow$ 'Very rough' photocathode surface required
     - $\therefore$ Roughness measurement by optical scattering techniques
2. Work function variation with crystal orientation (i.e., $\phi_{(ijk)}$)
   - $\Rightarrow$ Either (i) a polycrystalline photocathode; $\phi_{RMS} \approx$ constant (i.e., crystal facet surface distribution independent of roughness parameters $R_q$ and $\Delta_q$)
     - – polycrystalline Mo
   - Or (ii) single-crystal material with $\phi_{(ijk)} \approx$ constant
     - – GaSb(001)

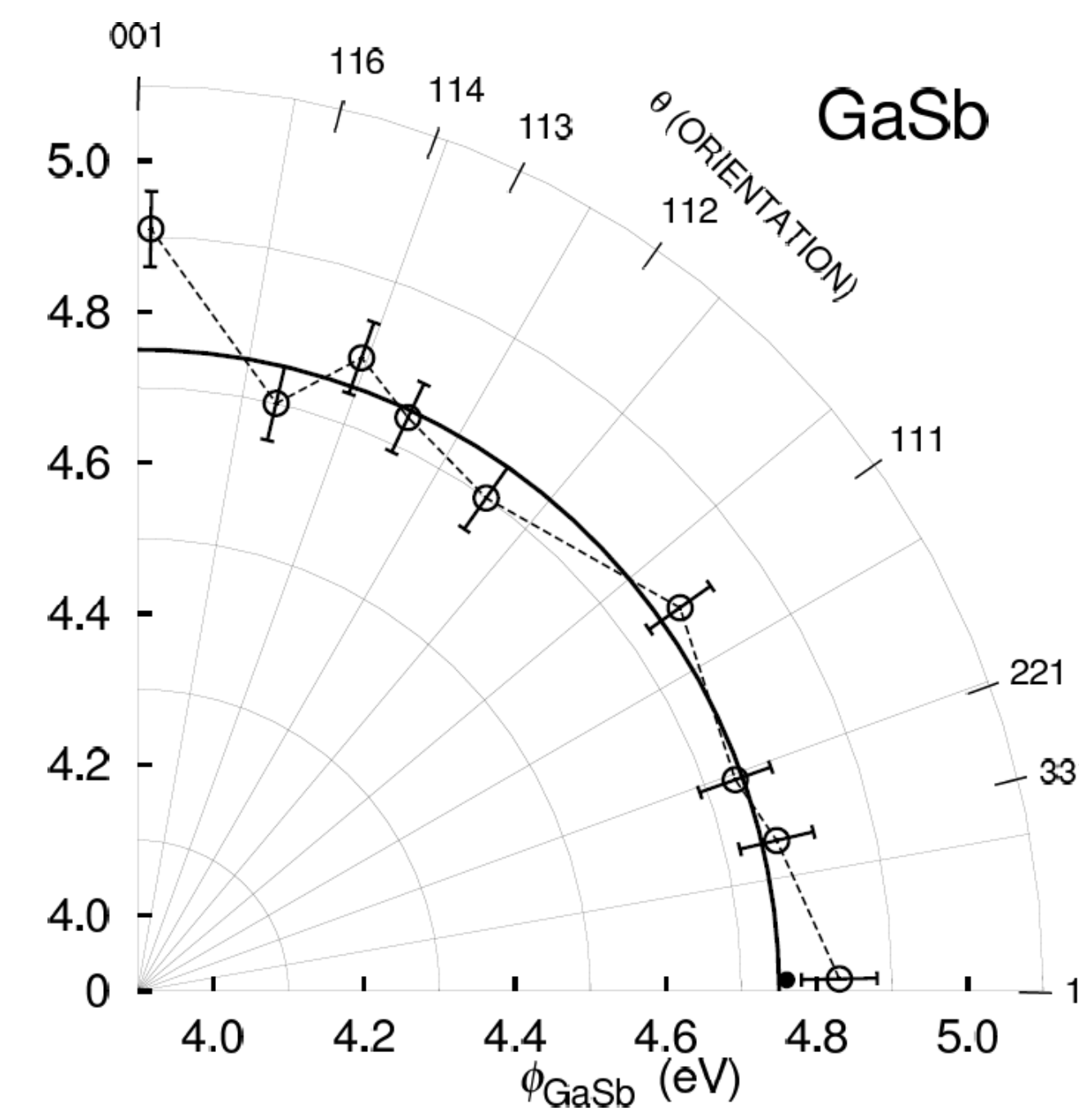


***Figure 1***
DFT-based thin-slab evaluation of $\phi_{(ijk)}$ for GaSb (open circles with $\pm$0.05eV uncertainty); $\hbar\omega$ = 4.75eV (solid line); literature value for $\phi_{(110)}$ = 4.76eV (black circle).

## Methods

### Optical measurement of $R_q$ and $\Delta_q$

- Definitions:

RMS surface roughness, $R_q = \sqrt{\frac{1}{L}\int_0^L h^2(x)dx}$

RMS slope, $\Delta_q = \sqrt{\frac{1}{L}\int_0^L \left(\frac{\partial h(x)}{\partial x}\right)^2 dx}$

… for $h(x) = a\cos\left(\frac{2\pi x}{b}\right)$; $R_q = \frac{a}{\sqrt{2}}$ and $\Delta_q = \frac{\sqrt{2}\pi a}{b}$ .

- Optical scattering measurement:
  - – Light source: Red ($\lambda$ = 635nm) diode laser beam
  - – Photocathodes roughened using 5μm to 120-grit 'polishing' paper
  - – Brass and stainless steel 'standards' employed to test technique
  - – Measurement of $R_{spec.}(\theta_i)$ and $I(\theta)$ allows extraction of $R_q$ and $\Delta_q$:

(i) Specular reflection, $R_{spec.}(\theta_i) = R_0 \exp\left[-\left(\frac{4\pi R_q \cos\theta_i}{\lambda}\right)^2\right]$

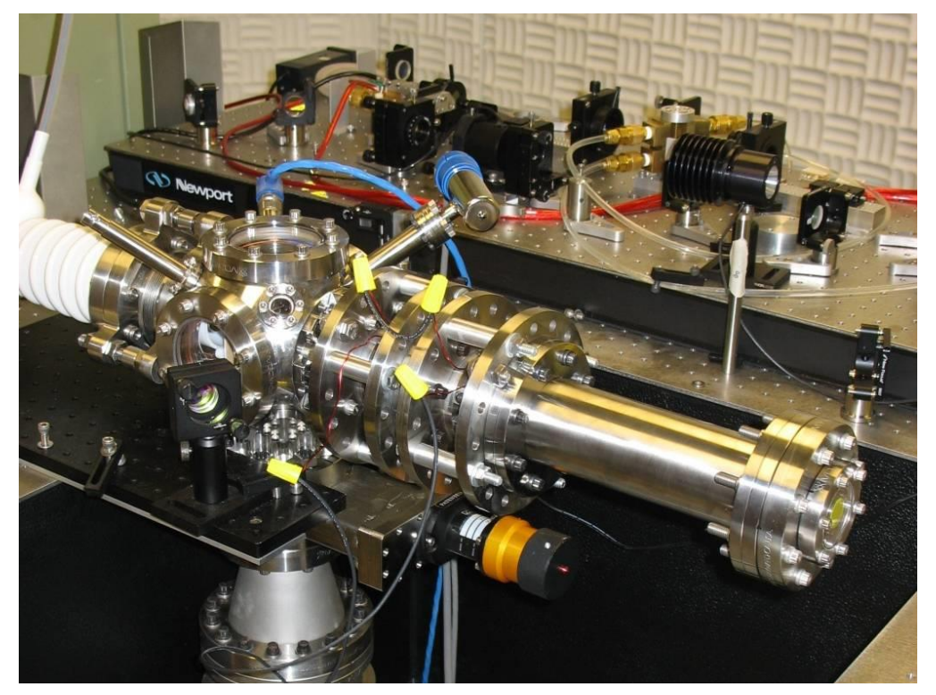
$\Rightarrow$ Measure width of specular reflection peak at different incident angles $\theta_i$ to extract $R_q$

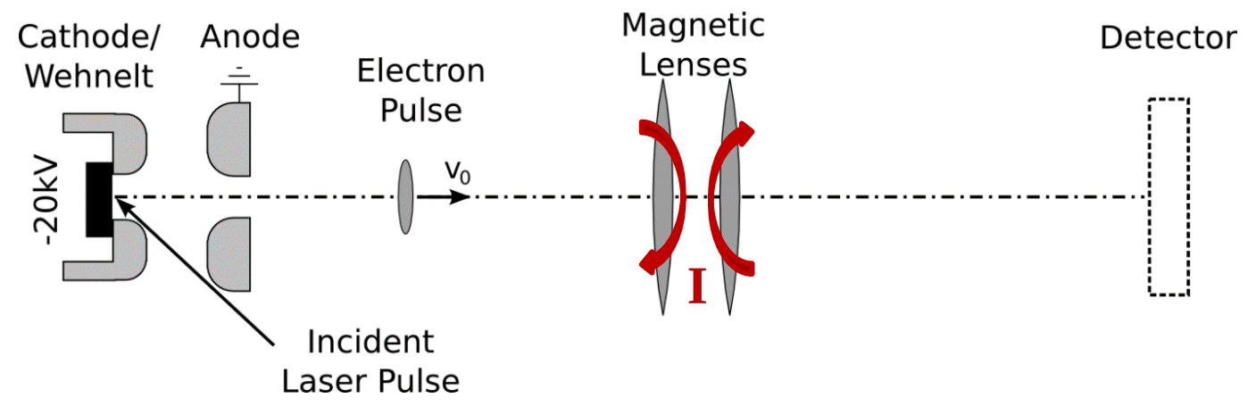
(ii) $\Delta_q = \frac{1}{2}\sqrt{\frac{1}{I_0}\int_{-\pi/2}^{\pi/2} d\theta\,(\theta-\theta_r)^2 I(\theta)}$

where $I_0 = \int_{-\pi/2}^{\pi/2} d\theta\, I(\theta)$ and $\theta_r = \frac{1}{I_0}\int_{-\pi/2}^{\pi/2} d\theta\, \theta I(\theta)$

$\Rightarrow$ Measure $I(\theta)$ for $\theta_i$ = 0° to extract $\Delta_q$

### Solenoid scan technique





- 2W, 250fs, 63MHz , diode-pumped Yb:KGW laser
  - – ~4ps at 261nm ($\hbar\omega$ = 4.75eV)
- YAG scintillator optically coupled to CCD camera
  - – Beam size vs. magnetic coil (lens) current measured
  - – Analytical Gaussian (AG) pulse propagation model to extract $\Delta p_T$

## Theory

For $h(x) = a\cos\left(\frac{2\pi x}{b}\right)$, transverse velocity 'kick' due to surface roughness

$$\dot{x}(x_0,\theta) = \underbrace{v_{x,0}(x_0,\theta)}_{\text{Transverse velocity due to slope angle}} + \underbrace{\frac{2\pi a}{b}\left(\frac{qE_0 b}{4m}\right)^{\frac{1}{2}} \exp\left[\frac{\pi m v_{z,0}^2(x_0,\theta)}{qE_0 b}\right] \operatorname{erfc}\left[\left(\frac{\pi m v_{z,0}^2(x_0,\theta)}{qE_0 b}\right)^{\frac{1}{2}}\right] \sin\left(\frac{2\pi x_0}{b}\right)}_{\text{Transverse velocity due to roughness-induced transverse field components}}$$

… $E_0$ is the acceleration field at the photocathode surface; $v_{x,0}$ and $v_{z,0}$ are the initial transverse and longitudinal electron velocity components at photocathode position $x_0$

$\Delta p_T$ can then be evaluated using $(\Delta p_T)^2 = \dfrac{\int_0^b dx_0 \int_{-\pi/2}^{\pi/2} d\theta\,\left(m\dot{x}(x_0,\theta)\right)^2 N(\theta)}{\int_0^b dx_0 \int_{-\pi/2}^{\pi/2} d\theta\, N(\theta)}$

… where $N(\theta)$ is the angular distribution of emitted electrons for a smooth surface.

Simple analytical expressions result for the 'slope' and 'field' contributions to $\Delta p_T$ in terms of $R_q$ and $\Delta_q$ :

$$\left.\begin{aligned} \Delta p_{T,slope} &= m_0 v \Delta_q \\ \Delta p_{T,field} &= \sqrt{\frac{\pi R_q \Delta_q q E_0 m_0}{2}} \end{aligned}\right\} \text{In limit } \frac{2\pi a}{b} << 1$$

The total RMS transverse momentum is then given by

$$\Delta p_T = \sqrt{(\Delta p_{T,0})^2 + (\Delta p_{T,slope})^2 + (\Delta p_{T,field})^2}$$

… where $\Delta p_{T,0}$ is the intrinsic RMS transverse momentum of the flat photocathode

This analytical result is in good agreement with detailed electron trajectory simulations for rough photocathode surfaces:

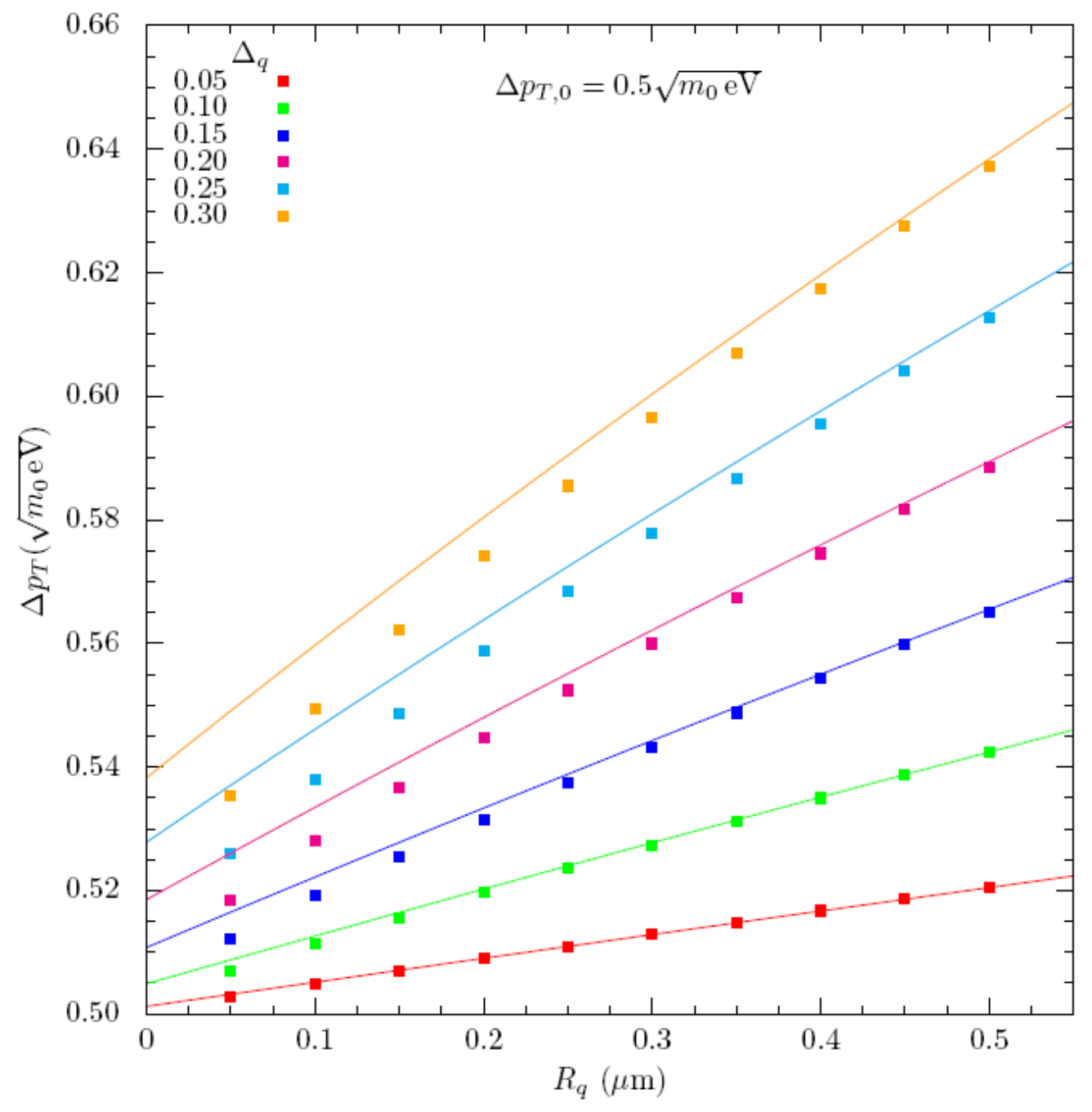
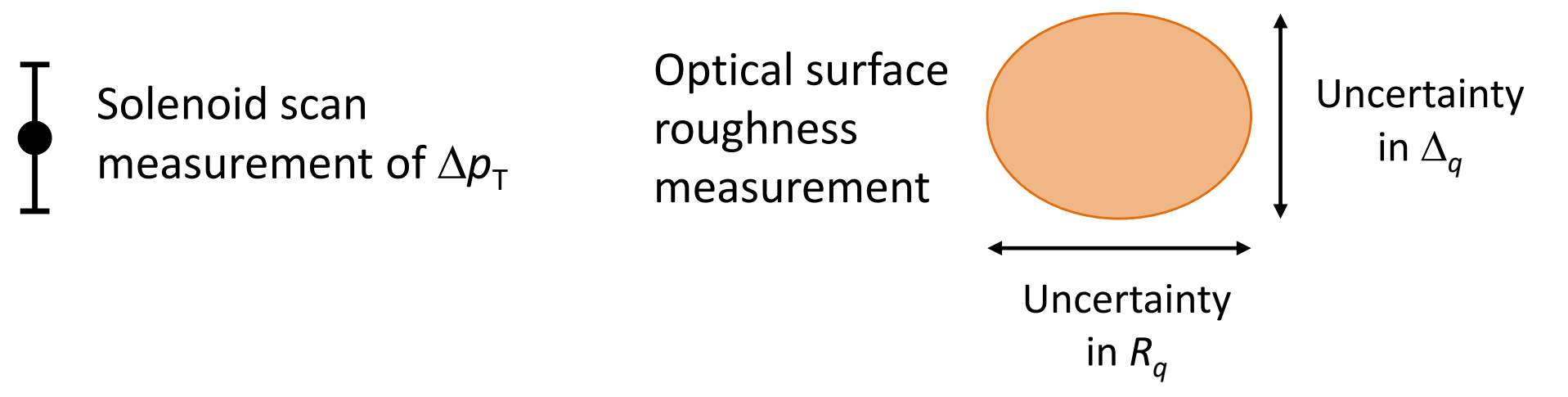


***Figure 2***
Comparison of analytic approximation (lines) with numeric electron trajectory simulations (points) when $E_0$ = 0.5 MV/m and $\Delta E$ = 0.25 eV for a rough photocathode with an intrinsic RMS transverse momentum $\Delta p_{T,0}$ = 0.5 $(m_0.\mathrm{eV})^{1/2}$.

## Results



Solenoid scan measurement of $\Delta p_T$

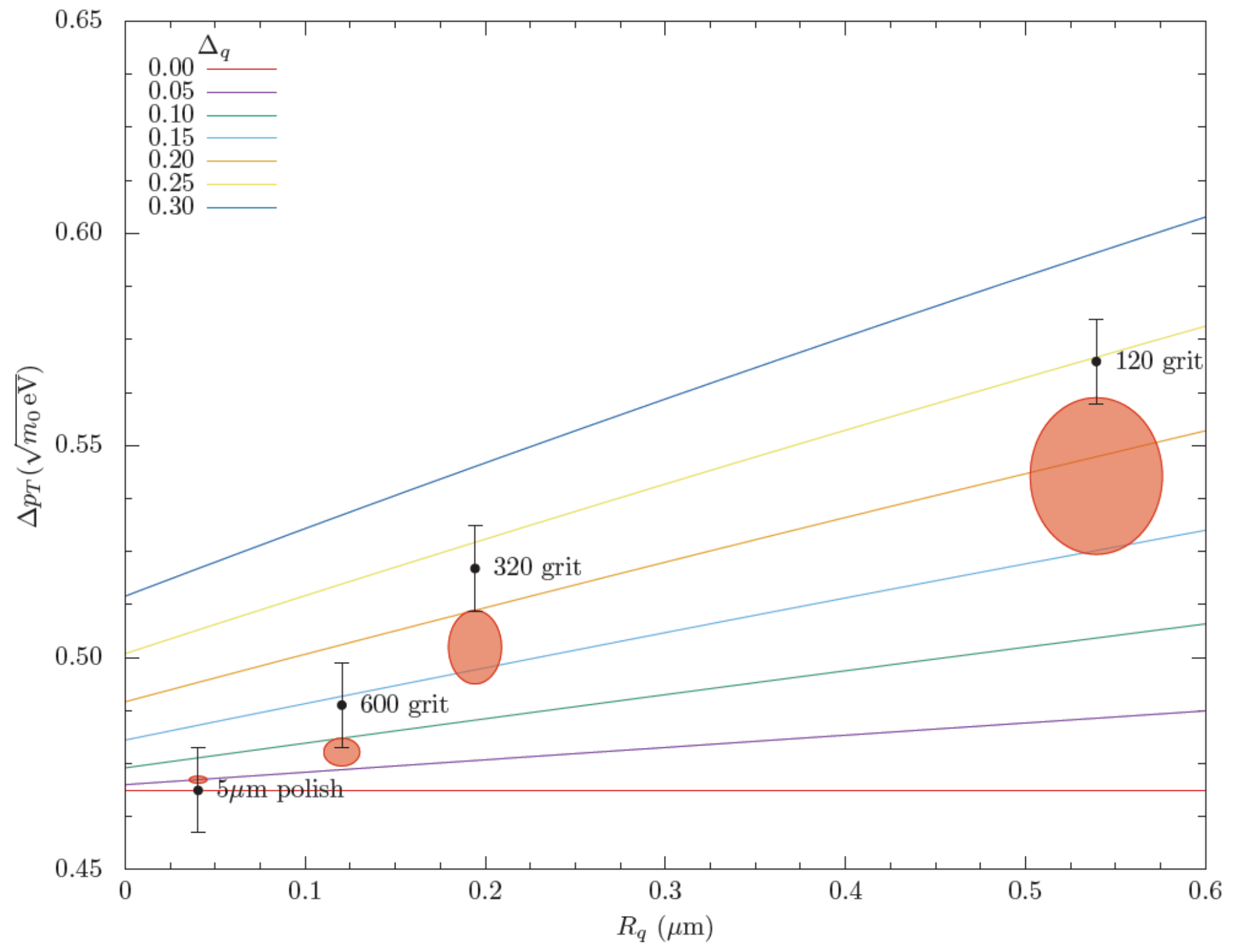
Optical surface roughness measurement

Uncertainty in $\Delta_q$

Uncertainty in $R_q$

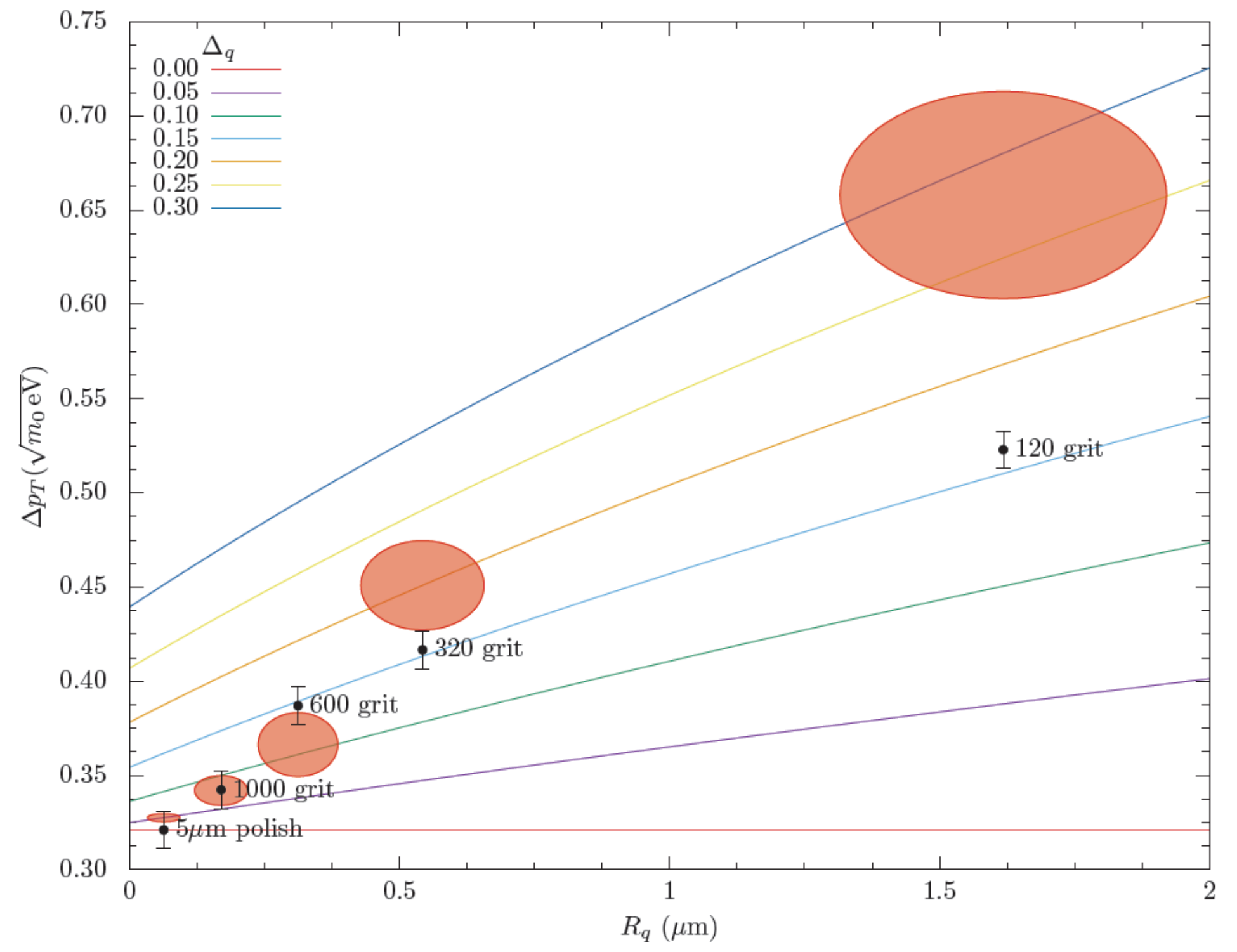
**Polycrystalline Mo**

– 'one-step' photoemission



**GaSb(001)**

– 'three-step' photoemission (via higher CB state)



- Results consistent with theoretical expectations for polycrystalline Mo [a 'hard' material] and at low values of $R_q$ for GaSb(001) [a 'softer' material]
- GaSb(001) shows deviation from theoretical analysis when $R_q$ > 1μm

## Conclusions

- Emission properties of rough photocathodes are well described by

$$\Delta p_T = \sqrt{(\Delta p_{T,0})^2 + (\Delta p_{T,slope})^2 + (\Delta p_{T,field})^2}$$

where $\Delta p_{T,slope} = m_0 v \Delta_q$

and $\Delta p_{T,field} = \sqrt{\frac{\pi R_q \Delta_q q E_0 m_0}{2}}$

… does **not** include $\Delta\phi$ effects on surface

- For hand-lapped photocathodes (5μm polish); $R_q \approx$ 50nm and $\Delta_q \approx$ 3°
  - $\Rightarrow$ Minimal effect on $\Delta p_T$ in 'low field' DC guns
    - $\therefore$ Prior solenoid scan measurements of $\Delta p_T$ validated
- Deviation from theory for GaSb(001) at high $R_q$ is likely due to penetration of acceleration field into the dielectric photocathode:

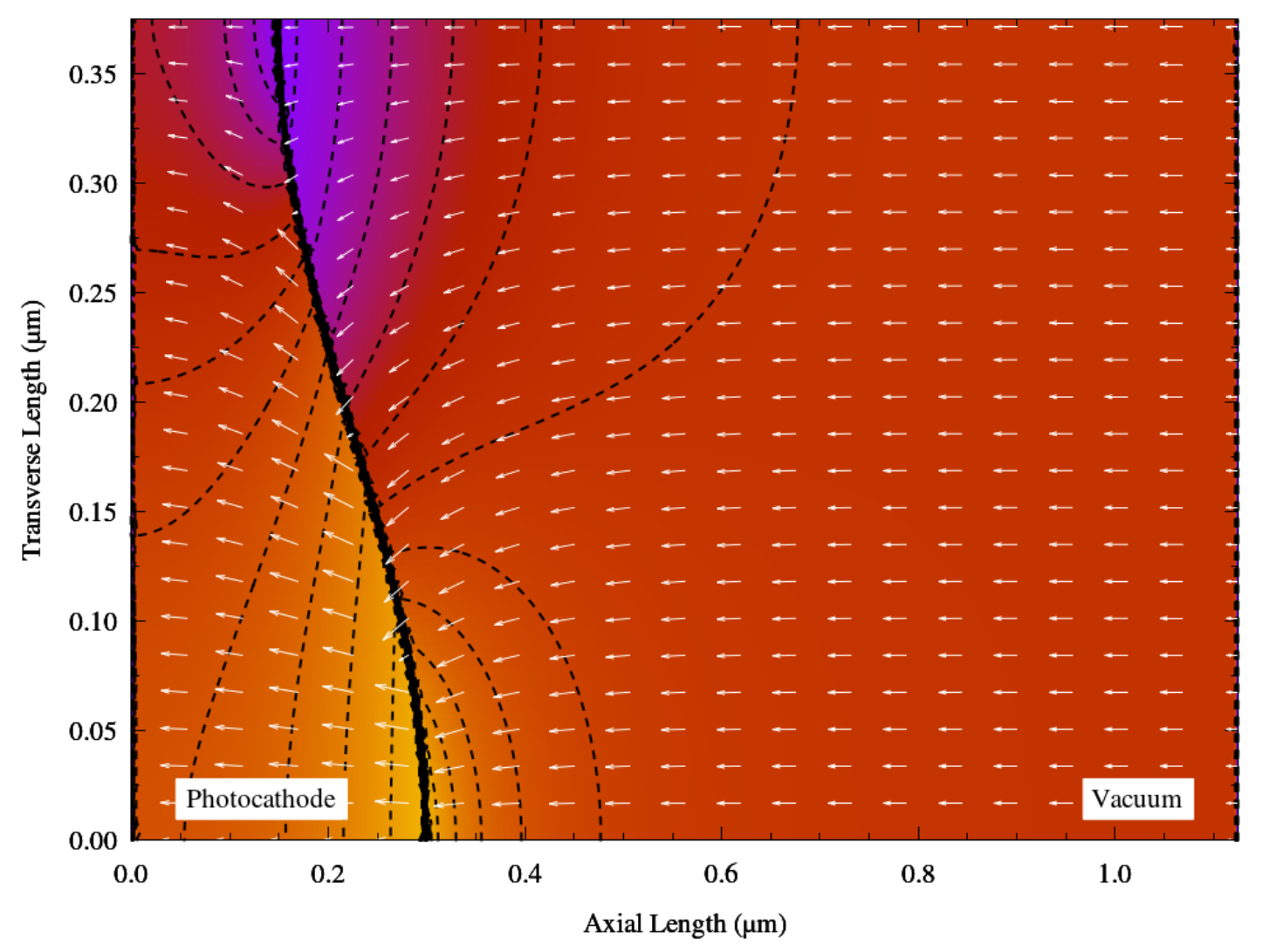


***Figure 3***
The electric displacement field **D** (vector arrows) at the interface of the vacuum with a dielectric (relative permittivity $\varepsilon_r$ = 15, e.g. GaSb) photocathode surface with a sinusoidal roughness (75μm period, 0.75μm amplitude); equipotentials indicated by dashed lines.

## Lemma

Extension to 3-D with $h(x) = a\cos\left(\frac{2\pi x}{b}\right)\cos\left(\frac{2\pi y}{b}\right)$ gives:

Areal RMS roughness, $S_q = \sqrt{\frac{1}{L^2}\int_0^L\int_0^L h^2(x,y)dxdy} = \frac{a}{2}$

Areal RMS slope, $\Gamma_q = \sqrt{\frac{1}{L^2}\int_0^L\int_0^L \left(\frac{\partial h(x)}{\partial x}\right)^2 dxdy} = \frac{\pi a}{b}$

$\Rightarrow$ $\Delta p_{T,slope} = m_0 v \Gamma_q$ ← Same as 2-D

and $\Delta p_{T,field} = \sqrt{\frac{\pi S_q \Gamma_q q E_0 m_0}{2\sqrt{2}}}$ ← Within $2^{-1/4}$ of 2-D

## Acknowledgements

National Science Foundation
PHYS-1535279