1st Topical Workshop on Laser Based Particle Sources

PHOTOEMISSION STUDIES OF COPPER

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Preliminary remarks

MOTIVATION: Breakdowns in high-gradient RF cavities are a major limit of their performance. For projects like CLIC it is therefore essential to get a good understanding of this phenomena. Breakdowns can be explained using the Fowler Nordheim law for electron emission (Field emission):

F-N Equation (RF field)

$$\bar{I} = \frac{5.79 \cdot 10^{-12} \exp(9.35\, \phi_0^{\,0.5}) A_e (\beta E_0)^{2.5}}{\phi_0^{\,1.75}} \exp\left(\frac{-6.53 \cdot 10^9 \phi_0}{\beta E_0}\right)$$

The field emission is attributed to local field enhancement ($E_{local} = \beta E$, where E_0: applied electric field, β: enhancement factor) due to geometrical perturbation whose emitting area is A_e. From this perspective the work function ϕ_0 is considered constant, β and A_e are extracted from measured field emitted current $I(E, A_e, \beta, \phi_0)$.

Alternative analysis (suggested by W. Wuensch and colleagues): local lowering of the work function ϕ_0 due to material perturbations (oxides, inclusions,..) instead of field enhancement may allow electron emission from the surface.
The aim of our studies is to investigate this process.

METHOD: Use the laser driven photoemission at different wavelengths (photon energies) as a probe of the work function profile. For photon energies below the work function one should measure an electron emission phenomena other than "normal photoemission".

Photoemission processes

“NORMAL PHOTOEMISSION”: THREE STEPS MODEL

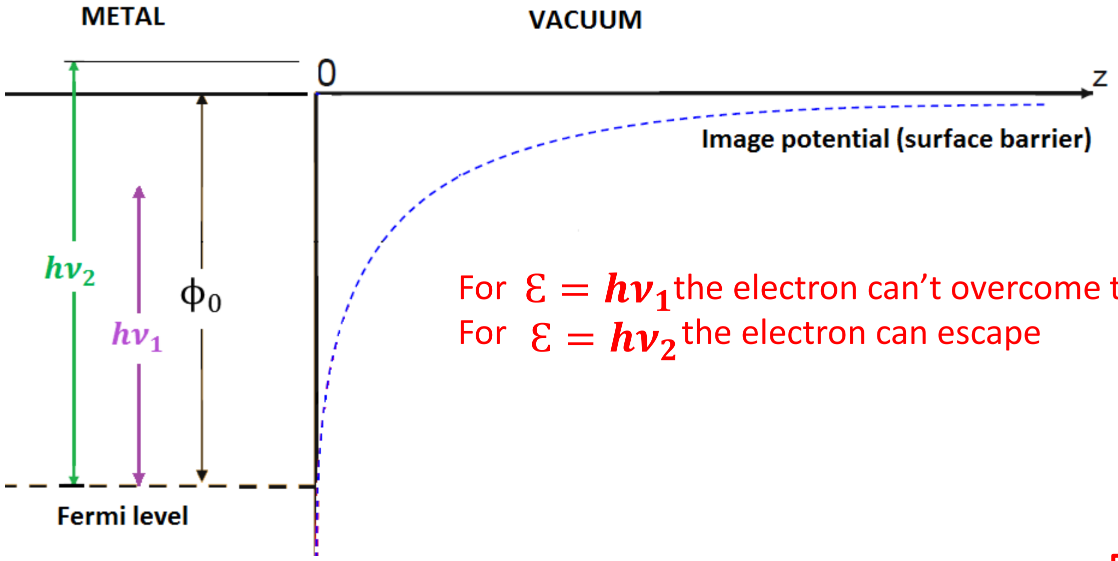
1. Absorption of a photon of energy $\mathcal{E} = h\nu \Rightarrow$ electron excitation.

2. Motion of the electron to the vacuum interface

$\Rightarrow$ IN METALS: the electron mainly losses energy by scattering with others electrons.

3. Escape of the electron over the surface barrier

$\Rightarrow$ IN METALS: the surface barrier is determined by the work function ϕ_0, i.e. the minimum energy needed to remove an electron from a solid to a point immediately outside the solid surface $\Rightarrow$ Photoemission threshold: $\boxed{h\nu > \phi_0}$



For $\mathcal{E} = h\nu_1$ the electron can’t overcome the surface barrier

For $\mathcal{E} = h\nu_2$ the electron can escape

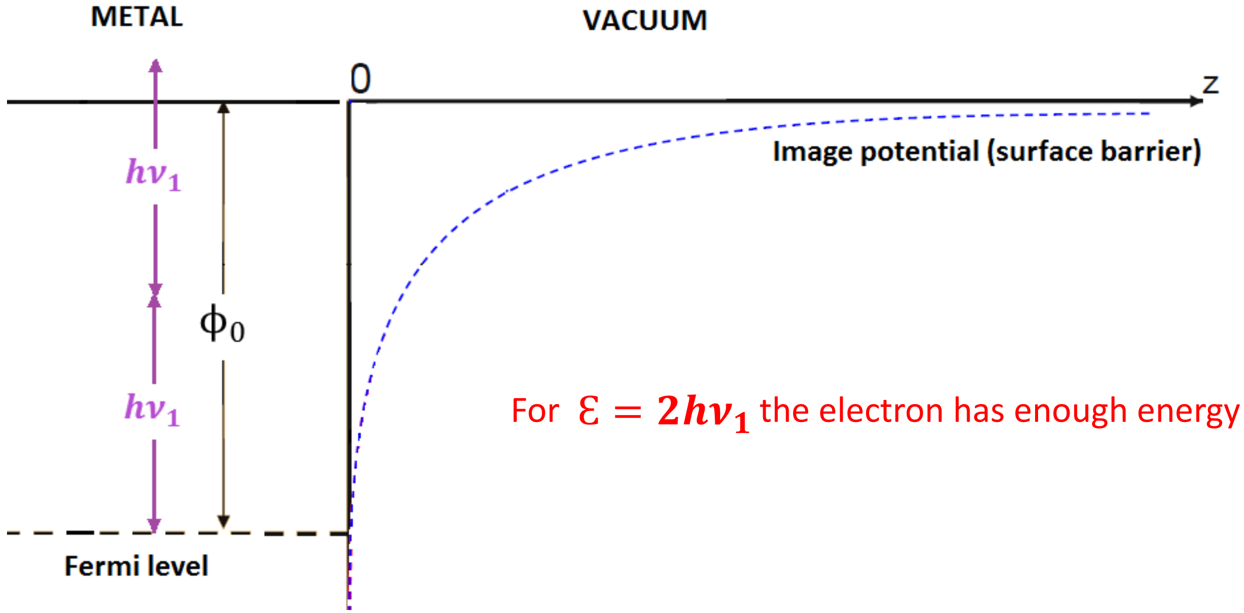
The photocurrent j_p increases as the light intensity I increases (k_1 *(Quantum Efficiency)*): $\boxed{j_p = k_1 \cdot I}$

Photoemission processes

MULTIPHOTON EFFECT:

Two or more photons are capable of exciting the same electron: the electron is emitted even if the photon energy is below the photoemission threshold.

TWO-PHOTON PHOTOEMISSION: it's possible if $\boxed{\frac{\phi_0}{2} < h\nu < \phi_0}$



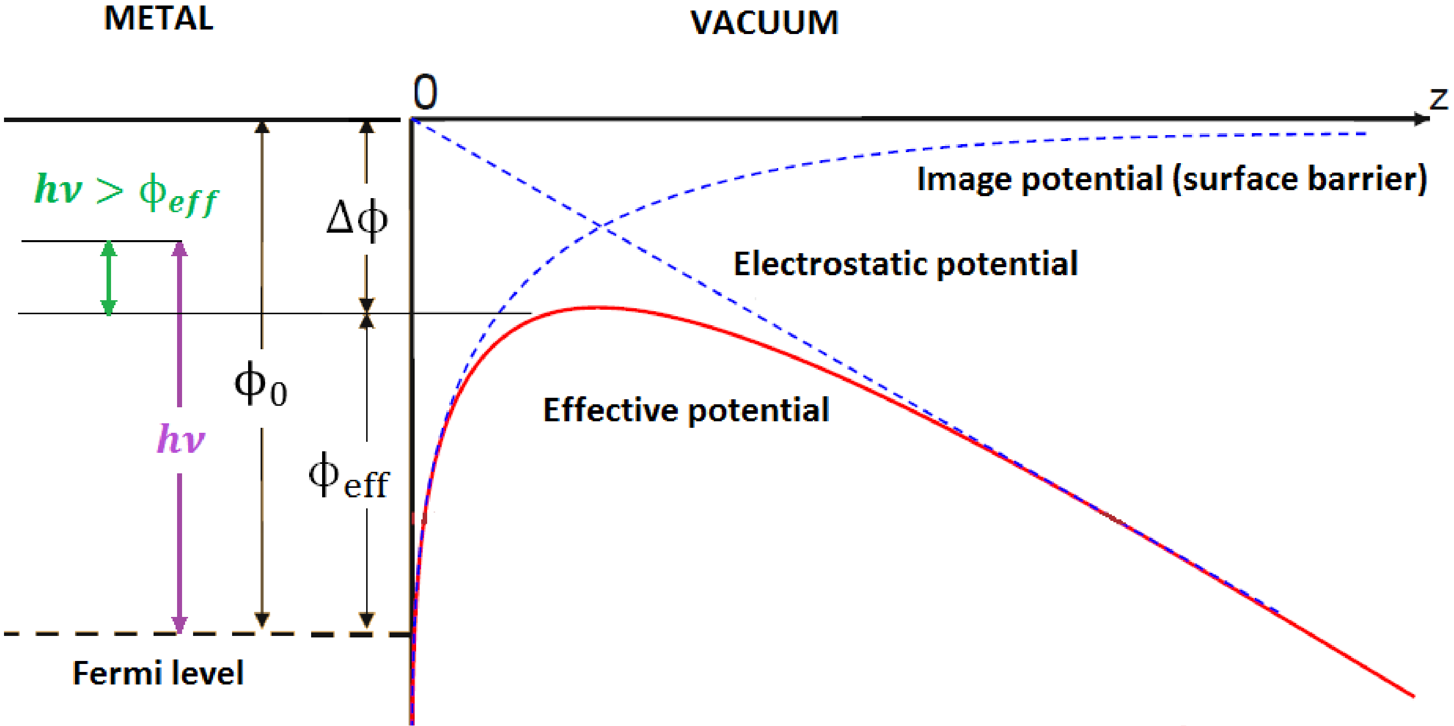
For $\mathcal{E} = 2h\nu_1$ the electron has enough energy to escape

The photocurrent j_p is dependent upon the square of the incident radiation intensity I: $j_p = k_2 \cdot I^2$
⇒ the photoemitted charge Q is proportional to the quadratic square of the photon energy $\mathcal{E}$: $\boxed{Q = k_3 \cdot \mathcal{E}^2}$

Photoemission processes

SCHOTTKY ENABLED PHOTOEMISSION

The same phenomena which causes **Field Emission** could lead to single-photon photoemission even if $h\nu < \phi_0$.
The high electric field lowers the potential barrier outside a metal surface.



The effective work function is then: $\phi_{eff} = \phi_0 - \Delta\phi$ where $\Delta\phi = \sqrt{\frac{E \cdot e^3}{4\pi\varepsilon_0}}$

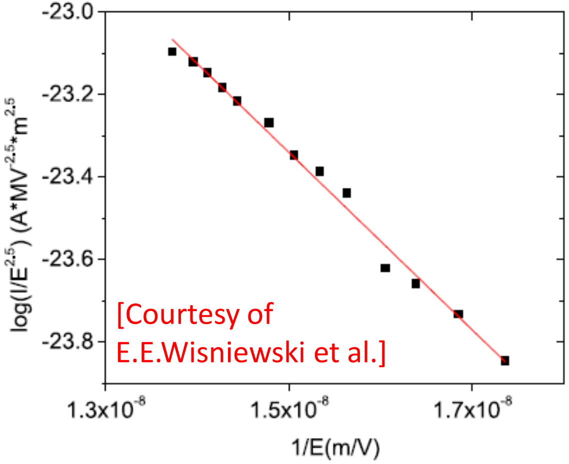
$\Rightarrow$ for $\phi_{eff} < h\nu < \phi_0$ single photon photoemission is possible!

Note: the stronger the electric field the lower the effective work function.

Measurements at Tsinghua Facility

FIELD EMISSION (Fowler-Nordheim plot)

Traditional analysis: ϕ_0=4.6 eV (nominal COPPER work function)
$\beta = 130$ (Extracted from the fit) [1],[2]



[Courtesy of E.E.Wisniewski et al.]

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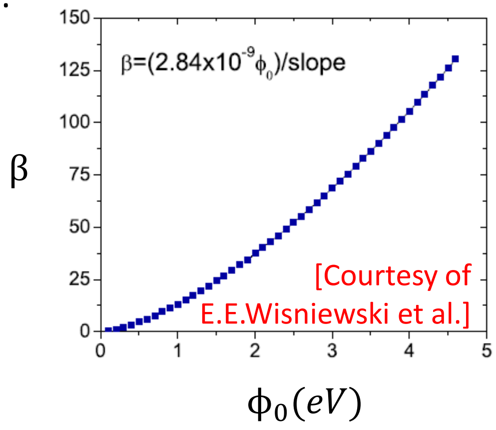
This result is considered unrealistic for the such surface leading to unphysical emission features 10 nm tall by 1 nm wide[1],[2].

Alternative analysis:
Different combination of (ϕ_0, β) can match the data.[1],[2]



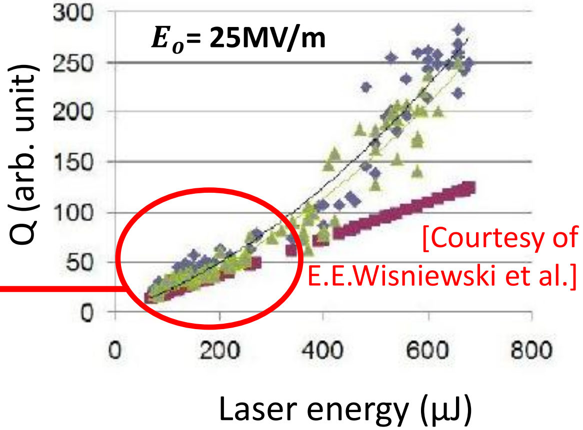
[Courtesy of E.E.Wisniewski et al.]

SCHOTTKY ENABLED PHOTOEMISSION

Schottky enabled photoemission was observed for λ=400 nm (3.1 eV) and different value of accelerating field E_o[1],[2].

Traditional analysis: For E_o=25 MV/m (linear part) ⇨ β = 60

Alternative analysis: Different combination of (ϕ_0, β), gives much more reasonable result as for field emitted electrons [1],[2].



[Courtesy of E.E.Wisniewski et al.]

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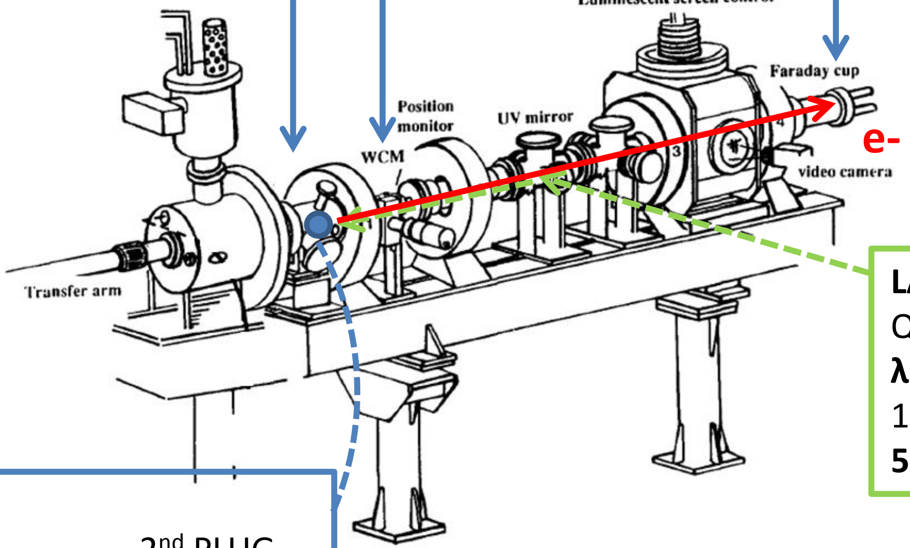
[1] J. Power et al., Schottky Enabled Photoemission & Dark Current Measurements at the S-band RF Gun Facility at Tsinghua, MeVArc Workshop, Finland (2011)
[2] E.E. Wisniewski et al., TUPPD069, Proceedings of IPAC2012, New Orleans, Louisiana, USA

CERN Lab measurement setup

We tried to reproduce the Schottky Enabled photoemission measurement with this setup:



DC GUN:
70.1 kV supplied voltage
(7 MV/m electric field)

Bunch charge measured by:
Wall Current Monitor (**WCM**)
Faraday Cup (**FC**)

LASER:
Q-switched Nd (YAG)
λ=355 nm or **λ=266 nm**
10 Hz repetition rate
5 ns pulse duration

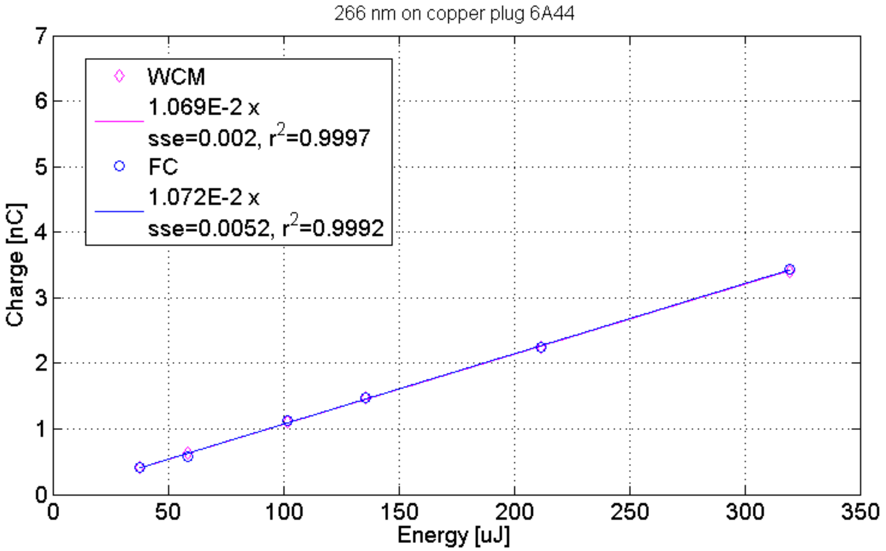
COPPER SAMPLES:

6A44 (diamond turning)	2nd PLUG
6A22 (diamond powder polishing)	3rd PLUG

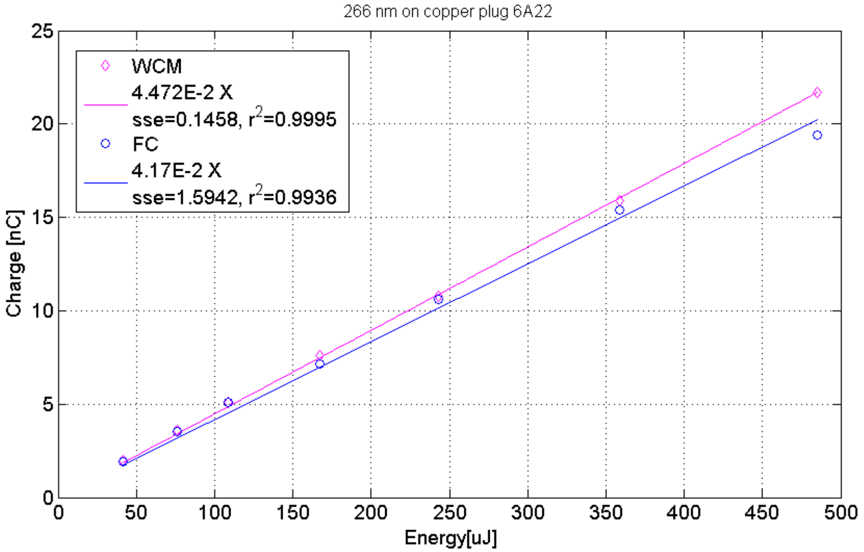
MEASUREMENT WITH 266 nm (4.7 eV)

$h\nu > \phi_0$

2nd plug



3rd plug



Linearity => Normal single-photon photoemission

QUANTUM EFFICIENCY : is the main feature of photoemissive material (it may be influenced by the surface condition). It is calculated from experimental data as:

$$QE = \frac{number\ of\ electrons}{number\ of\ photons} = \frac{Q\ (C)}{e} \cdot \frac{h\ (J \cdot s) \cdot \nu(Hz)}{\mathcal{E}(J)}$$

2nd plug: QE(266nm)= 5E-5

3rd plug: QE(266nm)= 2E-4

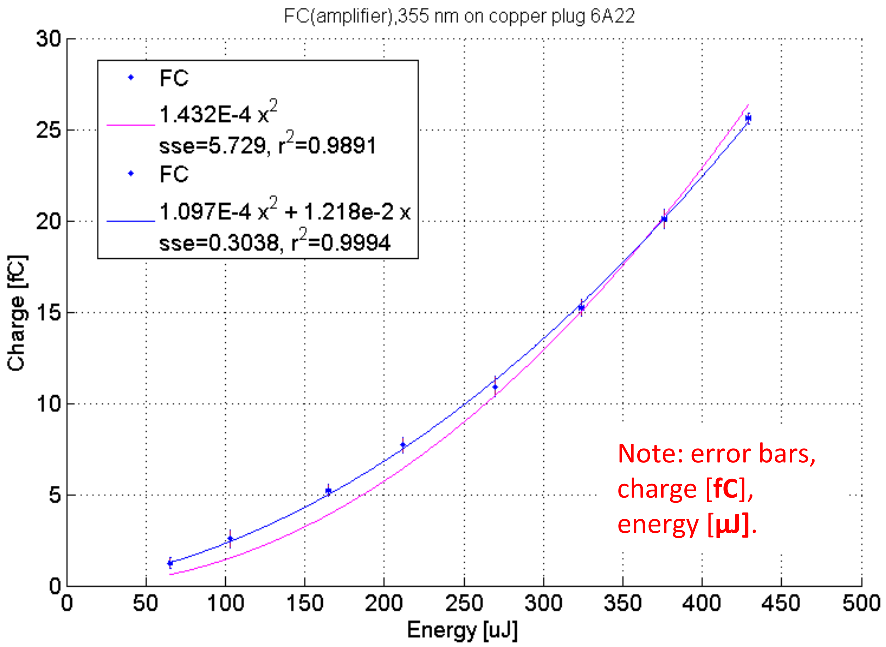
Copper QE(266nm)*=3E-5

*Previous measurement on copper with 266 nm (CERN-PSI, 2007)

MEASUREMENT WITH 355 nm (3.5 eV)

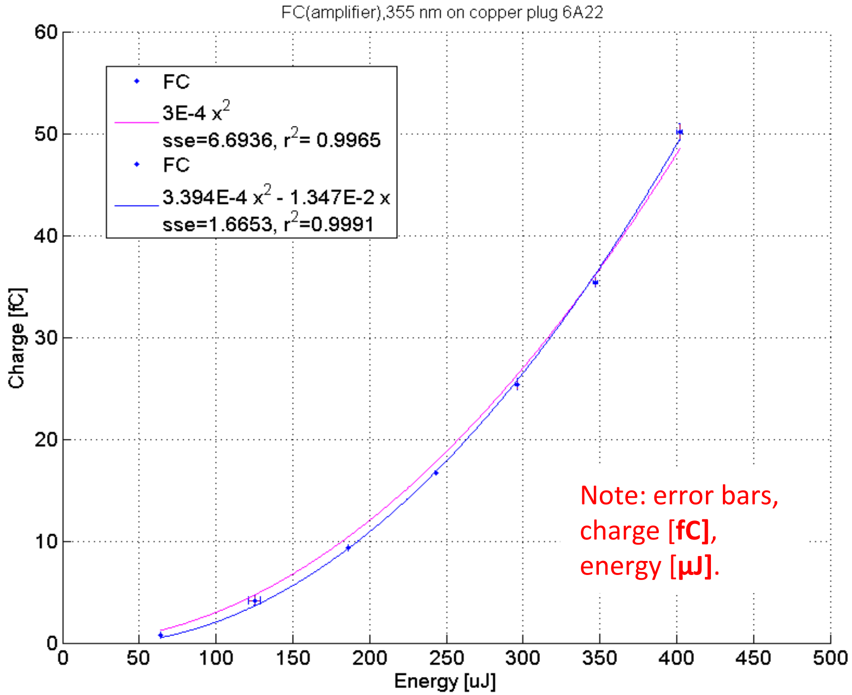
$$\frac{\phi_0}{2} < h\nu < \phi_0$$

2nd plug



Note: error bars, charge [**fC**], energy [**μJ**].

3rd plug



Note: error bars, charge [**fC**], energy [**μJ**].

Non linear trend: two-photon photoemission is predominant.

For pure two-photon photoemission a pure quadratic trend is predicted by the theory, but the equation with the linear term (blue line) fits better the data.

COMPARISON

REMARK: **Effective wavelength λ'**

$$\Delta\phi + h\nu = \frac{hc}{\lambda'}$$

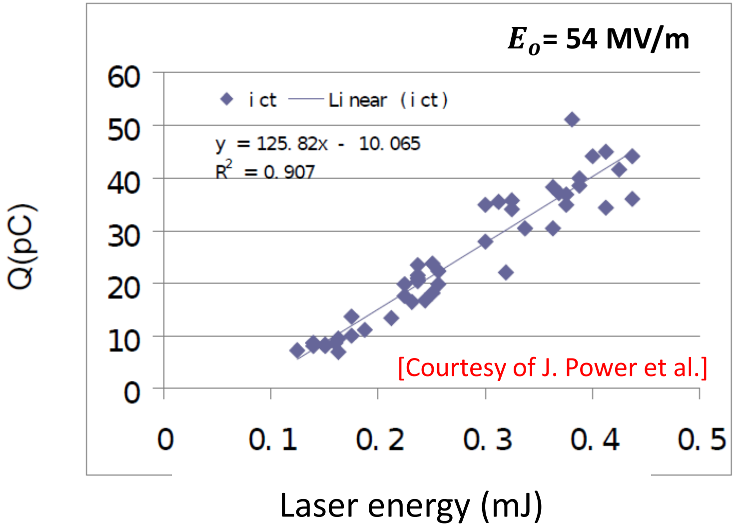
$$\Delta\phi = \sqrt{\frac{E\cdot\beta\cdot e^3}{4\pi\varepsilon_0}}$$

Work function lowering due to electric field (Schottky Effect)

CERN Lab: 7 MV/m, 355 nm } $\Delta\phi \sim 0.10$ eV $\lambda' \sim$ **346 nm** (β=1) $\lambda' \sim$ **335 nm** (β=5)

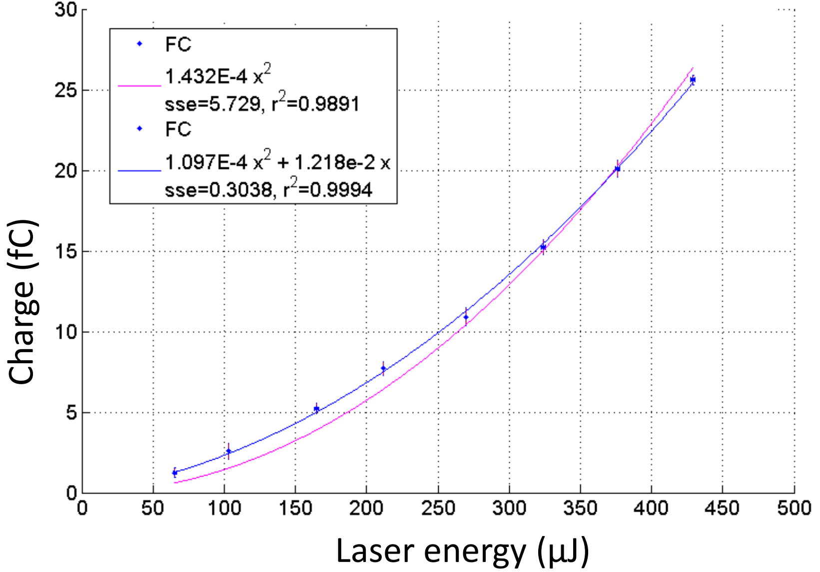
Tsinghua Facility: 54 MV/m, 400 nm } $\Delta\phi \sim 0.28$ eV $\lambda' \sim$ **368 nm** (β=1) $\lambda' \sim$ **334 nm** (β=5)

Tsinghua Facility



[Courtesy of J. Power et al.]

CERN Lab



Linear trend

Quadratic trend

Same range of energy but 3 orders of magnitude difference in charge.

COMPARISON

The difference between the Schottky enabled photoemission data taken at Tsinghua Facility and at CERN could be maybe explained by the different **laser fluence** involved in the two experiments.

CERN Lab:
1 mJ
1 mm^2
5 ns

Fluence ~ **$2\cdot10^7$ W/cm^2**

Threshold for plasma formation[3]**:**
Fluence ~ $5\cdot10^8$ W/cm^2
for ns pulses of λ=355 on copper.

Tsinghua Facility:
100 μJ
1 mm^2
1 ps

Fluence ~ **10^{10} W/cm^2**

⇩

Intense electron emission due to plasma formation:

For **ps** laser pulses and **high electric field gradient**: laser-induced plasma formation has been observed with subsequent emission of intense electrons (several orders of magnitude higher than normal photoelectrons)[4].
The **thresholds** for this phenomena are: **10^9 W/cm^2** (for 70 MV/m peak electric field, rf gun)
10^{11} W/cm^2 (for 7 kV/m, dc gun).

[3] W. Zhang et al., *"Modelling and Analysis of UV Laser Micromachining of Copper"*, Int J Adv Manuf Technol (2001) 18:323–331
[4] X.J. Wang et al., *"Intense electron emission due to picosecond laser-produced plasmas in high gradient electric fields"*, J. Appl. Phys. 72 (3), 1 August 1992

CONCLUSION AND OUTLOOK

1) For measurement driven by λ=266 we observed a single photon photoemission and a QE consistent with previous measurement on copper.

2) We observed non linear behaviour in photoemission measurement on copper for λ=355 nm and a very small charge (fC).

3) The Schottky Enabled Photoemission measurement done at Tsinghua Facility [1],[2] can maybe be explained by intense electron emission due to picoseconds laser-produced plasmas.

4) The photoemission data at λ=355 nm is very well fitted by a parabola with a **linear term**.
This linear term may be connected to some experimental drift but may be also related to a single-photon photoemission phenomena. This contribution could be due to some local lowering of the workfunction (as suggested by W. Wuensch and colleagues).

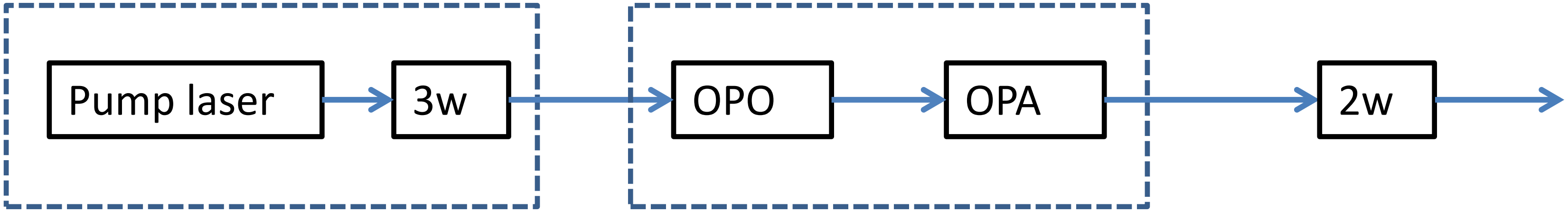
We have pushed our experimental setup to its limits: using an electrical amplifier we could measure in the range of **femtoCoulomb** (10^4 electrons**!**)

To further investigate the source of the linear term in the parabolic fit we need to **scan over the wavelengths** (266 nm→355 nm). The eventually presence of low workfunction spot would give a measurable contribution at intermediate photon energy (between two-photon photoemission and single-photon photoemission).

To do the scan an **OPO (Optical Parametric Oscillator)** is needed: this tunable laser system can provide a wide range of wavelengths with easy maintenance and reliability.

CONCLUSION AND OUTLOOK

OPTICAL PARAMETRIC OSCILLATOR SETUP



Pump laser with 3rd harmonic

Tunable OPO&OPA module

2nd harmonic conversion of the signal

Pump laser → 3w → OPO → OPA → 2w →

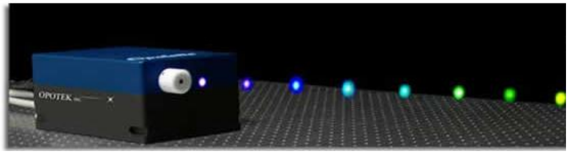
Nd:YAG 1064 nm

Pump 355 nm

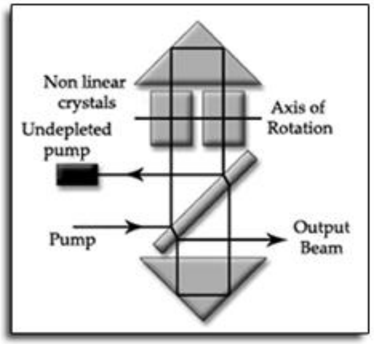
Signal 680-520 nm
Idler 740-1120 nm

340-260 nm
Energy ~ mJ

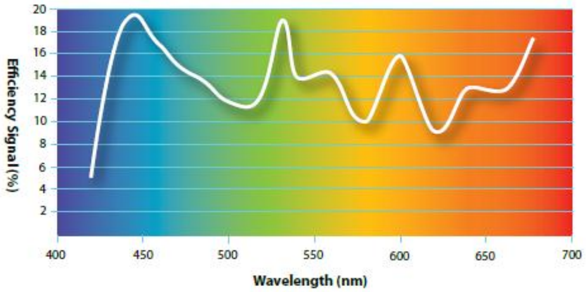
Pump laser



OPO scheme



Signal efficiency

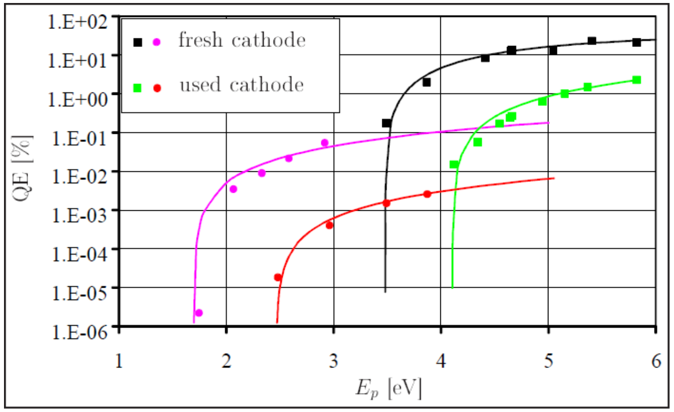


CONCLUSION AND OUTLOOK

BENEFITS OF THE OPO FOR PHOTOCATHODES R&D

1) Tunable laser system ⇒ SPECTRAL RESPONSE OF PHOTOCATHODES.

e.g: Cs_2Te photocathode



[Courtesy of H. Trautener et al.]

2) The OPO is a robust and with very easy maintenance system. It is the most suitable tunable system for our purpose (Photocathodes sensitive to visible laser beams).

Acknowledgment

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- clic
- LA3NET

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- *You all for your attention!*

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[4] X.J. Wang et al., J. Appl. Phys. 72 (3), 1 August 1992

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[6] R. L. Smith, Phys. Rev. 128, 5 (1962)

[7] W. E. Spicer, Phys. Rev. B 112, 114 (1958)

[8] E. Chevalley et al., "*Production and studies of photocathodes for high intensity electron beams*" (2000)