Photo-induced field emission for high brightness electron sources

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Introduction

Photo cathodes have long been established as high-brightness sources in electron accelerators. They provide high currents and short pulses. The emittance is limited by the emitter-spot size and the high transverse momenta of the ejected electrons in the thermal process [1-2]. Cathode lifetimes are typically short [3]. Other high-brightness electron sources employ field emission (FE) tips. In HRSEMs and TEMs those reach a higher normalised brightness than thermionic cathodes [4] since the tunnelling electrons are emitted preferentially perpendicular to the surface [5]. Field emission from flat cathodes requires extremely high surface electric fields (3 GV/m) and tip cathodes with high field enhancement deliver only insufficient currents for a linear collider.

The brightness of an electron source could be increased by a combination of photo excitation and field emission (photo-induced field emission, PFE) which utilises the short pulse of a laser and the low emittance of field-emitted electrons from a robust metal or semiconductor cathode [6-8]. In PFE, electrons are photo excited to states between the Fermi and vacuum level from where they tunnel into the vacuum subsequently. Many details in the excitation, relaxation and tunnelling processes are hardly understood today. Theories based on equilibrium models show inconsistencies as the laser-induced process occurs on a fs timescale [9]. A deeper understanding of the underlying principles should help to further improve the brightness of PFE cathodes.

First PFE experiments with focussed UV-VIS illumination of gold cathodes have shown promising results [10]. The systematic investigation of the PFE process, however, requires monochromatic light sources and energy spectroscopy of the field emitted electrons. A new UHV analysis system for PFE-spectroscopy (PFES) has been constructed. First measurements are shown. Measurements of the energy distribution of the electrons which are emitted from different materials at electric fields of up to some hundred MV/m and photons of up to 5 eV are planned with the new PFES system and will provide a deeper insight into the PFE process and its potential for high-brightness electron sources.

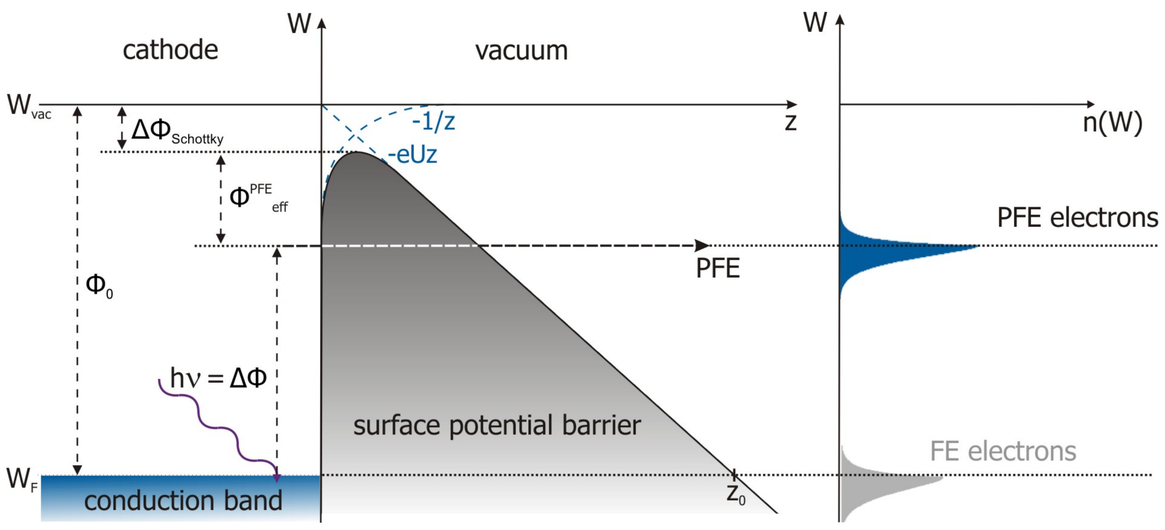
Basic principles

Field emission

- Tunnelling of electrons from around the Fermi level W_F into vacuum due to an applied electric field $E = \Phi_0/z_0$ with work function Φ_0 [11]
- Fowler-Nordheim emission current $I \sim \exp(-B\Phi_0^{3/2}/E)$, $B = 4/3\ (2m_e/\hbar^2e^2)^{1/2}$
- Low transverse momentum of emitted electrons
- Low energy spread at room temperature
- Nanosecond bunches in rf guns

Photo-induced field emission

- Photonic illumination of FE cathodes ($h\nu < \Phi_0 - \Delta\Phi_{Schottky}$, $\Delta\Phi_{Schottky} = (e^3E/4\pi\varepsilon_0)^{1/2}$)
- Excitation of electrons to states above W_F
- High emission current due to increased tunneling probability at $W = W_F + \Delta\Phi$
- Picosecond bunches possible with pulsed illumination

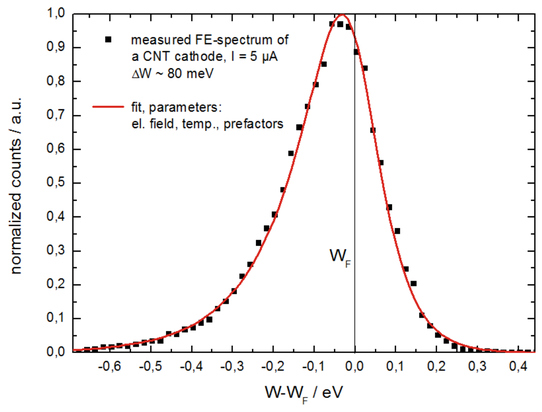


Schematic of the FE and PFE processes with energy distributions of the emitted electrons.

Possible PFE processes

- Full energy shift $\Delta\Phi = h\nu$ by tunneling of electrons from excited states [6].
- Relaxation of the photo-excited electrons to states above W_F, resulting in $\Delta\Phi < h\nu$ [12]. However, the relaxation processes are not fully understood (occurrence, loss mechanisms).
- Immediate tunnelling of excited electrons without existance of electronic states?

First measurements



FE spectrum of a carbon-nanotube (CNT) cathode measured at I = 5 µA with an energy resolution of 80 meV. The fit demonstrates a good agreement of the measured spectrum with the theoretical distribution.
The resolution yet has to be increased to resolve finer structures (e.g. the maximum of the spectrum).

Increasing resolution:

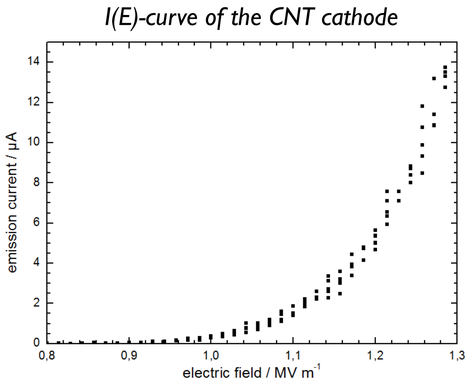
- decrease entrance slit width d: 4 mm → 0.5 – 4 mm ($\Delta W \sim d$)
- deconvolution with spectrometer transfer function (increases resolution by a factor 2-3 [13])

From the low energy tail of the spectrum ($n_{LE}(W) \sim \exp(c\cdot(W-W_F))$, measured at applied electric field E) and the I(E)-curve (FN-line with slope $m = \partial\ \ln(I/E^2) / \partial\ 1/E$) the work function of the cathode Φ_{CNT} can be calculated:

$$\Rightarrow \quad \Phi_{CNT} = -\frac{3}{2}\frac{m}{c}E^{-1} = 4.86 \pm 0.5\ eV$$

This is in good agreement with other measurements [14].

I(E)-curve of the CNT cathode



New apparatus for PFE-spectroscopy (PFES)

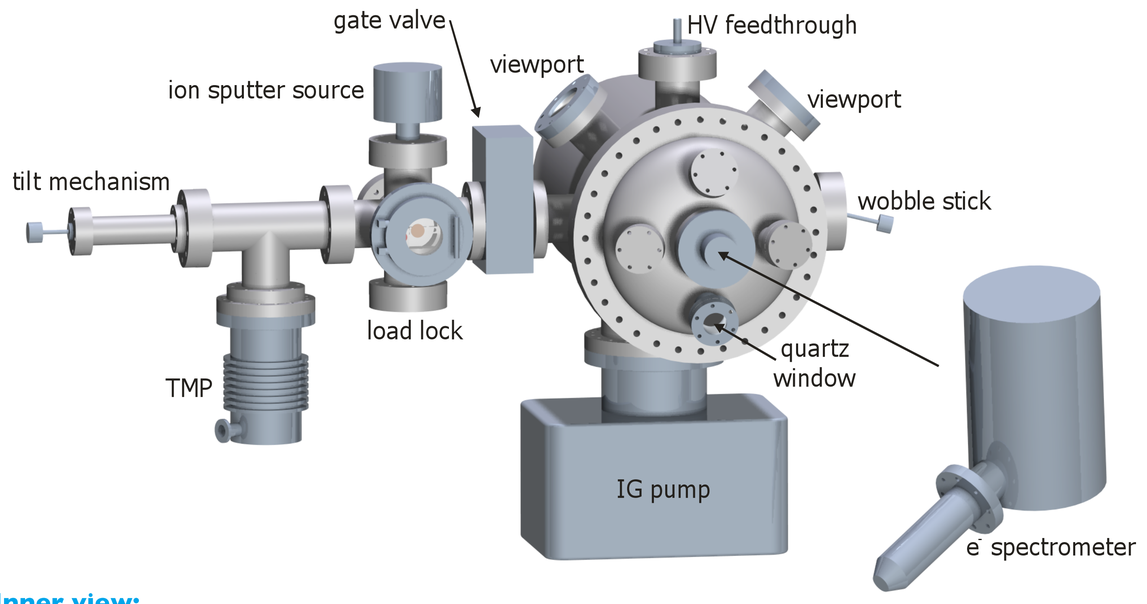
Preparation chamber ($p < 5\cdot10^{-7}$ mbar)

- Fast transfer of samples into analysis chamber
- Exchange of various anodes
- Tilt mechanism for in situ cleaning of sample surfaces with ion sputter source

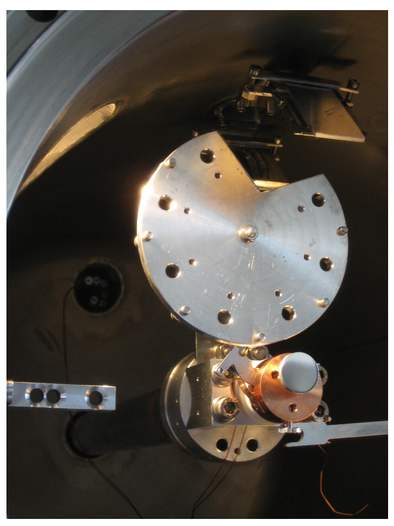
Analysis chamber ($p < 5\cdot10^{-9}$ mbar)

- Illumination of samples (0.5 eV < hν < 6.2 eV)
- I(E,...) curves (> pA) and electron spectroscopy simultaneously up to 500 MV/m
- Heating / cooling of samples (78 K < T < 1000 K)
- Various cathode and anode geometries possible
  - flat / structured (e.g. pyramids) / needle
  - hole / mesh

Outer view:

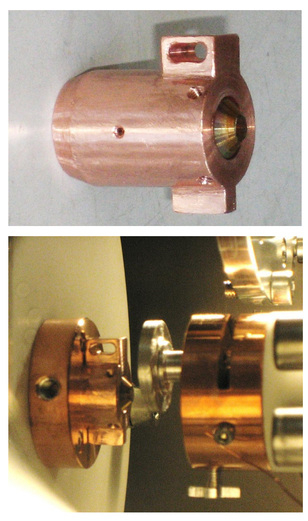


Inner view:

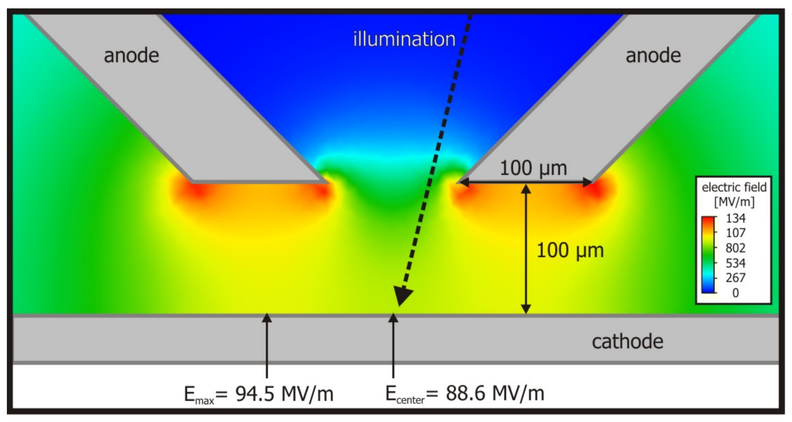


Cathode setup with spare sample holder

Tiltable anode setup



Anode holder with mesh anode
Electrodes in meas. position



Cross section of the electrode setup with conical hole anode ($\varnothing_{hole}$=100 µm, U=10 kV) opposite to flat cathode (U=0 V) with 2D simulation of the resulting electric field (ElecNet by Infolytica). For this geometry the field homogeneity on the cathode surface (E_{center}/E_{max}) is 0.937.
The anode hole serves for cathode illumination and electron transmission to spectrometer.

Outlook

The new PFES system provides many possibilities to get a deeper insight into the PFE process and its potential for high-brightness electron sources. Planned measurements include:

- PFES and integral current measurements simultaneously with monochromatic illumination or laser
- Systematic variation of relevant parameters (E, P_{Laser}, hν, $T_{cathode}$, …)
- Test of various materials with different electronic structures (metals, semiconductors, alloys)
- UPS measurements to investigate the excitation mechanism independet of the tunneling process
- Variation of emitter geometry (flat or with small field enhancement) and crystallinity
- In situ emittance measurements of optimized cathode materials at PITZ (DESY, Zeuthen)

References & Acknowledgements

[1] F. Boulware et al., Proc. FEL08, p. 481 (2008).
[2] S. Lederer et al., Proc. FEL07, p.350 (2007).
[3] P. Michelato et al., Proc. EPAC08, p.241 (2008).
[4] W. Qian et al., J. Appl. Phys. 73, 7041 (1993).
[5] H. Shimoyama, S. Maruse, Ultramicroscopy 15, 239 (1984).
[6] M.J.G. Lee, Phys. Rev. Lett. 30, 1193 (1973).
[7] C. Hernandez-Garcia, C.A. Brau, Nucl. Instr. Meth. In Phys. Res. A 483, 273 (2002).
[8] R. Ganter et al., Phys. Rev. Lett. 100, 064801 (2008).
[9] L. Wu, L.K. Ang, Phys. Rev. B 78, 224112 (2008).
[10] B. Bornmann, Diploma Thesis, University of Wuppertal, WU-D 08-04 (2008).
[11] R. H. Fowler, L. Nordheim, Proc. Roy. Soc. Lond., A119 (1928) 173.
[12] C. Hernandez-Garcia, C.A. Brau, Nucl. Instr. and Meth. A 429 (1999) 257.
[13] D. Sprenger, O. Anderson, Fresenius J Anal Chem (1991) 341:116-120.
[14] N. de Jonge, J. Bonard, Phil. Trans. R. Soc. Lond. A 2004 362, 2239-2266