

CLIC WORKSHOP 2013



PHOTOEMISSION MEASUREMENTS ON COPPER SURFACES

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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".

“NORMAL PHOTOEMISSION”: THREE STEPS MODEL

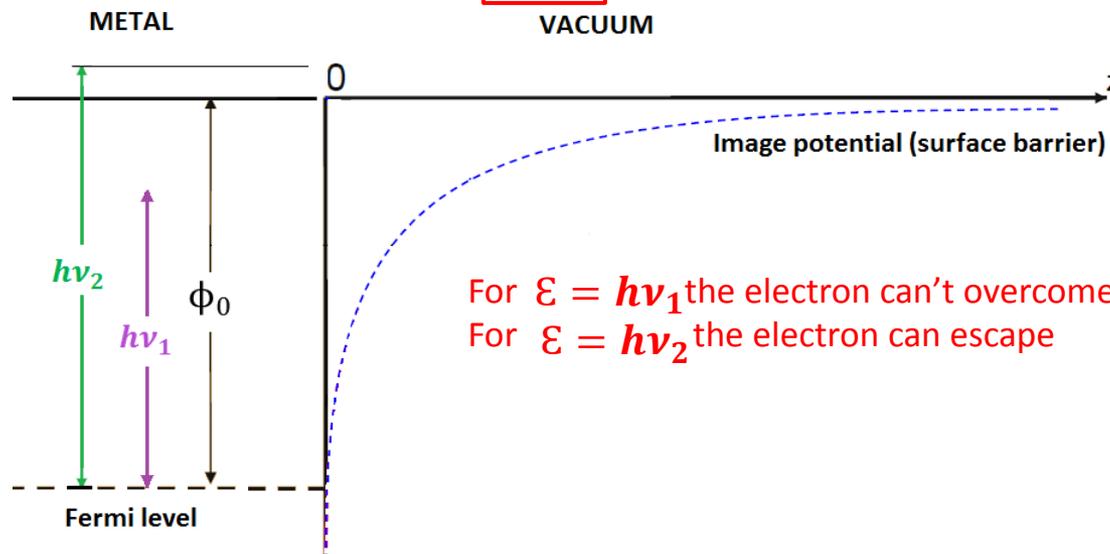
1. **Absorption of a photon** of energy $\mathcal{E} = h\nu \Rightarrow$ electron excitation.

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: $h\nu > \phi_0$



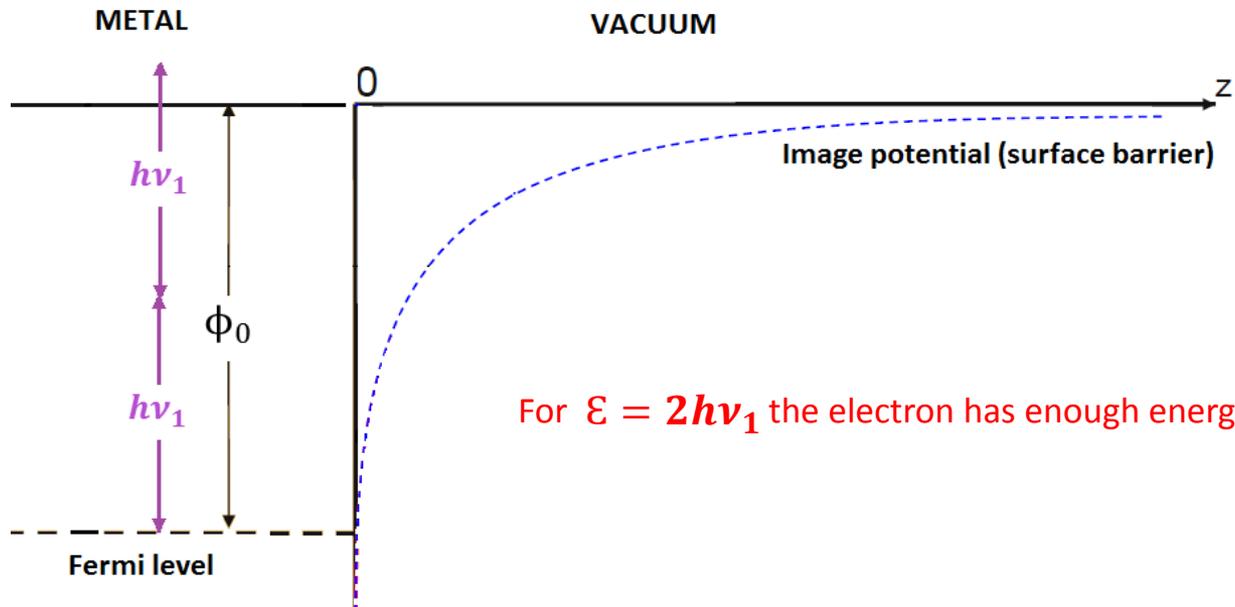
The photocurrent j_p increases as the light intensity I increases (k_1 (Quantum Efficiency)):

$$j_p = k_1 \cdot I$$

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.

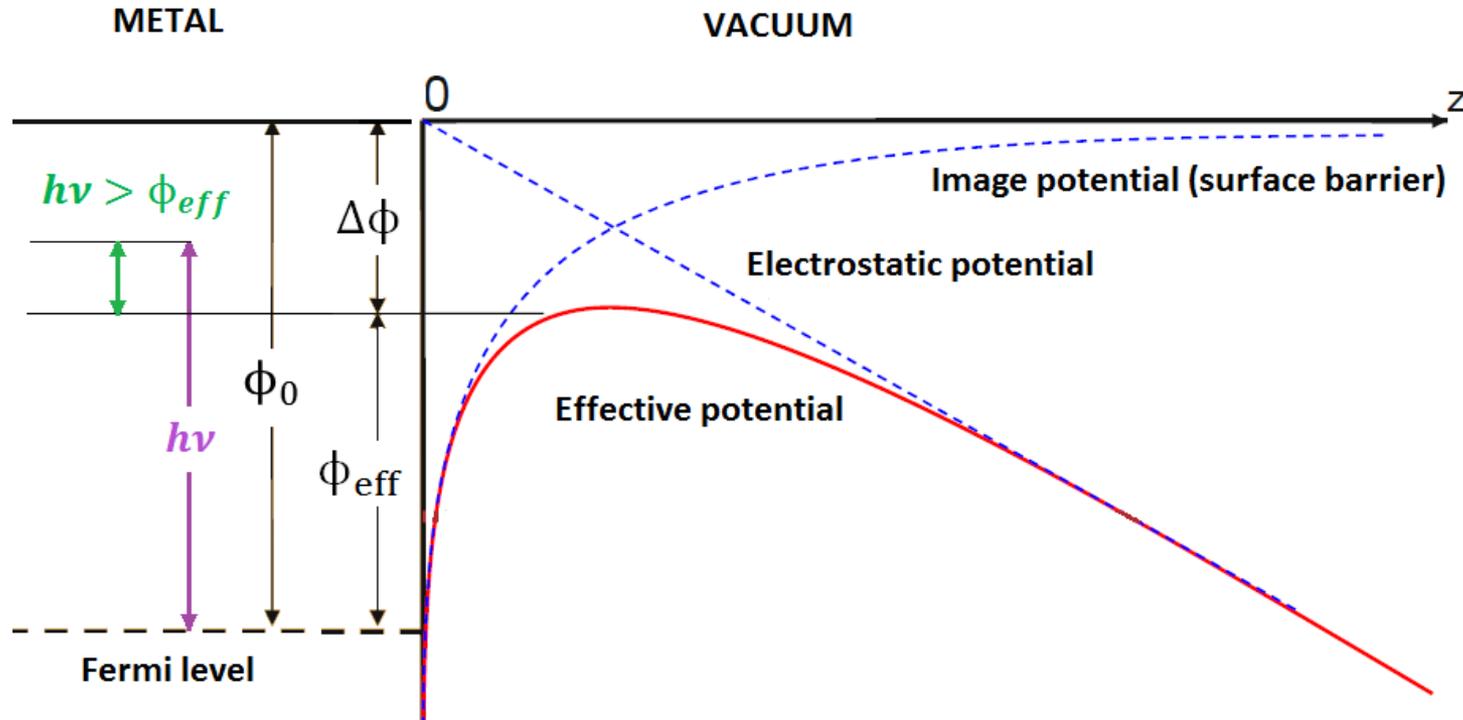
TWO-PHOTON PHOTOEMISSION: it's possible if $\frac{\phi_0}{2} < h\nu < \phi_0$



The photocurrent j_p is dependent upon the square of the incident radiation intensity I : $j_p = k_2 \cdot I^2$
 \Rightarrow the photoemitted charge Q is proportional to the quadratic square of the photon energy ϵ : $Q = k_3 \cdot \epsilon^2$

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.

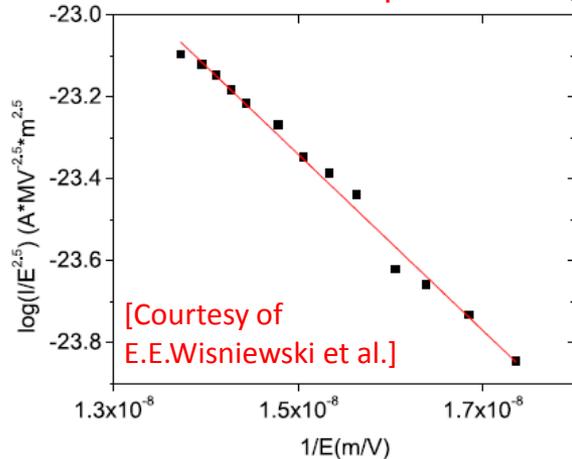


The effective work function is then: $\phi_{eff} = \phi_0 - \Delta\phi$ where $\Delta\phi = \sqrt{\frac{E \cdot e^3}{4\pi\epsilon_0}}$
 \Rightarrow for $\phi_{eff} < h\nu < \phi_0$ single photon photoemission is possible!

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

FIELD EMISSION (Fowler-Nordheim plot)

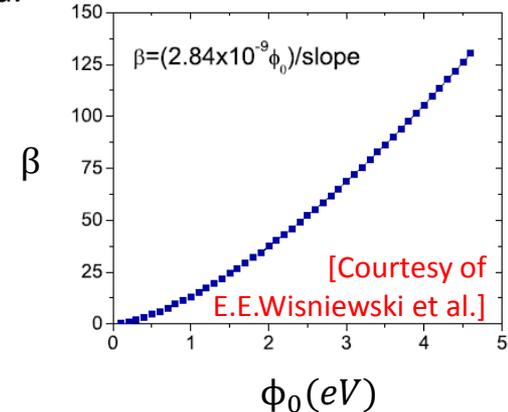
Traditional analysis: $\phi_0=4.6$ eV (nominal COPPER work function)
 $\beta = 130$ (Extracted from the fit) [1],[2]



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]

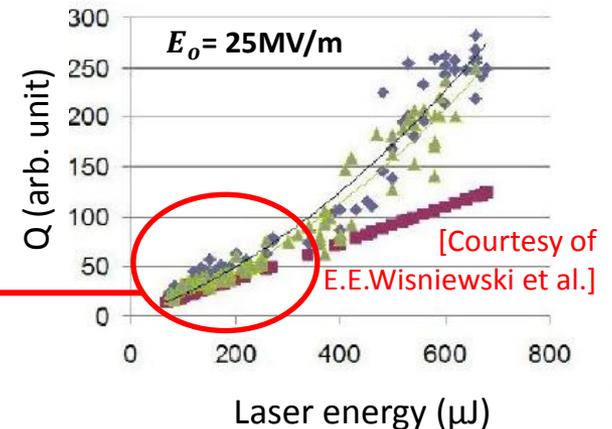


SCHOTTKY ENABLED PHOTOEMISSION

Schottky enabled photoemission was observed for $\lambda=400$ nm (3.1 eV) and different value of accelerating field E_0 [1],[2].

Traditional analysis: For $E_0=25$ MV/m (linear part) $\Rightarrow \beta = 60$

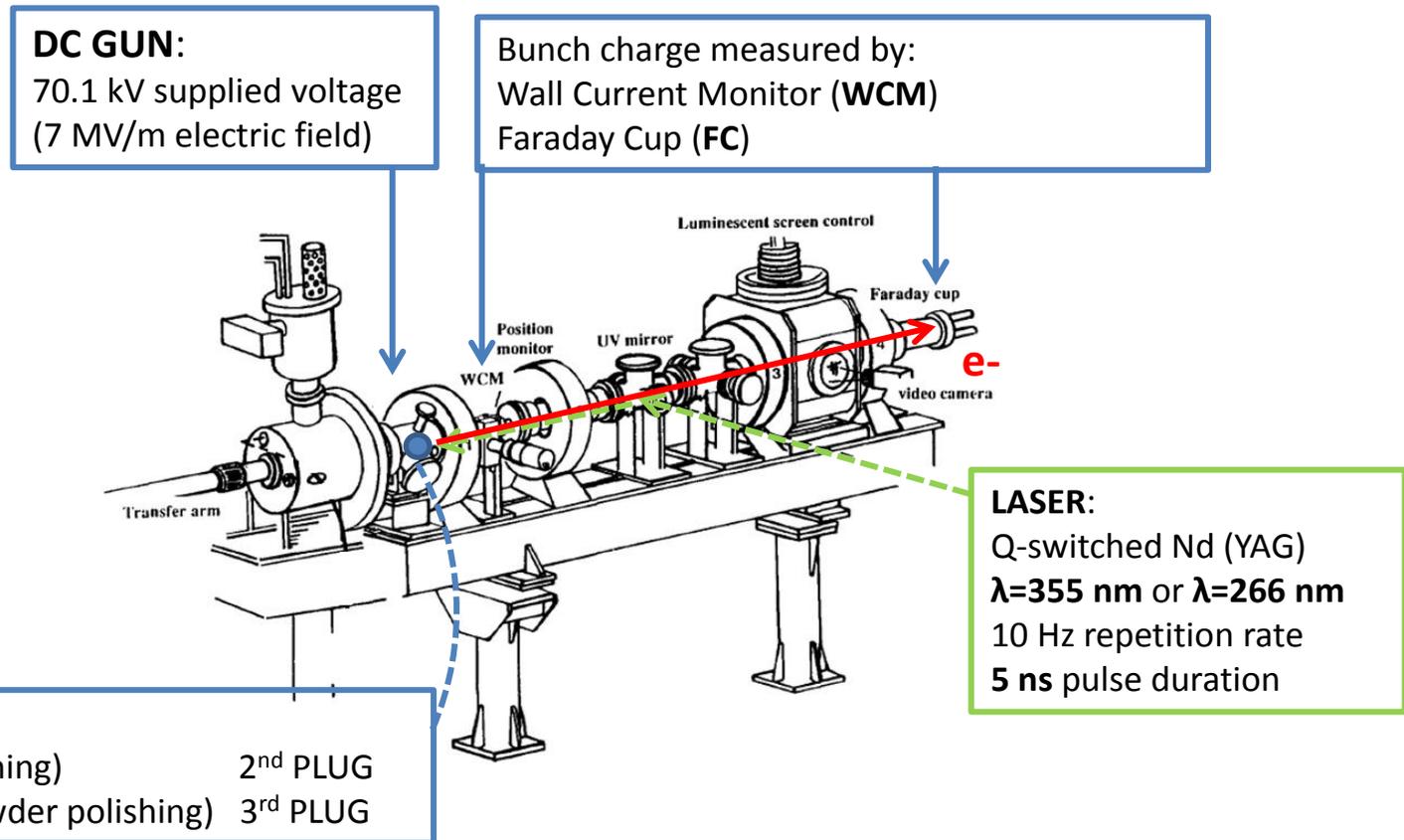
Alternative analysis: Different combination of (ϕ_0, β) , gives much more reasonable result as for field emitted electrons [1],[2].



[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

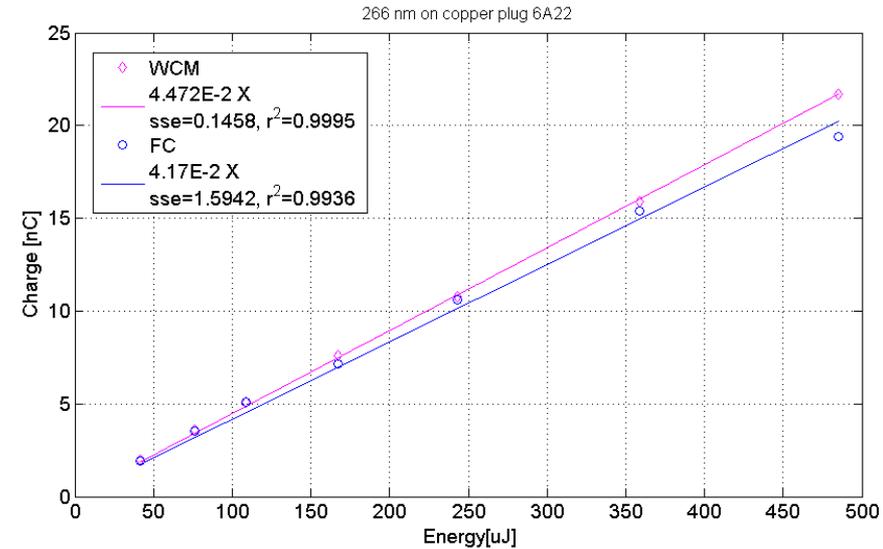
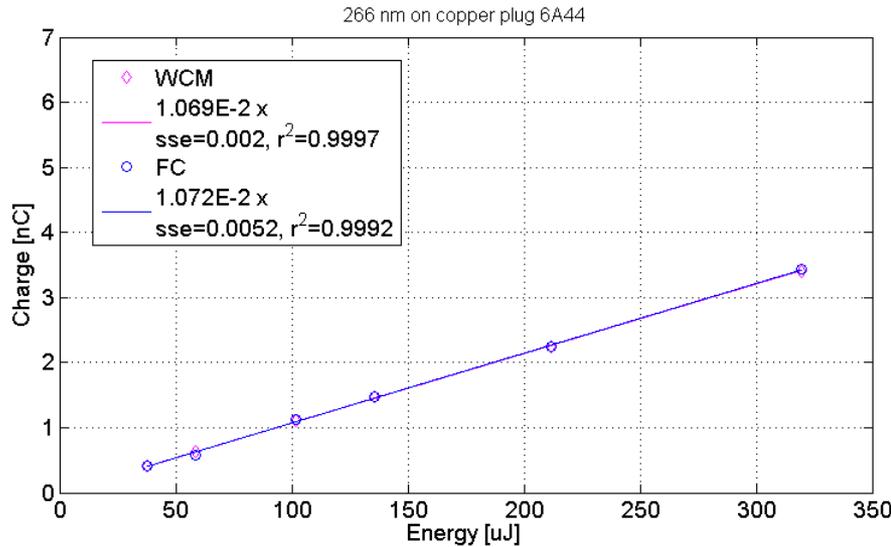
We tried to reproduce the Schottky Enabled photoemission measurement with this setup:



$$h\nu > \phi_0$$

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:

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

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

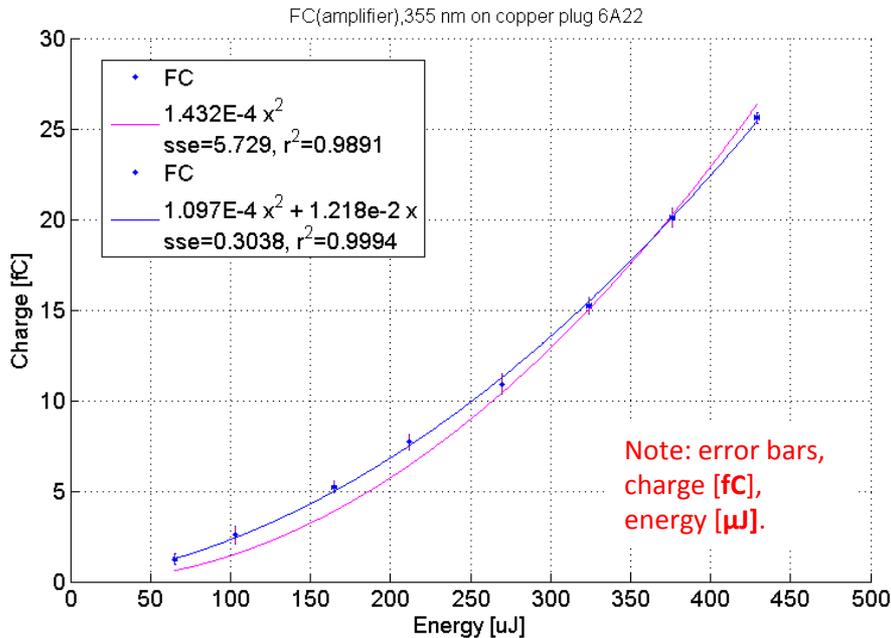
3rd plug: QE(266nm)= 2E-4

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

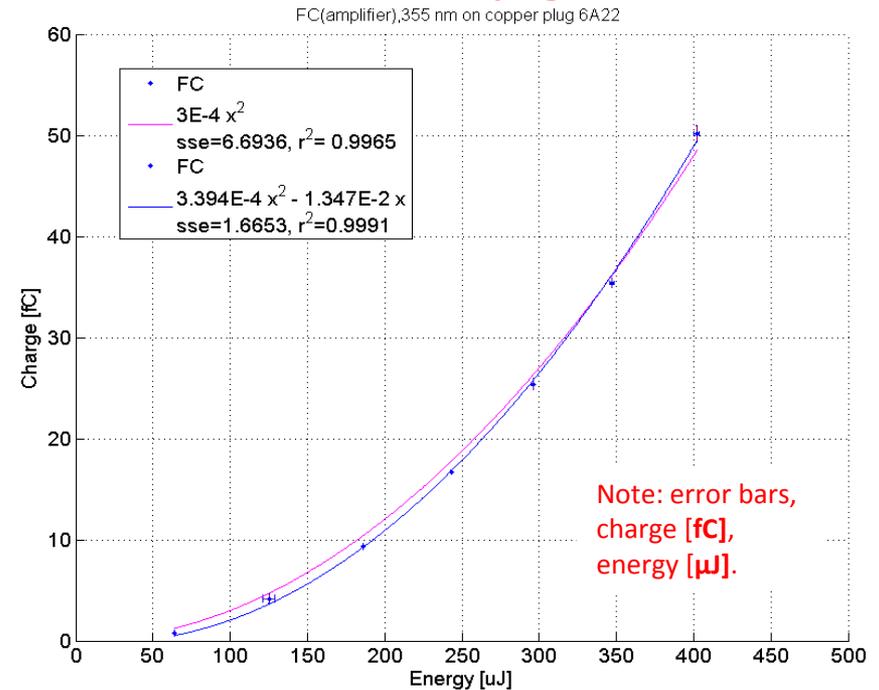
*Previous measurement on copper with 266 nm (CERN-PSI, 2007)

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

2nd plug



3rd plug



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.

REMARK: Effective wavelength λ'

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

$$\Delta\phi = \sqrt{\frac{E \cdot \beta \cdot e^3}{4\pi\epsilon_0}}$$

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 ($\beta=1$)

$\lambda' \sim 335$ nm ($\beta=5$)

Tsinghua Facility:

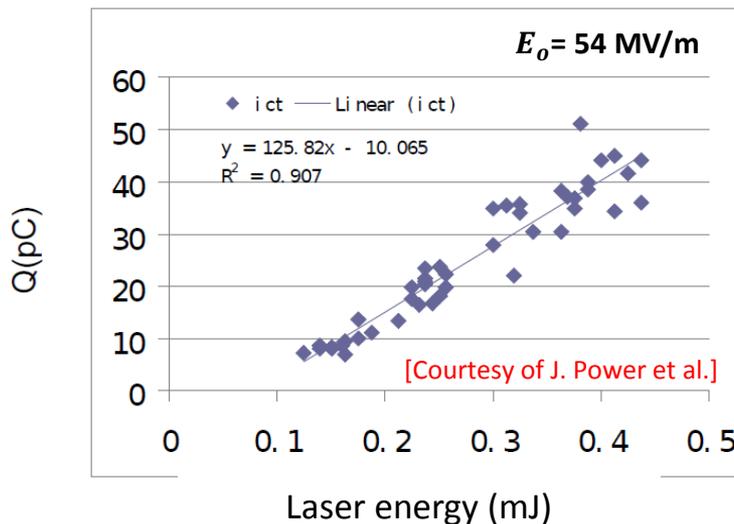
54 MV/m
400 nm

$\Delta\phi \sim 0.28$ eV

$\lambda' \sim 368$ nm ($\beta=1$)

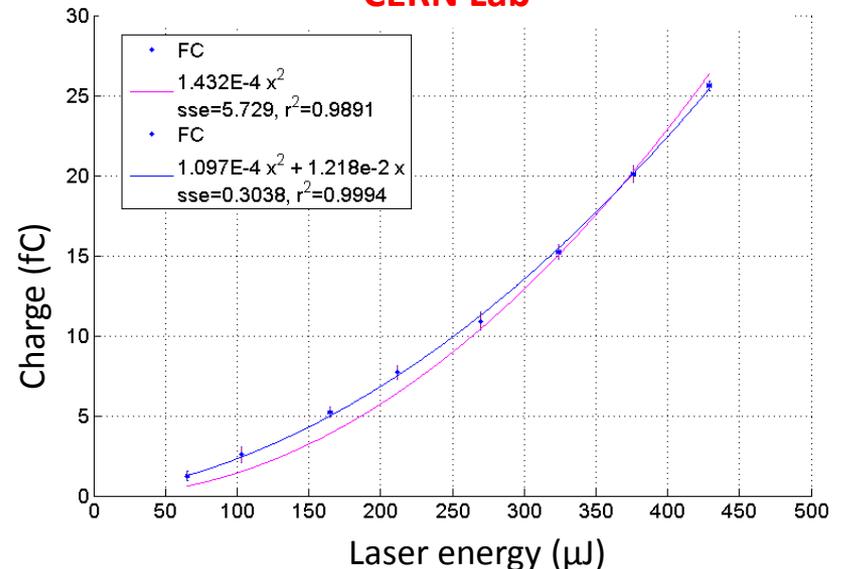
$\lambda' \sim 334$ nm ($\beta=5$)

Tsinghua Facility



Linear trend

CERN Lab



Quadratic trend

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

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 mm²
5 ns

Fluence ~ **2·10⁷ W/cm²**

Threshold for plasma formation^[3]:
Fluence ~ 5·10⁸ W/cm²
for ns pulses of λ=355 on copper.

Tsinghua Facility:

100 μJ
1 mm²
1 ps

Fluence ~ **10¹⁰ W/cm²**

↓

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: **10⁹ W/cm²** (for 70 MV/m peak electric field, rf gun)
10¹¹ W/cm² (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

- 1) For measurement driven by $\lambda=266$ 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 $\lambda=355$ 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 $\lambda=355$ 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 \rightarrow 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).

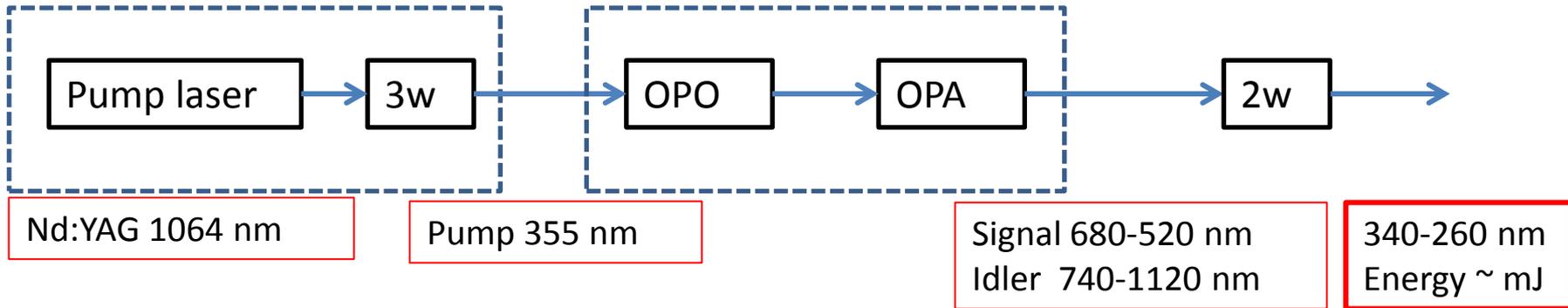
To do the scan an **OPO (Optical Parametric Oscillator)** is needed: this tunable laser system can provide a wide range of wavelengths with easy maintenance and reliability.

OPTICAL PARAMETRIC OSCILLATOR SETUP

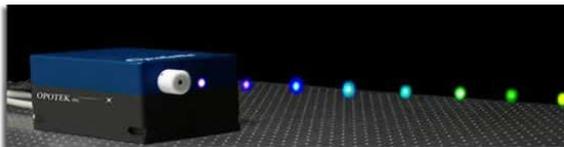
Pump laser with 3rd harmonic

Tunable OPO&OPA module

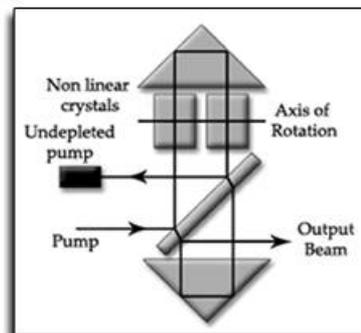
2nd harmonic conversion of the signal



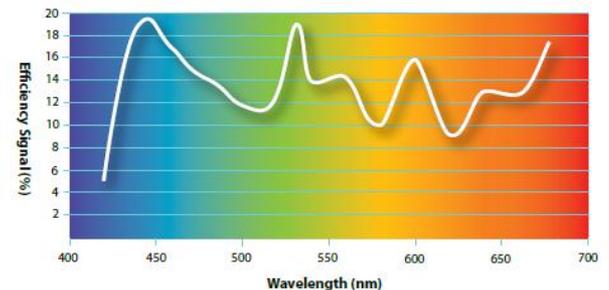
Pump laser



OPO scheme



Signal efficiency



Estimated cost of the whole setup: 120 kCHF

We would like to thank:

- *Walter Wuensch and colleagues for valuable discussions.*



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- *You all for your attention!*

- [1] J. Power et al., Schottky Enabled Photoemission & Dark Current Measurements at the S-band RF Gun Facility at Tsinghua

- [2] E.E. Wisniewski et al., TUPPD069, Proceedings of IPAC2012, New Orleans, Louisiana, USA

- [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., J. Appl. Phys. 72 (3), 1 August 1992

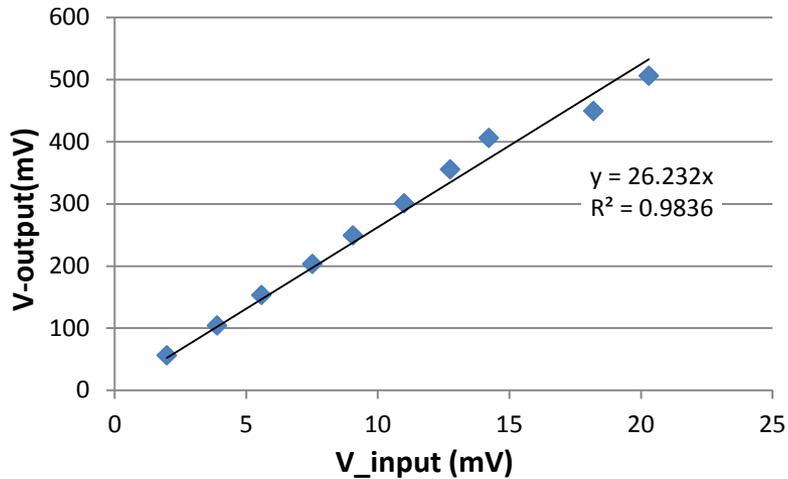
- [5] A.H. Sommer, Photoemissive Materials (Wiley, New York, 1968)

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

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

Backup slides

Amplifier response
(input signal from waveform generator)



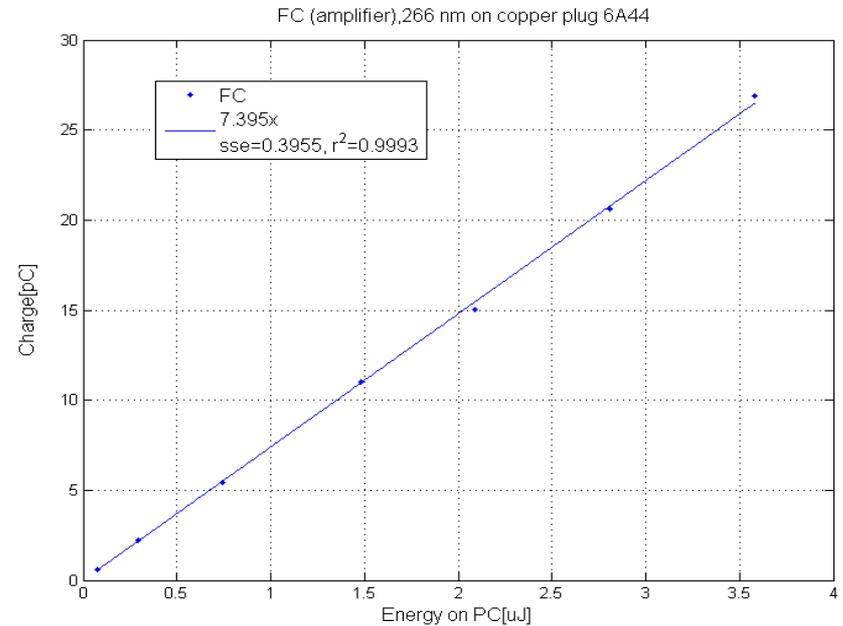
ZFL-1000VH



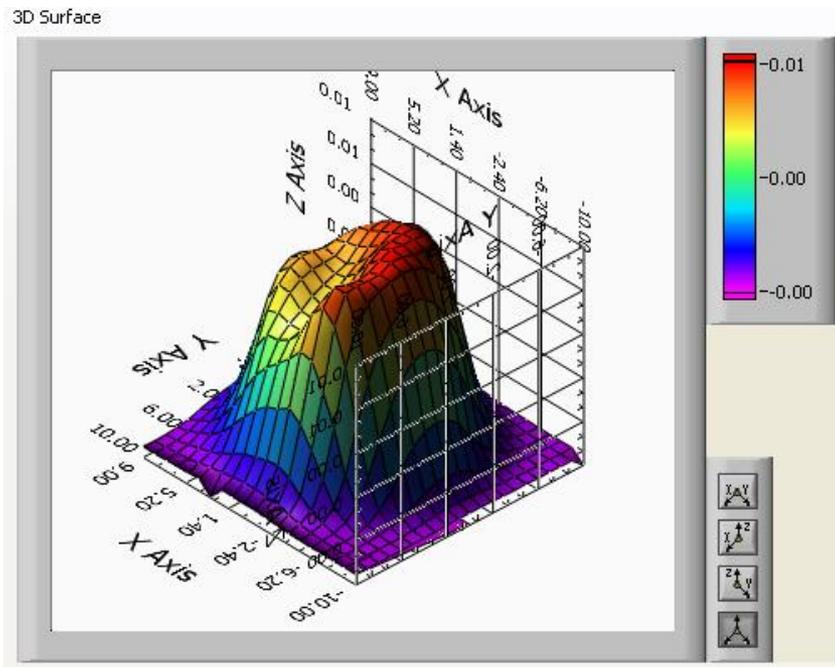
Features

- wideband, 10 to 1000 MHz
- low noise, 4.5 dB typ.
- high IP3, +38 dBm typ.

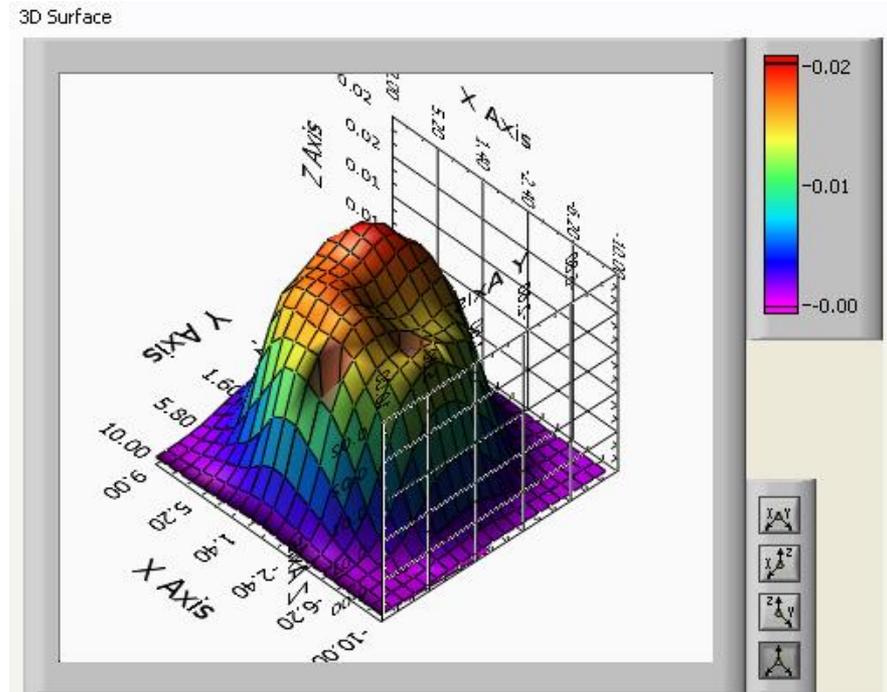
FC signal with amplifier for 266 nm on copper plug 6A44 : the amplifier doesn't distort the actual linear trend.



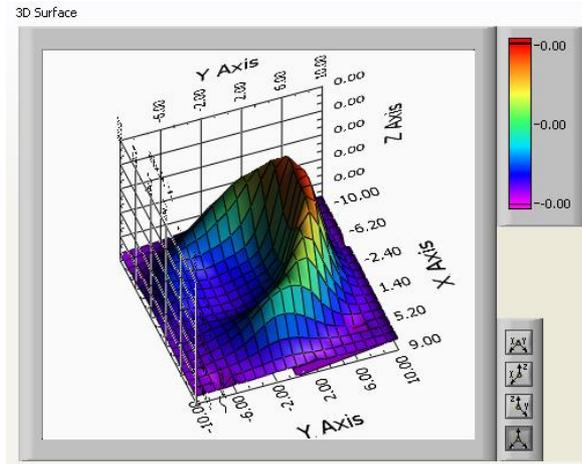
2nd plug
(266 nm and pencil beam)



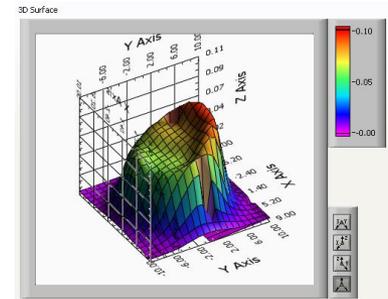
3rd plug
(266 nm and pencil beam)



3D scan (QE over the surface)
with 355 nm
and pencil beam

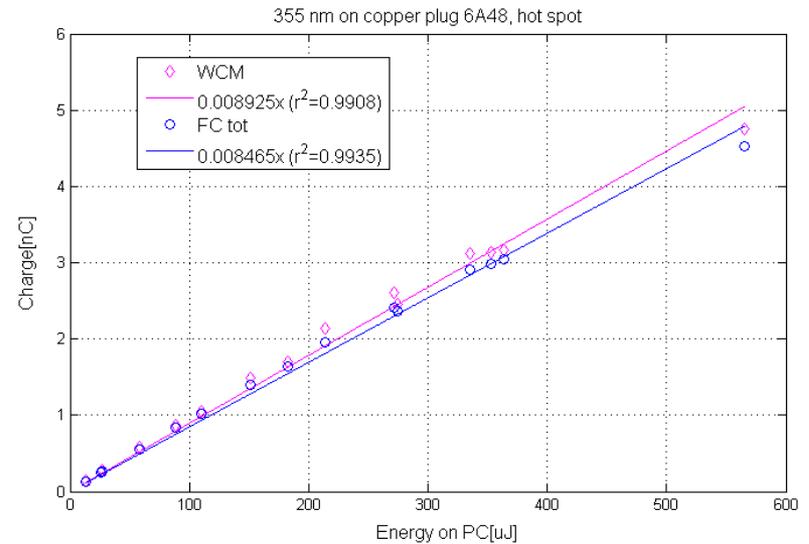
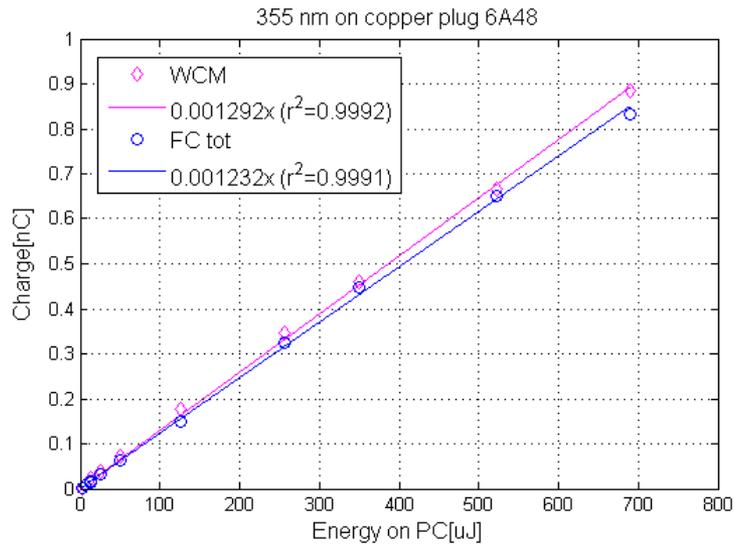


3D scan with 266 nm
and pencil beam



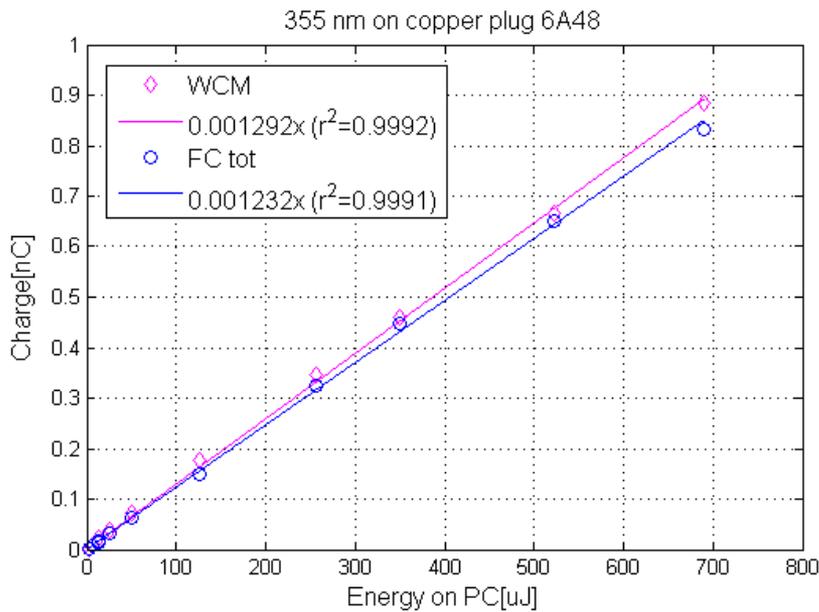
355 nm, pencil beam, in the middle of the PC

355 nm, pencil beam, on the hot spot



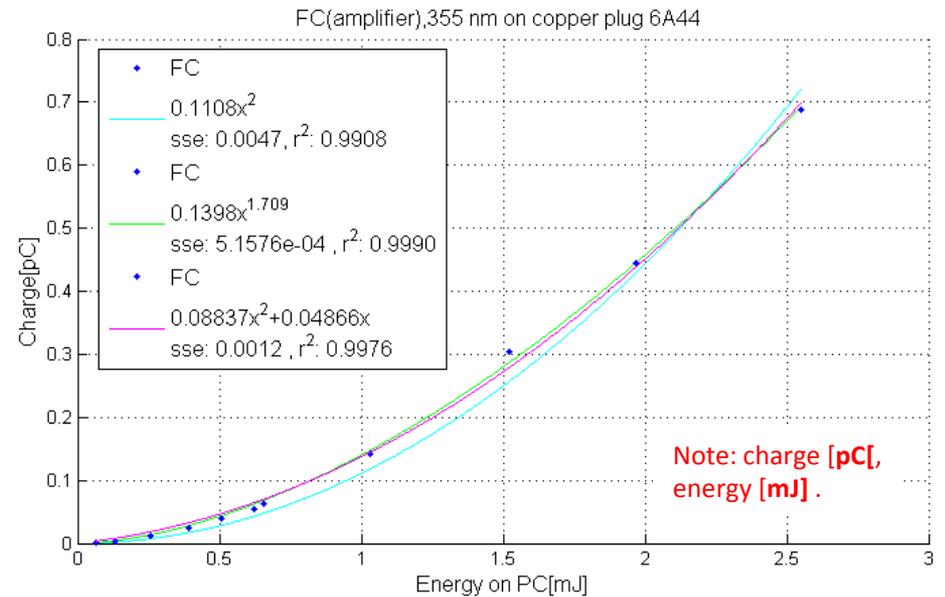
1st plug

LINEAR TREND



2nd plug (Amplifier introduced, only FC signal available.)

NON LINEAR TREND



Note: charge [pC], energy [mJ].