PAUL SCHERRER INSTITUT

Metal photocathode research for 4th generation light sources : The needs and the achievements

F. Le Pimpec

LAL, February 2012

Outline

High Brightness Source for High Brilliance XFEL
  - Brilliance / Brightness
  - Which Electron sources

General Problematic for photocathodes
  - Emittance and QE of metal photocathodes
  - Lifetime of photocathodes

Summary & Conclusions

Future…

XFEL performances

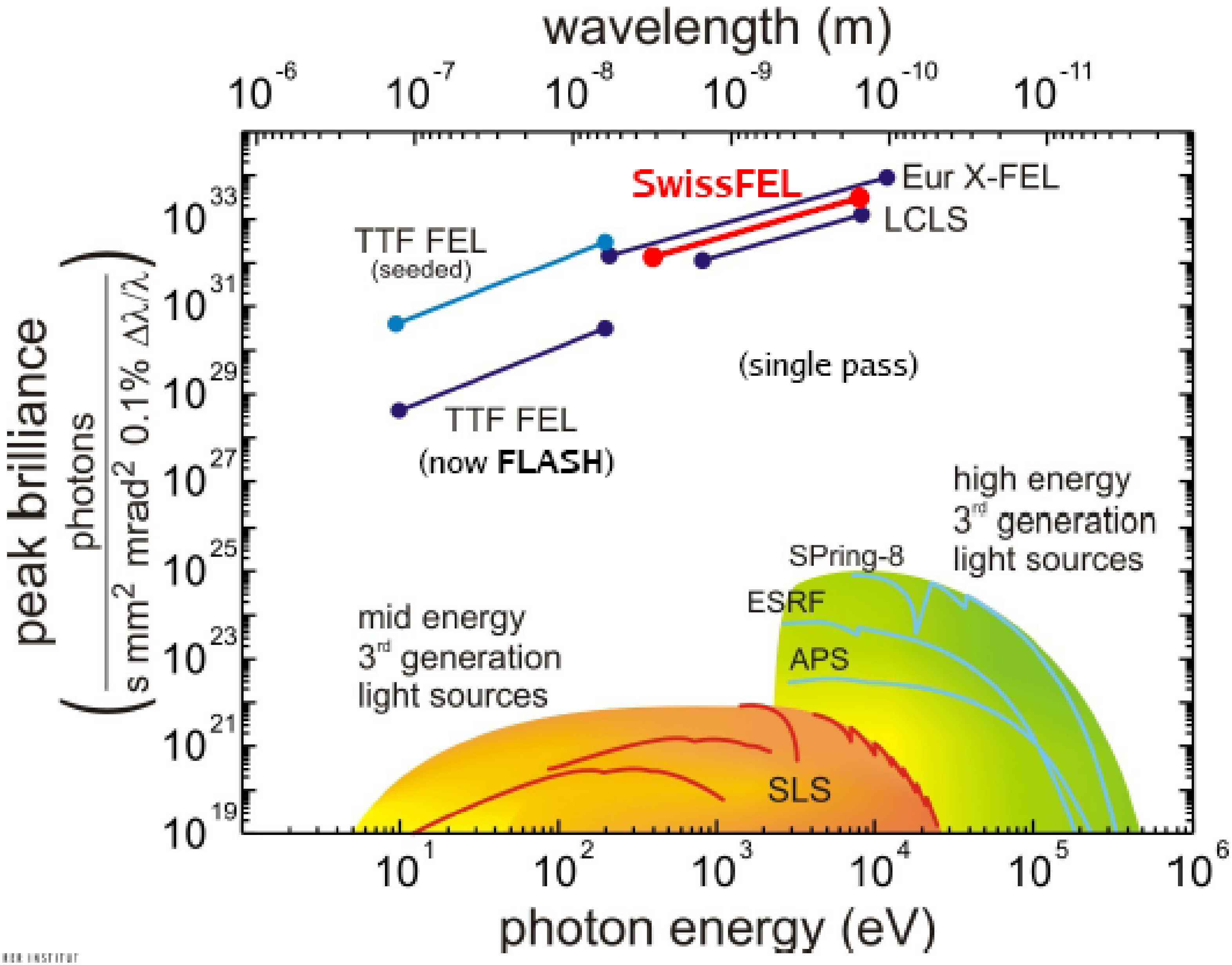
SASE FELs have a peak brilliance of a few order of magnitude above 3rd generation light sources (SLS - Soleil - ALS…)

Scientifically interesting

PSI-XFEL Workshop Crazy Ideas and Challenges ...

$$B = \frac{d^4 N}{dt d\Omega dS d\lambda / \lambda}$$

XFEL performances



How to obtain the Brilliance

Produce a beam of high Brightness

$$B = \frac{dI}{dS\,d\Omega}$$

For particle distribution whose boundary in 4D trace space is defined by an hyperellipsoid

$$\overline{B} = \frac{2I}{\pi^2 \varepsilon_x \varepsilon_y}$$ [A/(m-rad)^2]

$$\overline{B}_n = \frac{2I}{\pi^2 \varepsilon_{nx} \varepsilon_{ny}}$$ Normalized Brightness

A. Cianchi

- Increase beam peak current
  More QE (laser damage, response time)
  e$^-$ beam compression (magnetic bunch compressor)
- Decrease the Emittance ε (mm.mrad)
  Find an electron source of a low thermal emittance.

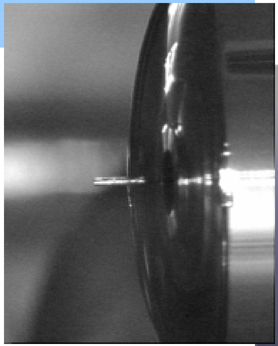
RMS emittance:

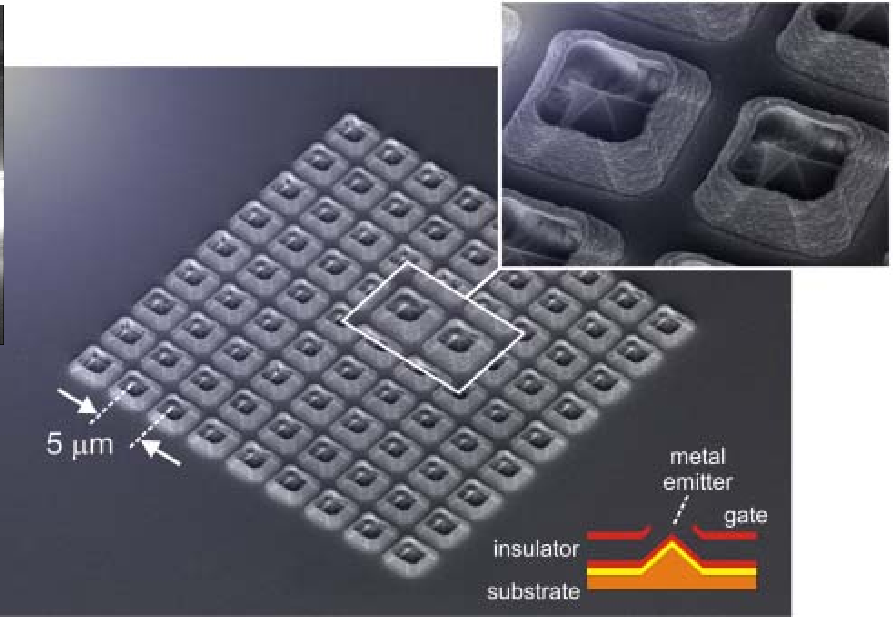
$$\varepsilon_{x,rms} = \sqrt{\langle u^2 \rangle \cdot \langle u'^2 \rangle - \langle uu' \rangle^2}$$

$$\varepsilon_{n,x,rms} = \beta\gamma \cdot \sqrt{\langle u^2 \rangle \cdot \langle u'^2 \rangle - \langle uu' \rangle^2}$$

Electron Sources :

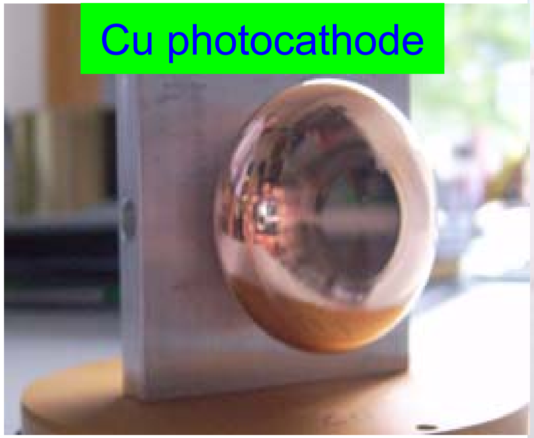
1. Field Emitter
   a) Array
      - Commercial (metal, CNT…)
      - PSI made
   b) Single tip FE

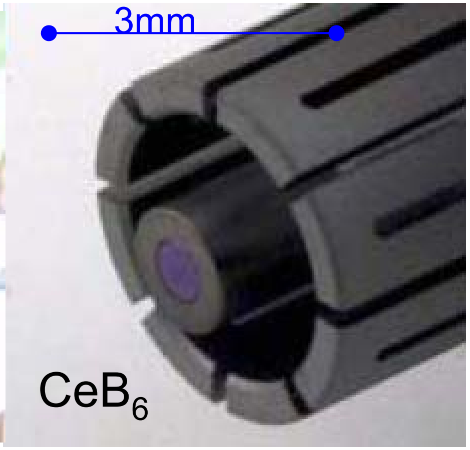




2. Photocathode

3. Thermionic





4. Hybridizing the sources is also possible

Which source and why ?

- FEL theory : high peak I, and low beam σ required for high gain FELs
- For a compact XFEL ($$) : compensate beam E with a lower initial ε

Ultimate limit in Accelerators: Thermal emittance of the Electron Source

$$\varepsilon_{n,rms} = \frac{\sigma}{2}\sqrt{\frac{2E_{kin}}{3mc^2}}$$

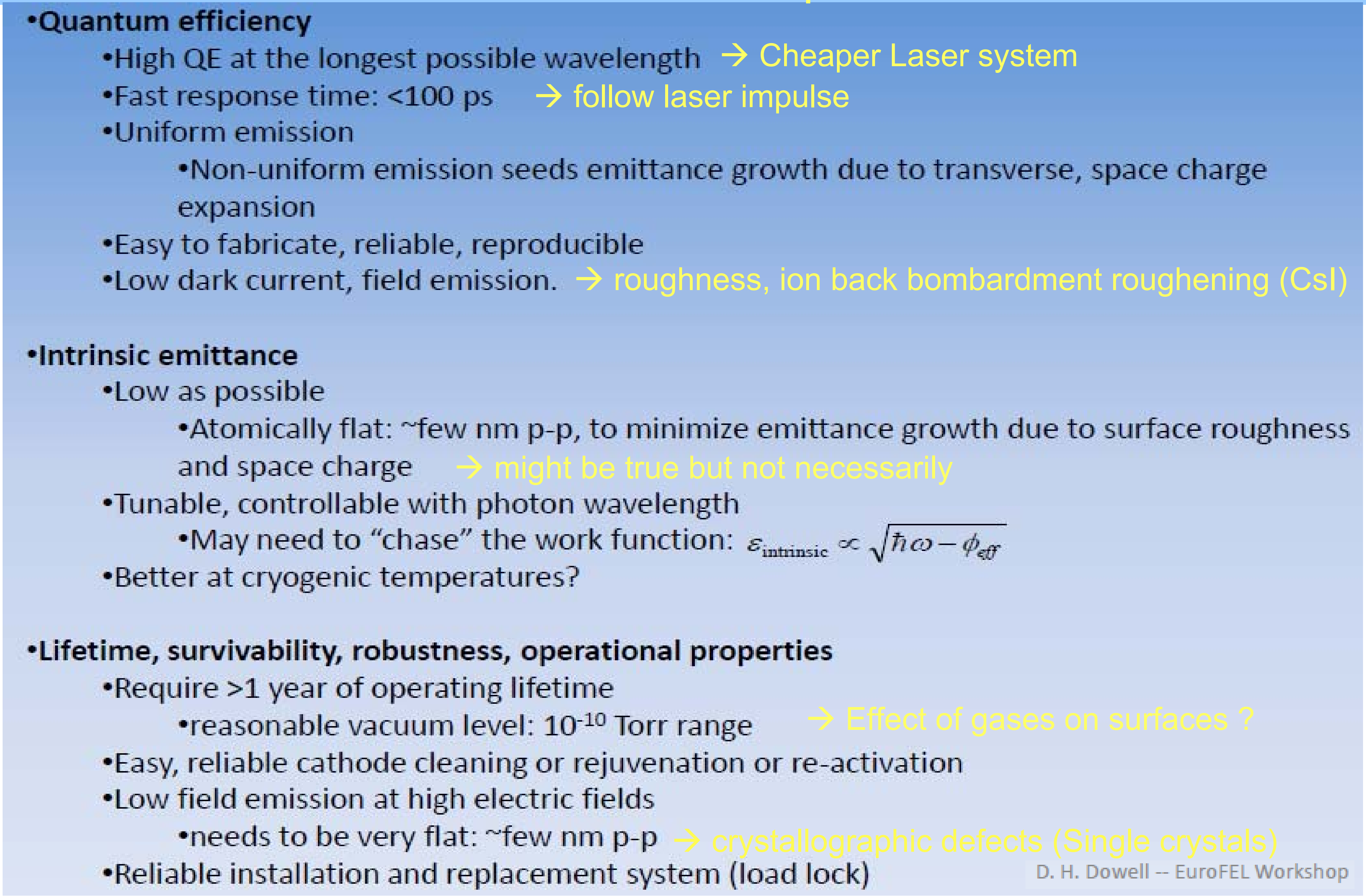
σ : Size of the produced Electron Beam

E_{kin}: Thermal Agitation of produced electrons

Thermionic Emission	**Photoemission**	**Field Emission**
$E_{kin,r} \sim \frac{3}{2}kT_{Solid}$	$E_{kin,r} \sim h\nu - \Phi + e\sqrt{\frac{eE}{4\pi\varepsilon_0}}$	$E_{kin,r} \sim \frac{3}{2}kT_{Solid}$
$J < 10^6\ A.m^{-2}$	$J < 10^9\ A.m^{-2}$	$J < 10^{12}\ A.m^{-2}$
T=1500K	**T=300K**	**T=300K**

If hν ≈ Φ, E ≈ 0 – very cold beam, but QE is bad !

The (obviously) most important Photocathode Properties



- **Quantum efficiency**
  - High QE at the longest possible wavelength → Cheaper Laser system
  - Fast response time: <100 ps → follow laser impulse
  - Uniform emission
    - Non-uniform emission seeds emittance growth due to transverse, space charge expansion
  - Easy to fabricate, reliable, reproducible
  - Low dark current, field emission. → roughness, ion back bombardment roughening (CsI)

- **Intrinsic emittance**
  - Low as possible
    - Atomically flat: ~few nm p-p, to minimize emittance growth due to surface roughness and space charge → might be true but not necessarily
  - Tunable, controllable with photon wavelength
    - May need to "chase" the work function: $\varepsilon_{\text{intrinsic}} \propto \sqrt{\hbar\omega - \phi_{\text{eff}}}$
  - Better at cryogenic temperatures?

- **Lifetime, survivability, robustness, operational properties**
  - Require >1 year of operating lifetime
    - reasonable vacuum level: 10^{-10} Torr range → Effect of gases on surfaces ?
  - Easy, reliable cathode cleaning or rejuvenation or re-activation
  - Low field emission at high electric fields
    - needs to be very flat: ~few nm p-p → crystallographic defects (Single crystals)
  - Reliable installation and replacement system (load lock)

D. H. Dowell -- EuroFEL Workshop

Atomically clean - Atomically flat

Vacuum : Desorption

What is a good vacuum Surface ?

An atomically clean surface !

What about a surface with an outgassing rate = 0 ?!

Development of barrier diffusion thin films and thin film NEGs

Photocathode : Emittance

What is a good Photocathode Surface ?

An atomically flat surface !

What about a surface which emits electron with $P_\perp = 0$?!

Need to seriously understand the emission mechanism of electrons from a material !!!

Cu cathode - The usual choice

Metal photocathode :

- Fast response time to laser impulse
- Rather resilient to adverse vacuum conditions
- In-situ cleaning is not too complicated
- Easy to get and manufacture
- QE is much lower than SC photocathode
- Require UV laser of high power ($, UV cracking, ablation)

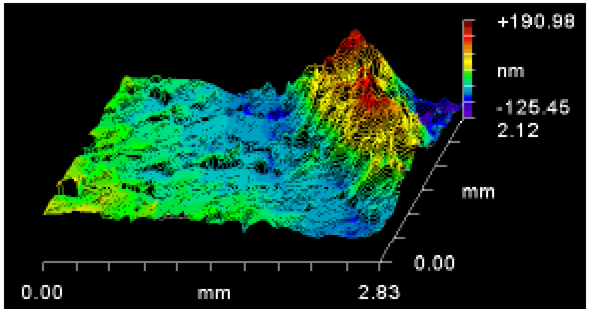
Copper cathode is a usual choice as a metal photocathode (tradition ?) Why not Mg or AlLi or Y or … ?

Grain Size ~ 0.3- 0.5 mm

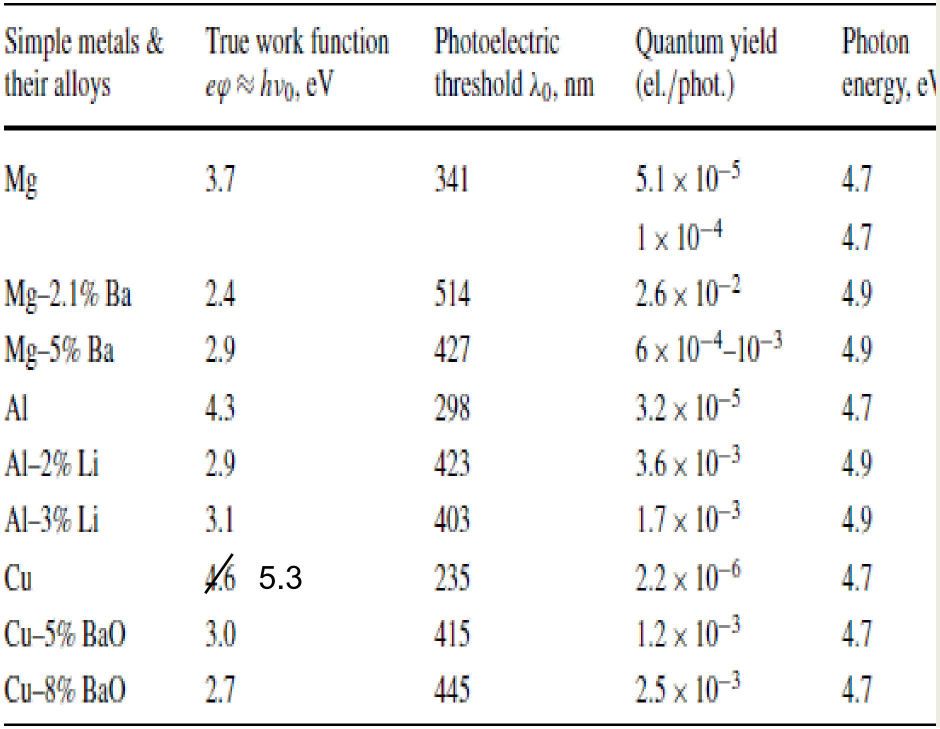
Roughness: Ra ~3 nm; PV= 15 nm (bfr)

Roughness: Ra ~ 8 nm; PV= 110 nm (aftr)

Diamond Tool Waviness: 0.1 mm

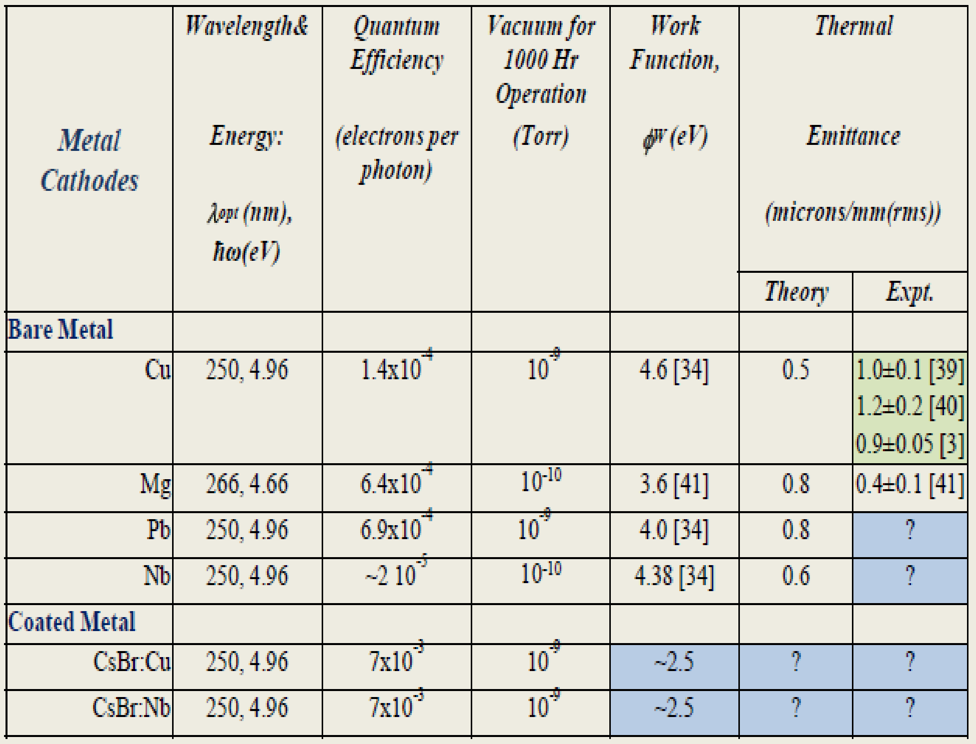


Survey of cathode testing : QE



Simple metals & their alloys	True work function $e\varphi \approx h\nu_0$, eV	Photoelectric threshold λ_0, nm	Quantum yield (el./phot.)	Photon energy, e
Mg	3.7	341	5.1×10^{-5}	4.7
			1×10^{-4}	4.7
Mg–2.1% Ba	2.4	514	2.6×10^{-2}	4.9
Mg–5% Ba	2.9	427	6×10^{-4}–10^{-3}	4.9
Al	4.3	298	3.2×10^{-5}	4.7
Al–2% Li	2.9	423	3.6×10^{-3}	4.9
Al–3% Li	3.1	403	1.7×10^{-3}	4.9
Cu	~~4.6~~ 5.3	235	2.2×10^{-6}	4.7
Cu–5% BaO	3.0	415	1.2×10^{-3}	4.7
Cu–8% BaO	2.7	445	2.5×10^{-3}	4.7

V. G. Tkachenko, A. I. Kondrashev and I. N. Maksimchuk
Applied Physics B - 98 (4), 2010



Metal Cathodes	Wavelength& Energy: λ_{opt} (nm), $\hbar\omega$(eV)	Quantum Efficiency (electrons per photon)	Vacuum for 1000 Hr Operation (Torr)	Work Function, ϕ_W (eV)	Thermal Emittance (microns/mm(rms)) Theory	Thermal Emittance (microns/mm(rms)) Expt.
Bare Metal						
Cu	250, 4.96	1.4×10^{-4}	10^{-9}	4.6 [34]	0.5	1.0±0.1 [39] 1.2±0.2 [40] 0.9±0.05 [3]
Mg	266, 4.66	6.4×10^{-4}	10^{-10}	3.6 [41]	0.8	0.4±0.1 [41]
Pb	250, 4.96	6.9×10^{-4}	10^{-9}	4.0 [34]	0.8	?
Nb	250, 4.96	~2 10^{-5}	10^{-10}	4.38 [34]	0.6	?
Coated Metal						
CsBr:Cu	250, 4.96	7×10^{-3}	10^{-9}	~2.5	?	?
CsBr:Nb	250, 4.96	7×10^{-3}	10^{-9}	~2.5	?	?

D. H. Dowell, I. Bazarov, B. Dunham, K. Harkay, C. Hernandez-Garcia, R. Legg, H. Padmore, T. Rao, J. Smedley and W. Wan, NIM A622 (2010) 685-697.

The same article survey other cathodes including SC photocathodes.

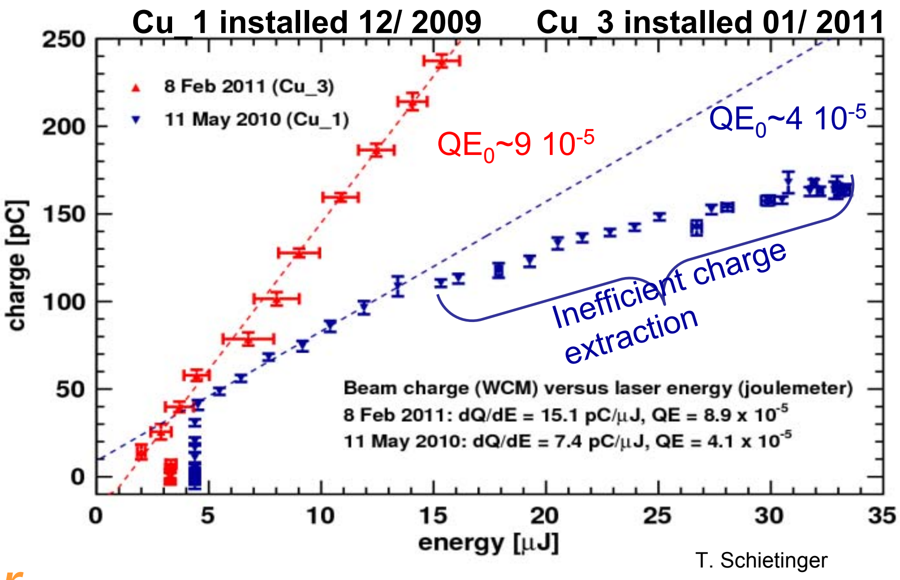
QE are not comparable easily - Cathode preparation

RF gun, Diode gun (Field presence on the surface)

Simple laser experiment - UV lamp experiment

QE : to plot or not to plot ?

$$QE = \frac{number\ of\ \ extracted\ electrons}{number\ of\ \ incident\ Photons}$$

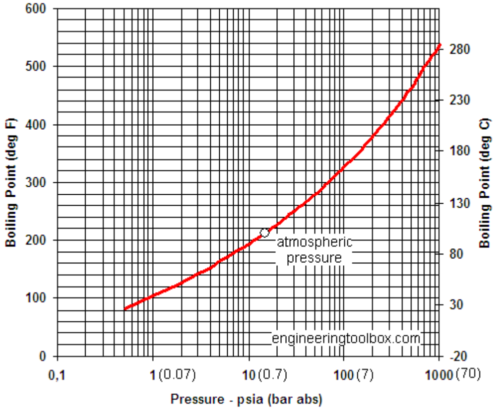


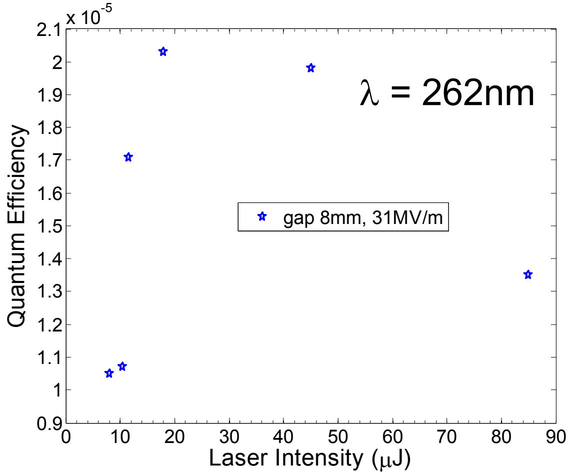
T. Schietinger

QE is intrinsic to the material, what we usually measure is not the QE, hence we should not plot it but show more the charge extracted over the laser intensity (W/cm²)

Le Pimpec et al, JVSTA, 28(5) 2010

QE is as intrinsic as the boiling point …

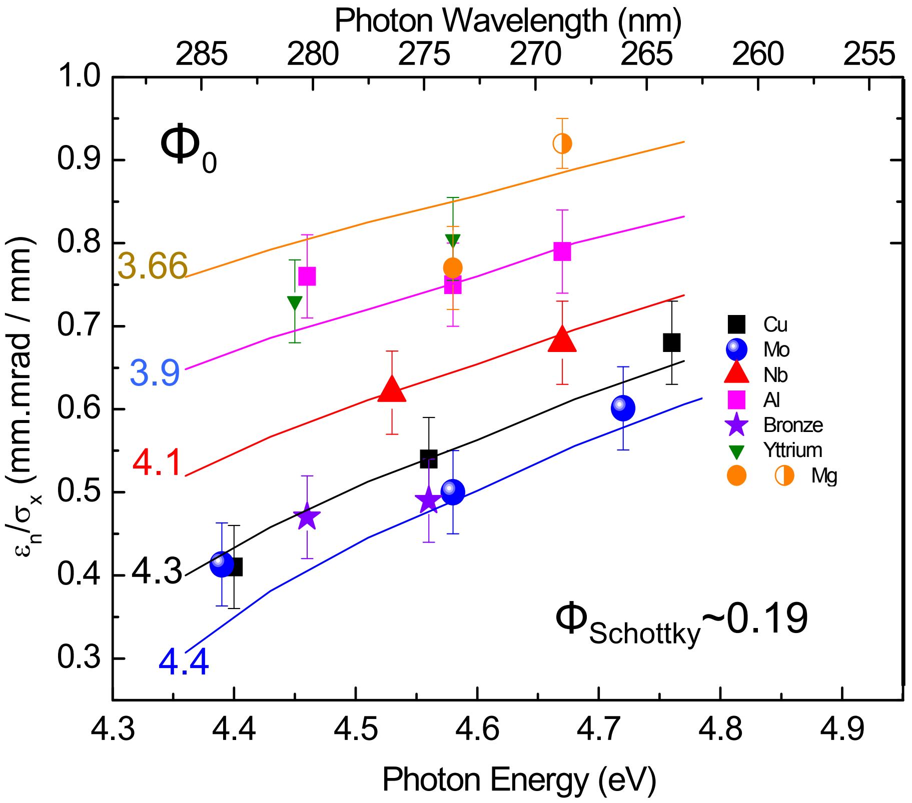




One can use QE$_0$ and QE$_{effective}$

Thermal $\varepsilon(\lambda)$; QE(λ); QE(Ɇ)

C.P. Hauri et al, PRL 104, 234802, 2010



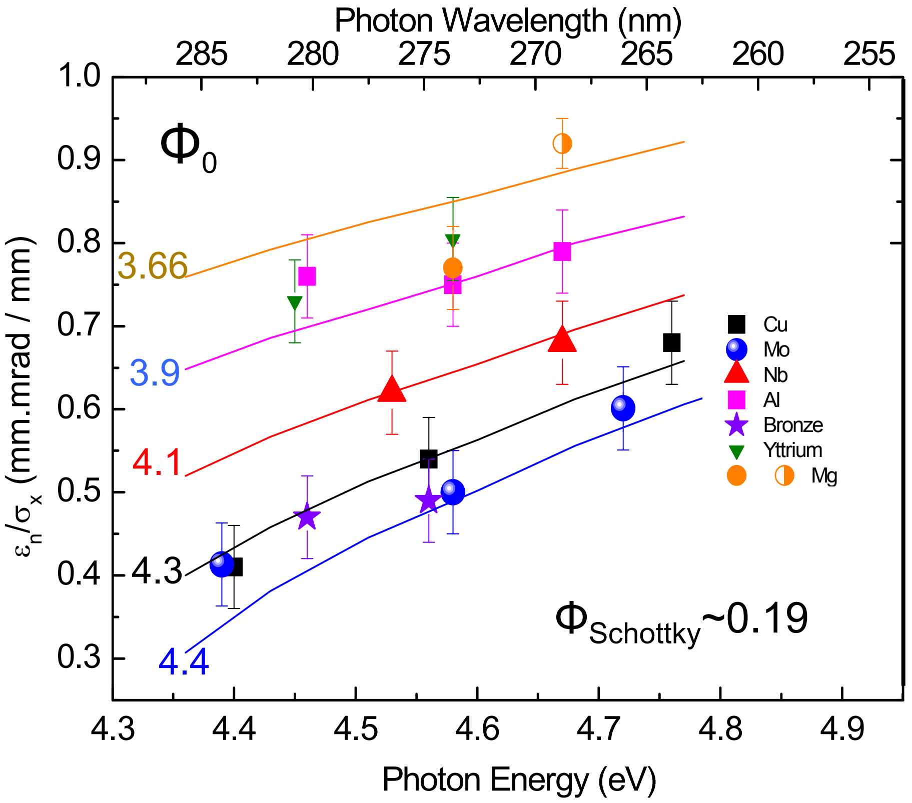
$$\varepsilon_{Intrinsic,Simple} = \sigma_{x,laser}\sqrt{\frac{h\nu - \Phi_0 + e^{3/2}\dfrac{F_{eff}^{1/2}}{(4\pi\varepsilon_0)^{1/2}}}{3mc^2}}$$

PolyC metal	Φ_0 (eV) Literature	Φ_0 (eV) Expt	λ (nm) lit
Cu	4.65 4.53-5.1	4.3	267
Mo	4.6	4.4	270
Nb Nb(110)	4.3 4.77	4.1	260
Mg	3.66	3.7 - 3.9	339
Al	4.28	3.9	290

Difference in WF input is dominated by Chemistry (O_2) not by topology nor Stress

Thermal $\varepsilon(\lambda)$; QE(λ); QE($\mathcal{E}$)

C.P. Hauri et al, PRL 104, 234802, 2010



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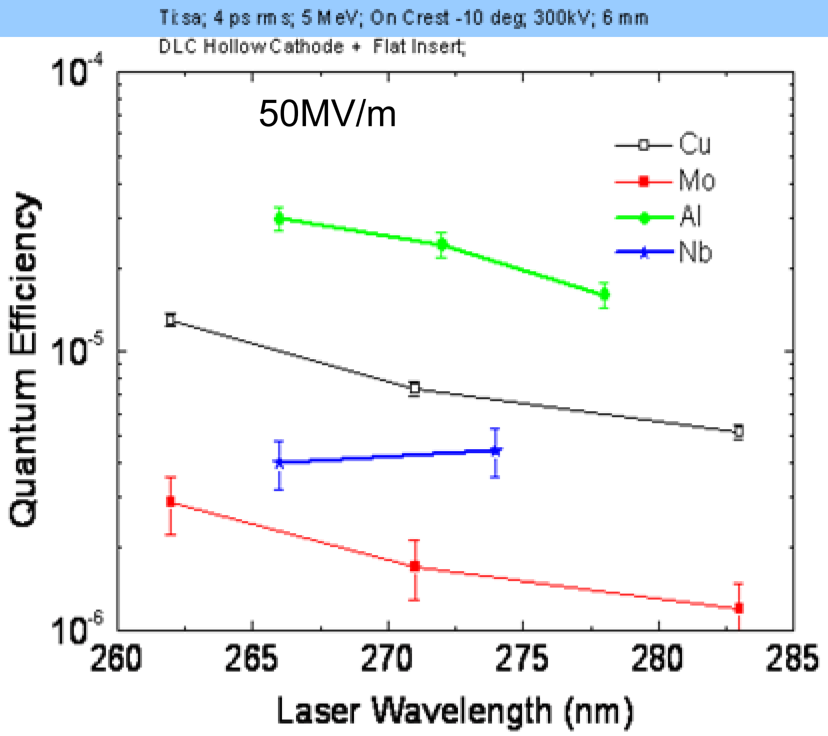
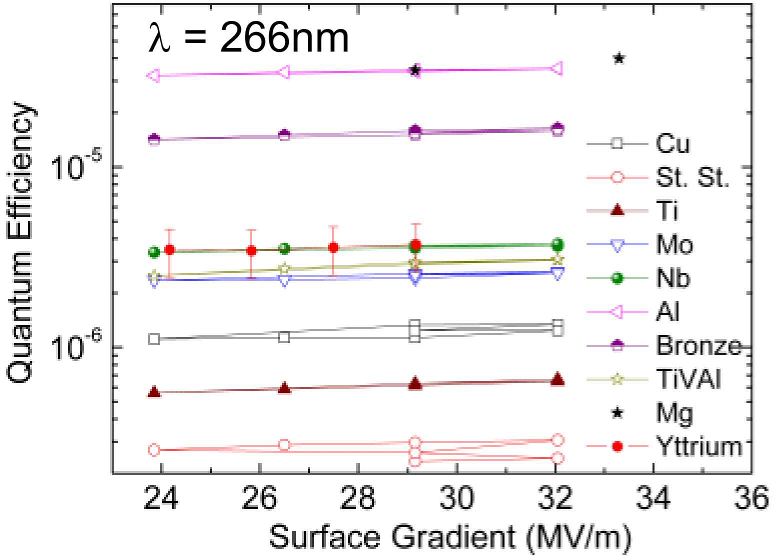
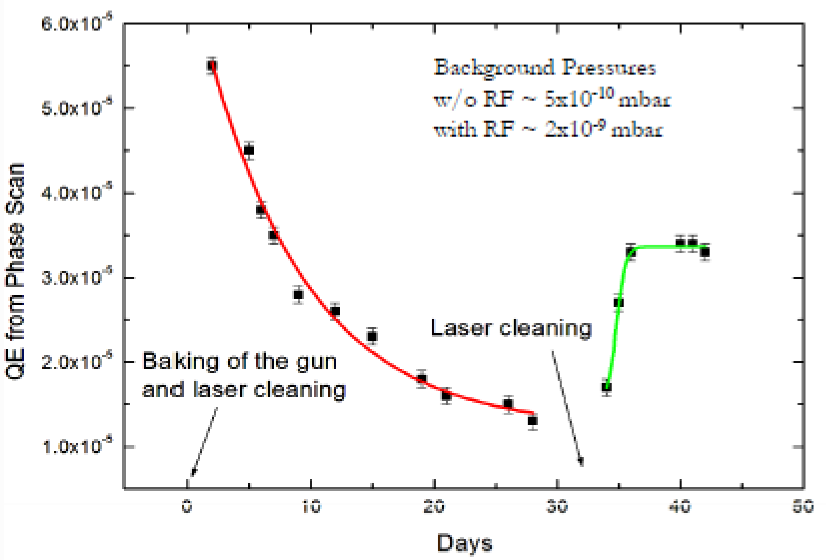

Ti:sa; 4 ps rms; 5 MeV; On Crest -10 deg; 300kV; 6 mm
DLC Hollow Cathode + Flat Insert;



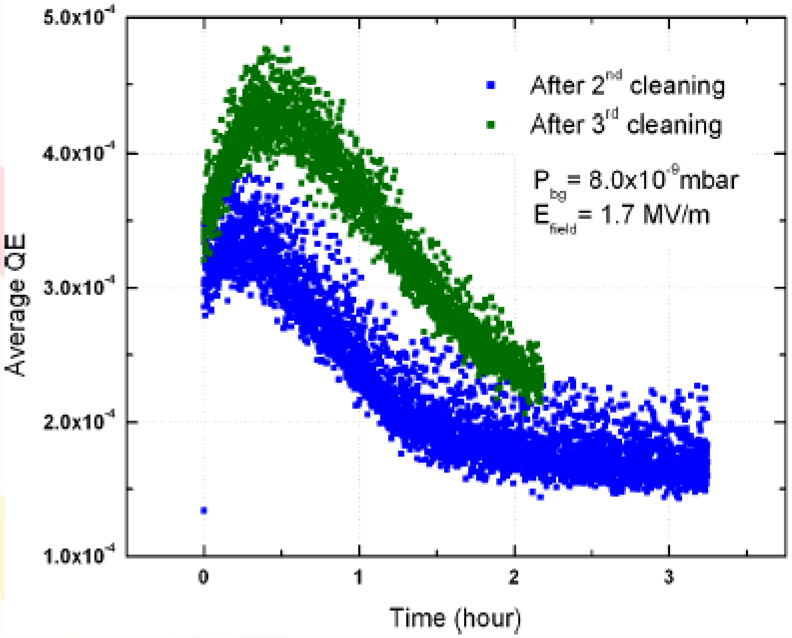
Metallic photocathode: lifetime

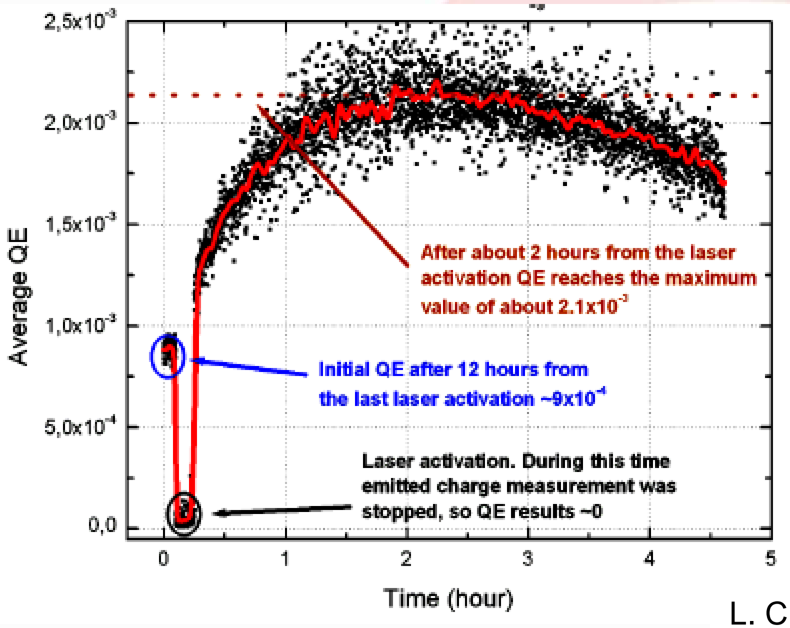
Cu



Despite their lower claimed contamination sensitivity even in UHV (10^{-9} mbar range) low work function metals as Mg, Y but also the most inert Cu may suffer from the contamination due to chemical species present in residual gases (H_2, CO, CO_2, H_2O).

Y





After about 2 hours from the laser activation QE reaches the maximum value of about 2.1x10^{-3}

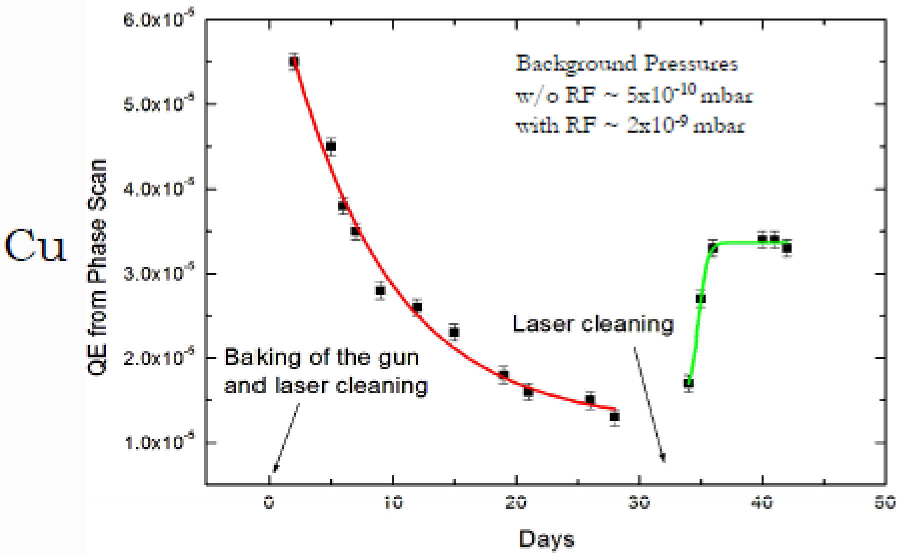
Initial QE after 12 hours from the last laser activation ~9x10^{-4}

Laser activation. During this time emitted charge measurement was stopped, so QE results ~0

Mg

L. Cultrera

Metallic photocathode: lifetime



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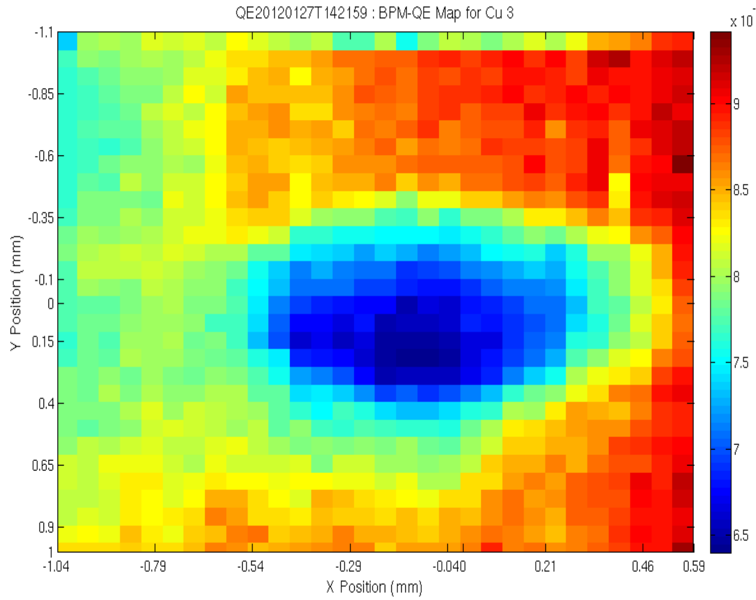
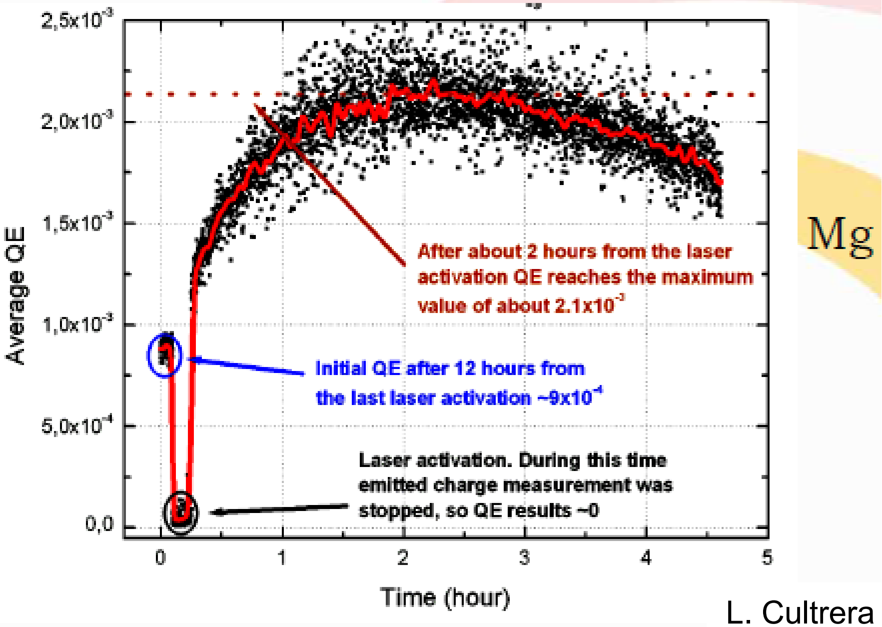
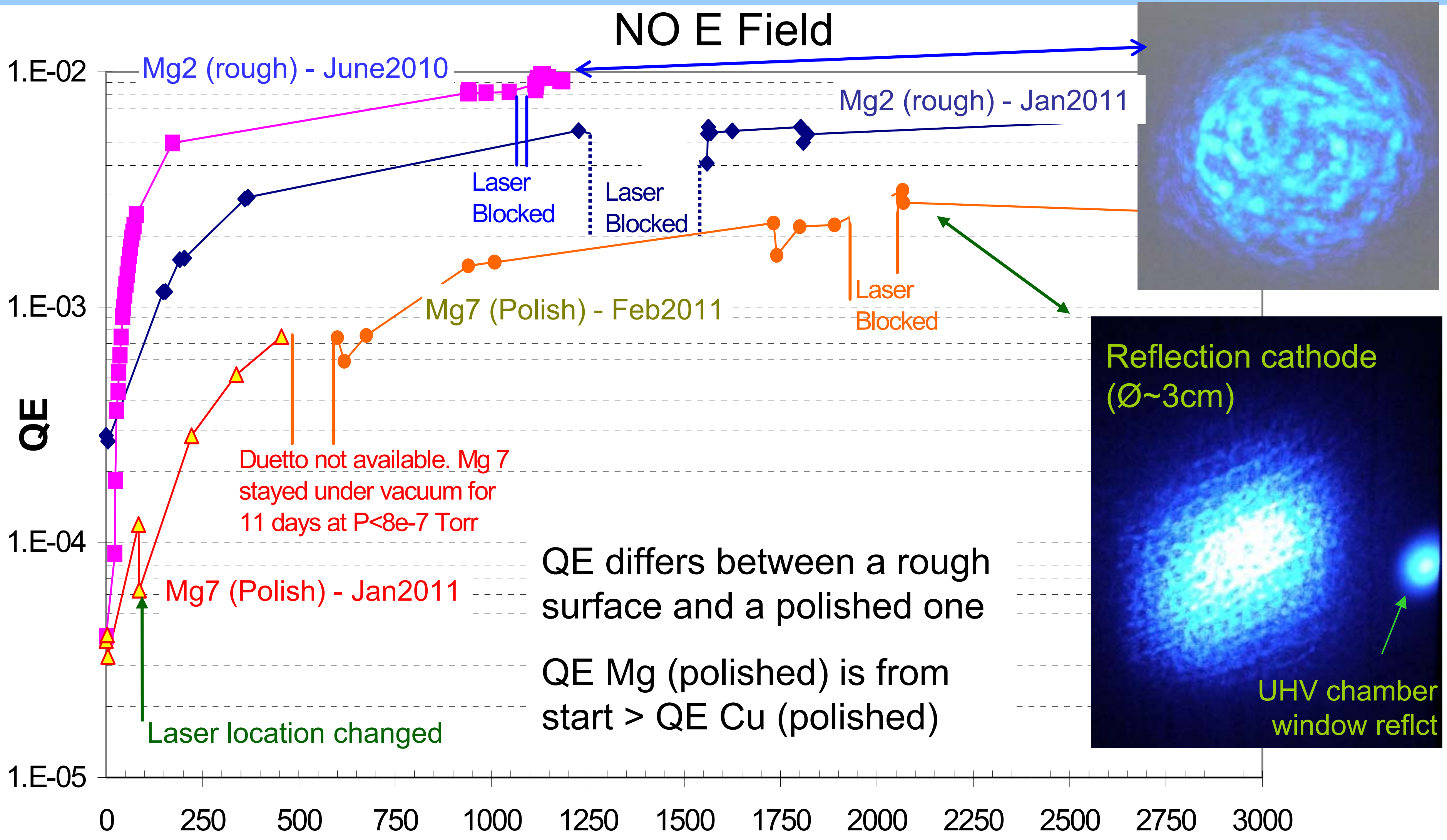




L. Cultrera

Mg Laser Cleaning and lifetime



QE differs between a rough surface and a polished one

QE Mg (polished) is from start > QE Cu (polished)

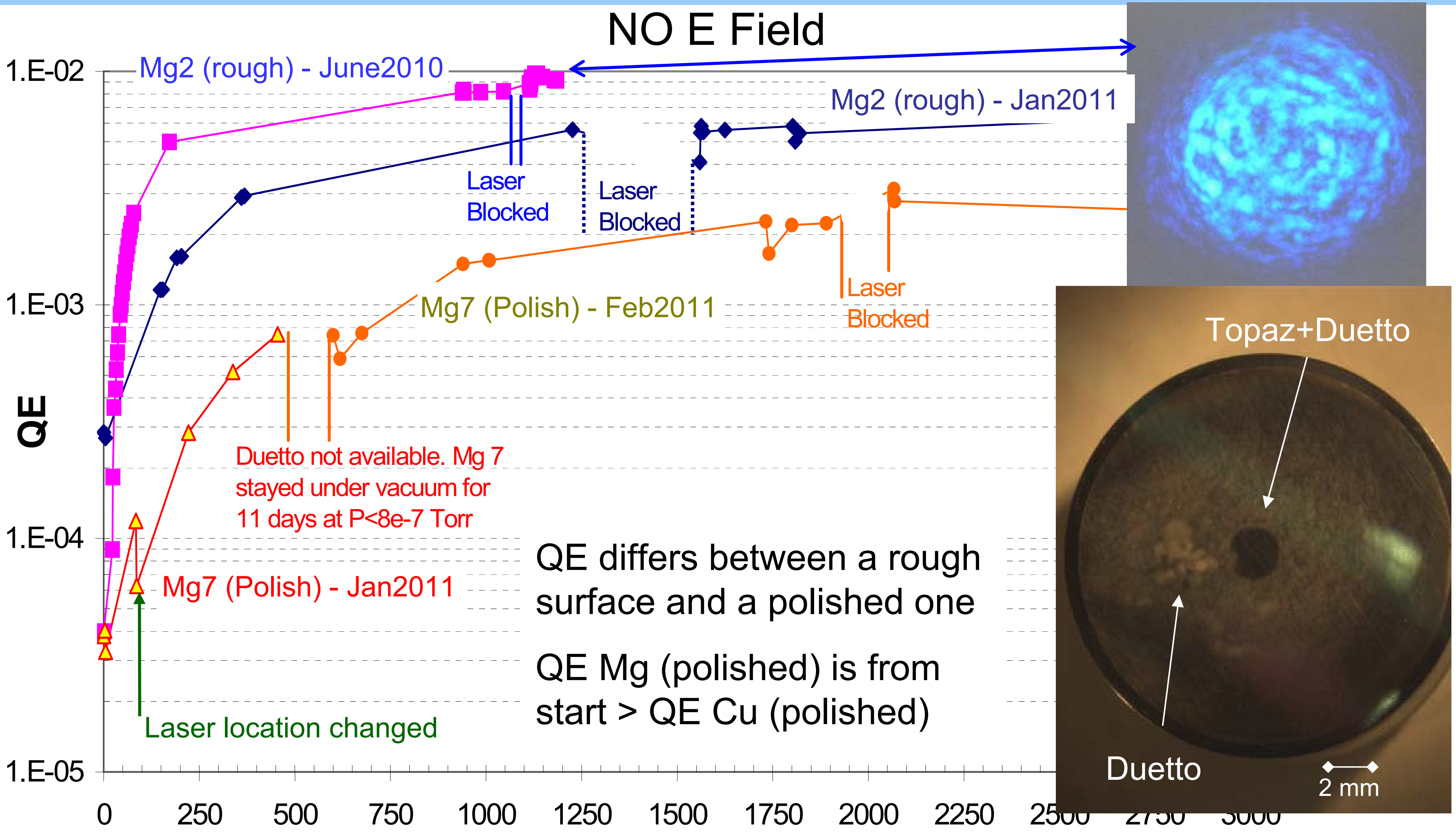
Time (min)

Laser size on sample : Ø=8 mm
Fluence ~ 1.2 μJ/cm²

Duetto laser, 355 nm; 10 ps, 115 mW to 150 mW , 200 kHz rep rate

F. Le Pimpec et al, arXiv:1202.0152, (2012)

Mg Laser Cleaning and lifetime



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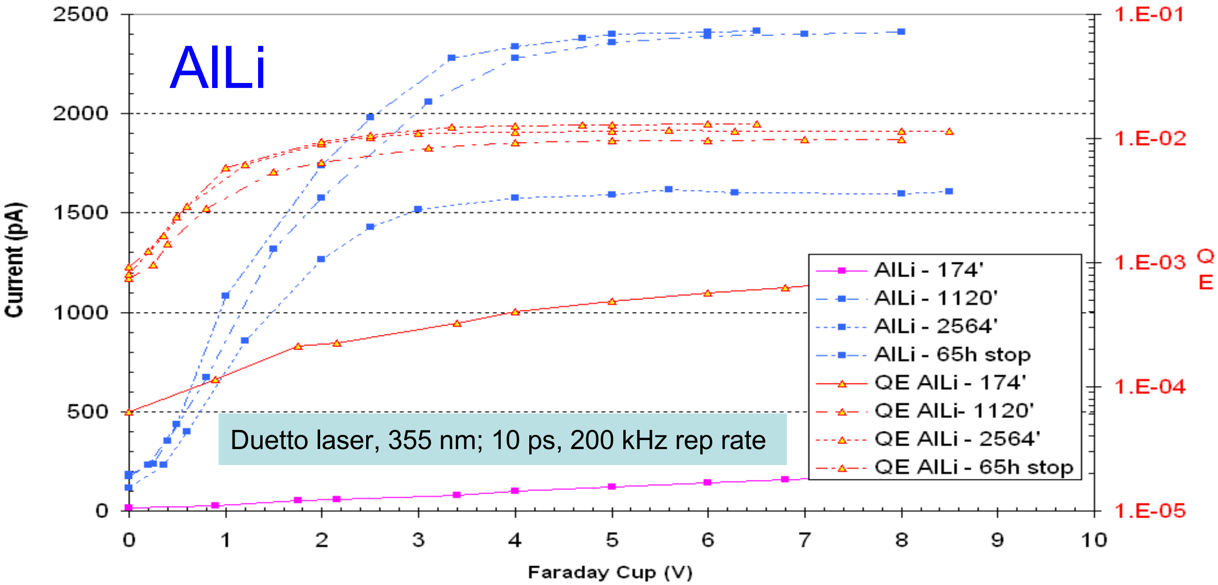
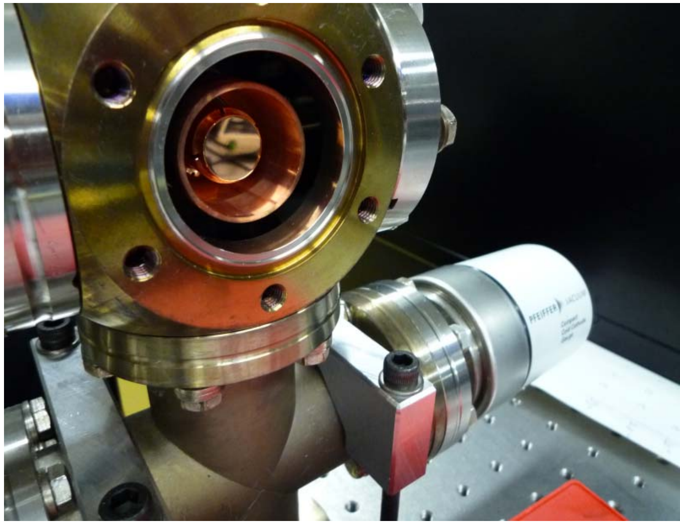
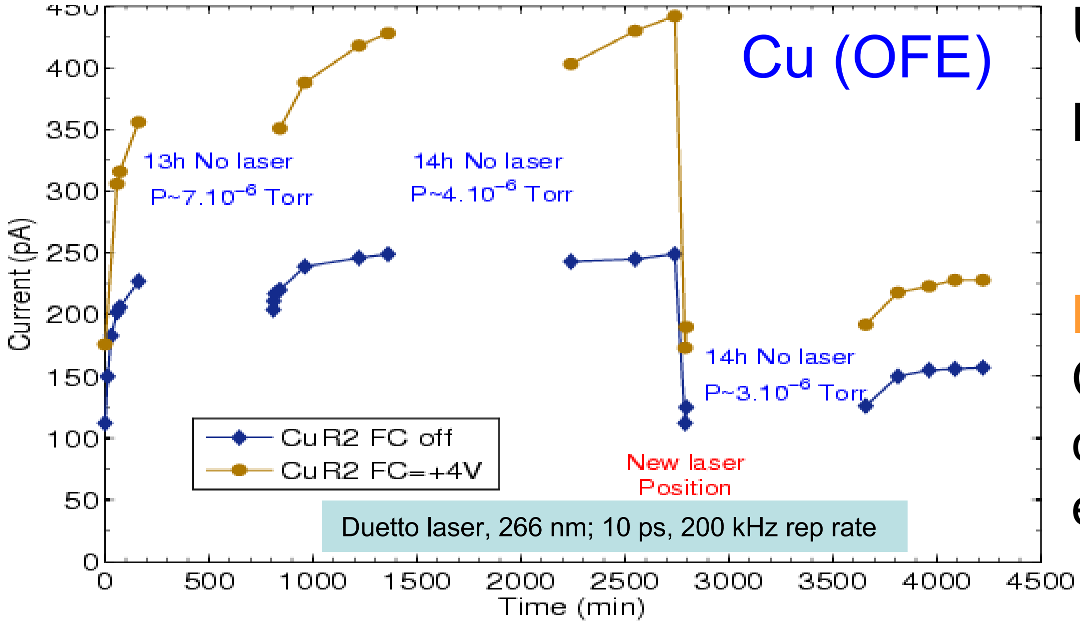
Lifetime in absence of RF field







Unbaked Vacuum : P~10^{-6} Torr

Main peak: H_2O at first, then H2

NO QE degradation on Al, AlLi, Cu or Mg cathodes. On the contrary increase of the extracted current with time.

F. Le Pimpec et al, arXiv:1202.0152, (2012)

Summary & Conclusions

- Compact ($$) High Brilliance XFEL requires a high Brightness electron beam → Need for low thermal emittance electron source.
- RF Photogun technology has matured. Not quite off the shelves yet.
- Cathodes are easily available (SC too) - They provide the charge, lifetime is sufficiently long. This is what is often requested.
- Metal photocathodes in XFEL RF guns do suffer from QE degradation over the months. *Not acceptable !*
- Laser (Ozone) Cleaning on Mg is very efficient: low rep rate high laser E density and high rep rate low laser E are both very efficient in improving QE. *For how long ?*
- In the community this degradation is attributed to vacuum effect (photocracking on the surface ?). We showed that this is not the case. Is the native oxide presence beneficial ? The presence of the RF field is important !!!

Future…

- The XFEL community wants an *Emittonium* cathode : QE ~ %%, $P_{\perp}$~0, fast response time, long life time, resilient to adverse vacuum conditions.

- Constructing such lattice will require a much better theoretical understanding of the electron transport-emission, more R&D in material science… TIME !!!!

Photocathode Physics

for Photoinjectors

October 12-14, 2010 • Brookhaven National Laboratory

Aimed at bringing the photocathode community together to discuss and explore the current state of the art in accelerator photocathodes, from both a theoretical and a materials science perspective.

All types of photocathode materials were discussed, including metals, NEA and PEA semiconductors, and 'designer' photocathodes with bespoke properties.

Share documentation

Learn from our predecessors

http://www.bnl.gov/pppworkshop/

Fay Hannon

http://photocathodes2011.eurofel.eu/talks/

- US national labs are trying to seriously tie up on this topic.
- Europe : Some talks about collaboration (UK, PSI, DESY, Milan…)


THANK YOU

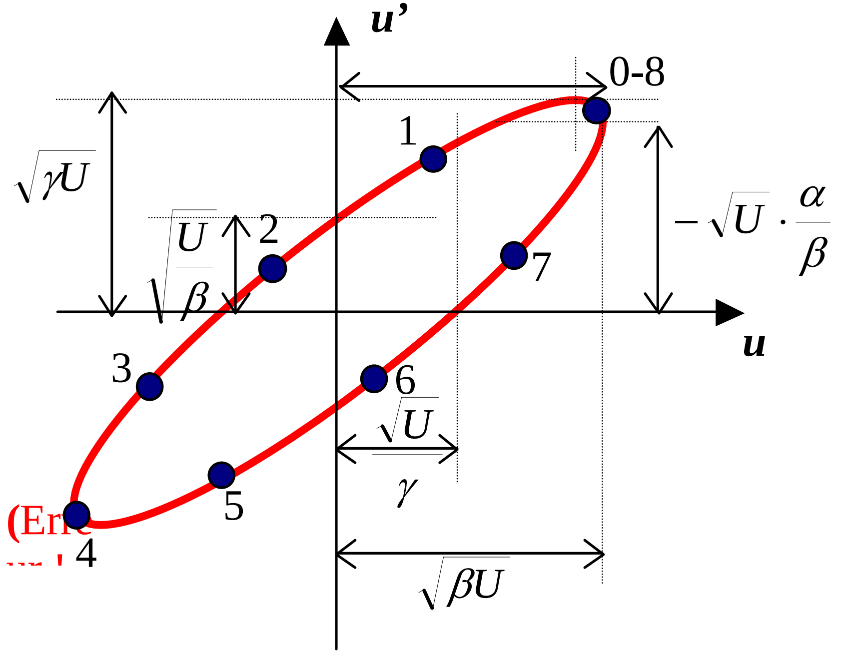
Emittance (ε) , what is that ?

- ε describes the phase space area/volume occupied by the beam
- ε is a measure for the “parallelism” of the beam (size *x* divergence).
- ε is a measure of the beam quality (ε : mm.mrad)

Ellipse equation

$$\gamma\cdot u^2 + 2\cdot\alpha\cdot u\cdot u' + \beta\cdot u'^2 = U$$

Area of the ellipse = π. ε ≡ U



RMS emittance:

$$\varepsilon_{x,rms} = \sqrt{\langle u^2\rangle\cdot\langle u'^2\rangle - \langle uu'\rangle^2}$$

$$\varepsilon_{n,x,rms} = \beta\gamma\cdot\sqrt{\langle u^2\rangle\cdot\langle u'^2\rangle - \langle uu'\rangle^2}$$

The normalized emittance is a quantity which is invariant upon acceleration