The characterization of metal photo-cathode for high brightness electron beam photo-injectors

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On behalf of SPARC_LAB collaboration

Outline

- Motivation
- Background
- Machining and Results
- Fourier transform of AFM images and surface roughness induced emittance
- Emittance measurements
- Preliminary study of Yttrium photocathodes
- Quantum Efficiency measurement
- Conclusions

6D brightness

- The requirements for a large number of quasi-"monochromatic" electrons, concentrated in very short bunches, with small transverse size and divergence, translate into high particle density 6D phase-space, or in other words, in high brightness B:

$$B\left[A/m^2\right] \propto \frac{Q}{\varepsilon_{nx}\varepsilon_{ny}\sigma_t\sigma_\gamma}$$

$$\boxed{QE = \frac{n_e}{n_p} = (q/e)\left(\frac{E_L}{h\nu}\right)}$$

$$\boxed{\varepsilon_{TOT} \approx \sqrt{\varepsilon^2_{chromatic} + \varepsilon^2_{rf} + \varepsilon^2_{roughness} + \varepsilon^2_{SC} + \varepsilon^2_{\mathrm{int}} + \varepsilon^2_{Busch}}}$$

- The brightness generated at the electron source represents the ultimate value for such a quantity, and cannot be improved but only spoiled along the downstream accelerator.

Motivation

- High efficiency acceleration of charged particle beams at high gradients of energy gain per unit length that is Multi GeV acceleration in cm scale plasma structures

- High brightness electron beams produced by photo-injector are required for the Plasma Wake Field Acceleration, either particle or laser driven (PWFA or LWFA, respectively)

- Acceleration of high brightness electron beams and their transport up to the final application, preserving the high quality of the 6D phase space

Motivation

- A R&D activity on photo-cathodes, the electron source in a photo-injector, must be under development in order to fully know and characterize each stage of the photocathode "life"
- The improvement of brightness , consisting in preserving the homogeneity of the quantum efficiency (QE) and in a minimization of thermal emittance, ε_{th} , means the study and the characterization of know and/or novel electron sources
- A suitable photocathode machining procedure is useful to reduce surface roughness, that is one of contributions to the total beam emittance, and avoid surface contamination caused by standard procedures, for example the polishing with diamond paste or the machining with oil

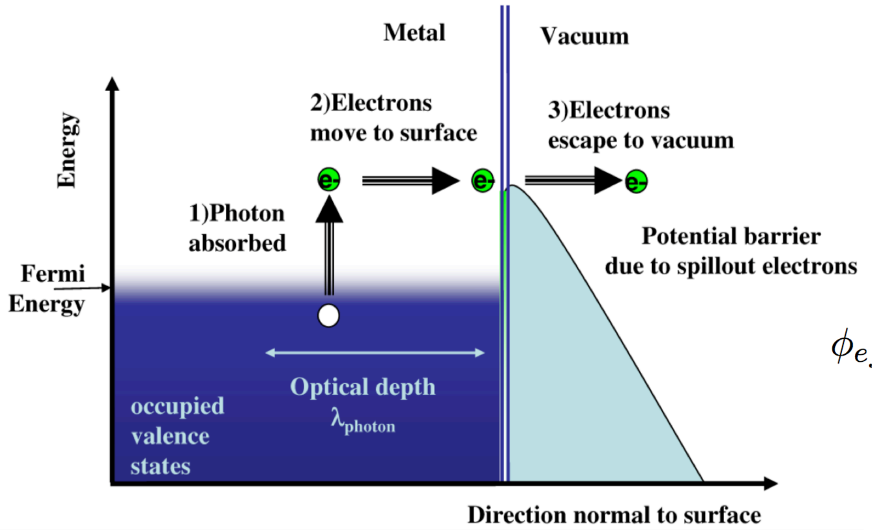
Photoemission Theory Background

➤ **ELECTRON EMISSION PROCESS OF METALLIC PHOTOCATHODES AND THE 3-STEP MODEL**

Photoelectric emission from a metal given by Spicer's 3-step model:

1. Photon absorption by the electron
2. Electron transport to the surface
3. Escape through the barrier

QE and emittance depend upon electronic structure of the cathode



D. H. Dowell, K.K. King, R.E Kirby and J.F. Schmerge, PRST-AB 9, 063502 (2006)

Intrinsic emittance:

$$\varepsilon_n = \sigma_x \sigma_{p_x} = \sigma_x \sqrt{\frac{\hbar\omega - \phi_{eff}}{3mc^2}}$$

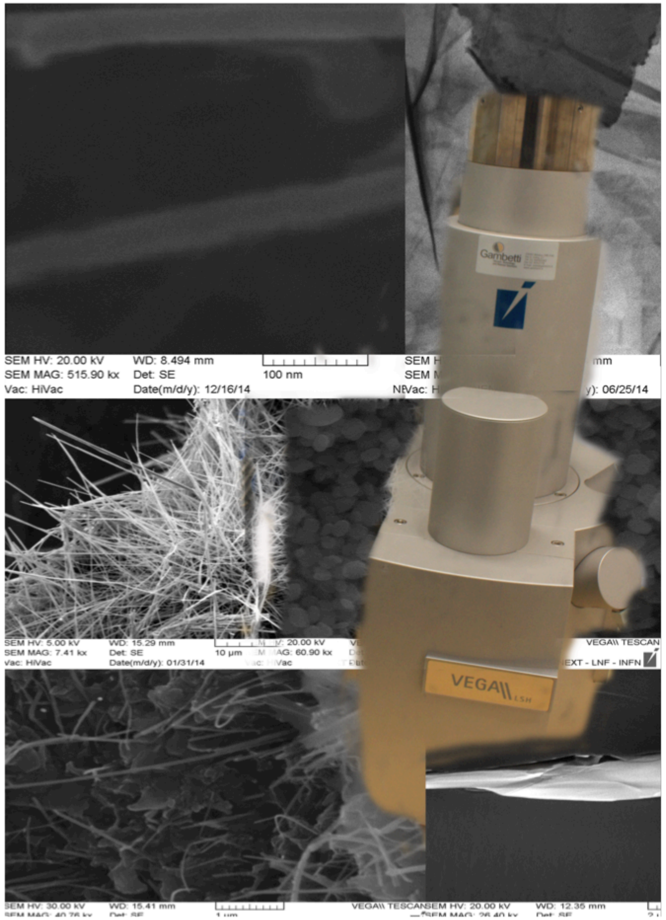
where

$$\phi_{eff} = \phi_w - \phi_{Schottky} = \phi_w - \alpha\sqrt{\beta E_{RF}} = \phi_w - e\sqrt{\frac{e}{4\pi\varepsilon_0}(\beta E_{RF})}$$

Quantum Efficiency:

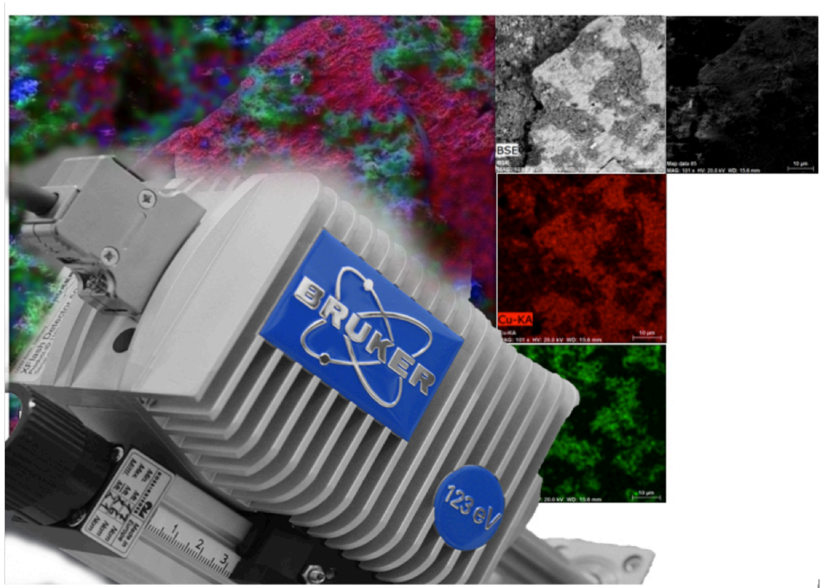
$$QE(\omega) \approx \frac{1 - R(\omega)}{1 + \frac{\lambda_{ph}}{\lambda_{e-e}}} \frac{(\hbar\omega - \phi_{eff})^2}{8\phi_{eff}(E_F + \phi_{eff})}$$

DIAGNOSTIC TOOLS: SEM and EDS



The types of signals produced by a SEM include:

- secondary electrons (*SE*), emitted from very close to the sample surface (***morphology***);
- back scattered electrons (***BSE***): electrons beam that are reflected from the sample by elastic scattering (**atomic number, *Z***).



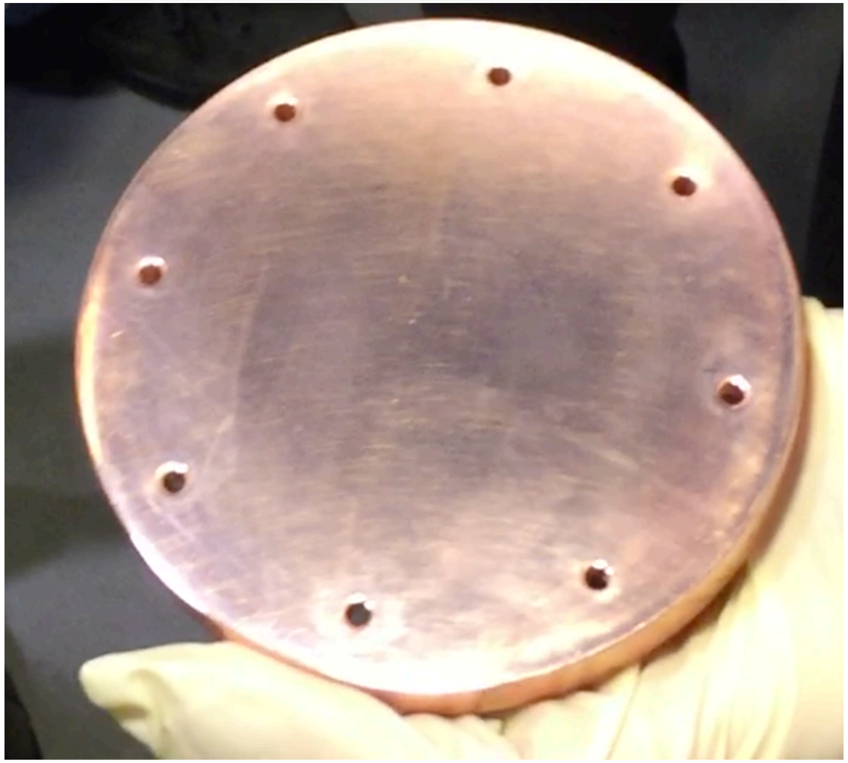
➢ We are able to determine the chemical composition of the test sample with the **Energy Dispersive Spectroscopy (EDS).**

Activity at SPARC_LAB test facility: Cu photocathode surface analysis with SEM before and after machining

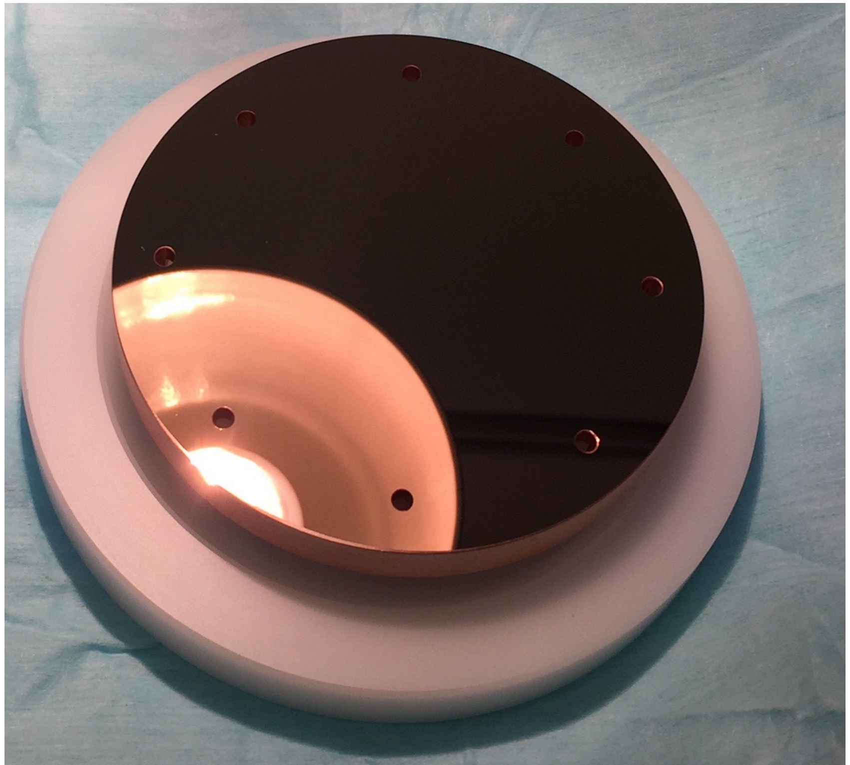
- The photocathode surface has been machined by means of diamond milling and blown with nitrogen. The machining has been done without the use of any oil or cooling fluid (dry machining).

BEFORE MACHINING

Our cathode time life was about 6 years

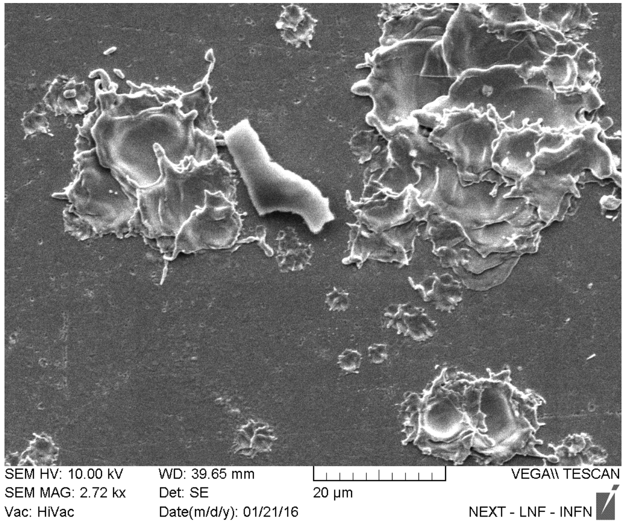


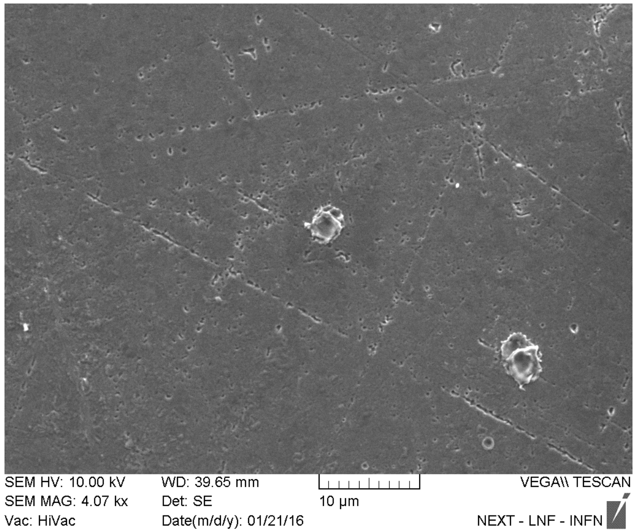
AFTER MACHINING



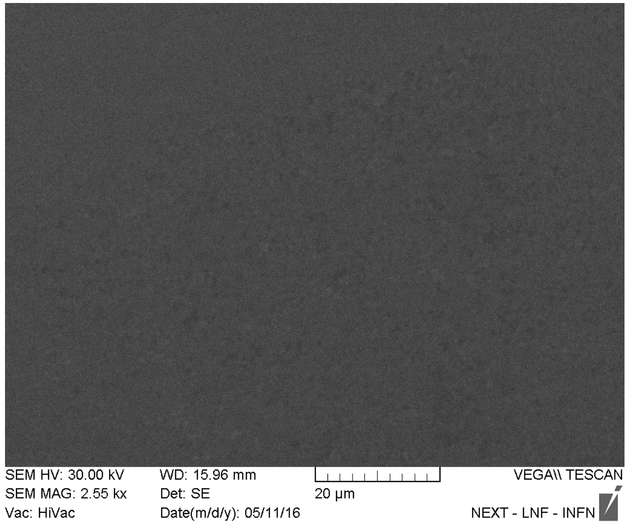
Activity at SPARC_LAB test facility: Cu photocathode surface analysis with SEM before and after machining

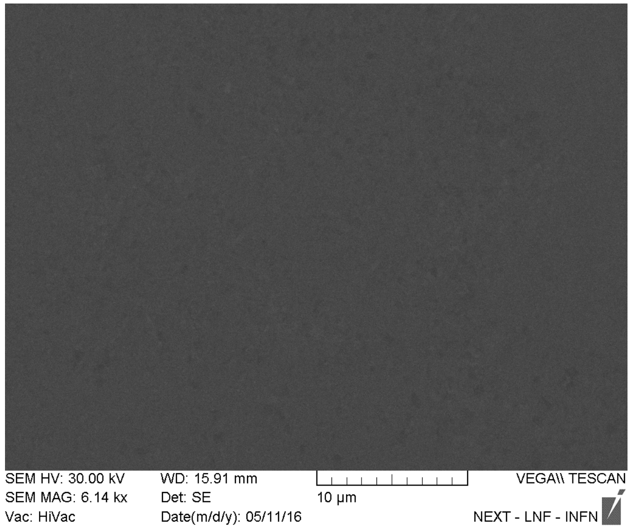
BEFORE MACHINING



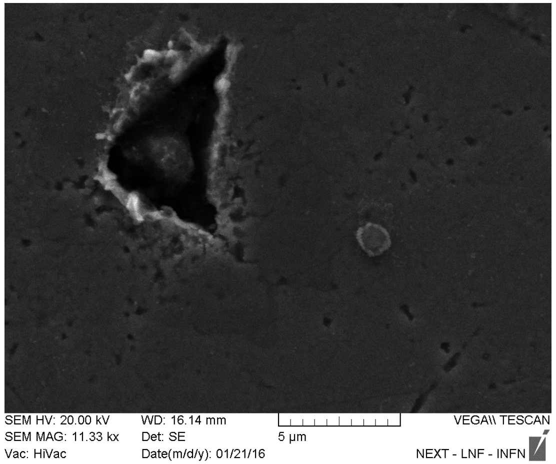


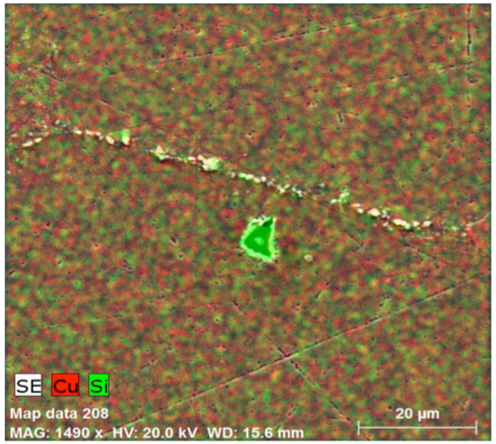
AFTER MACHINING

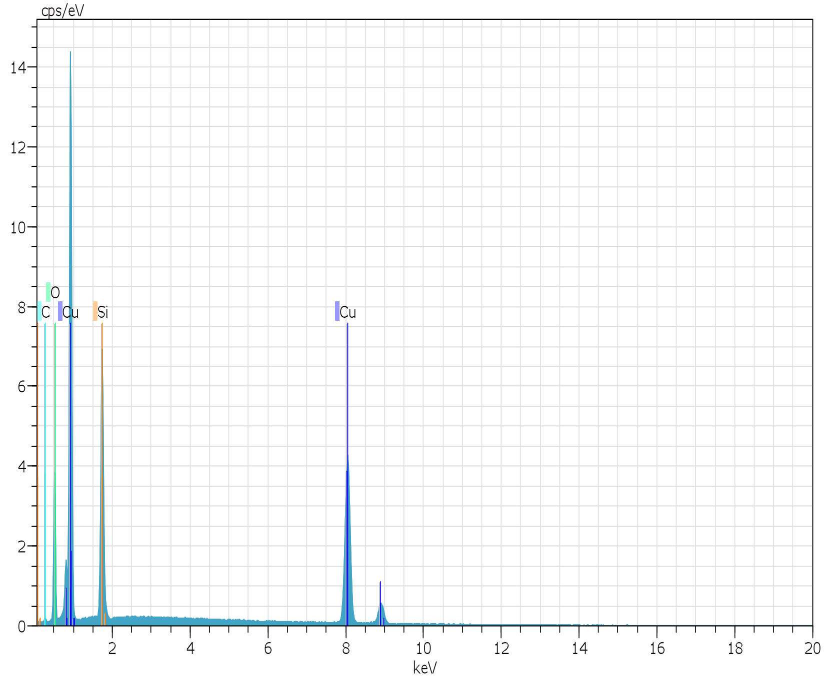




Chemical composition before machining



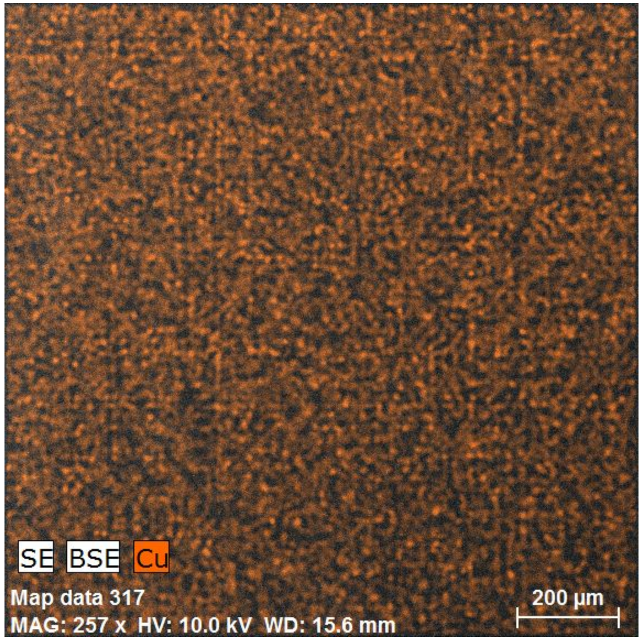


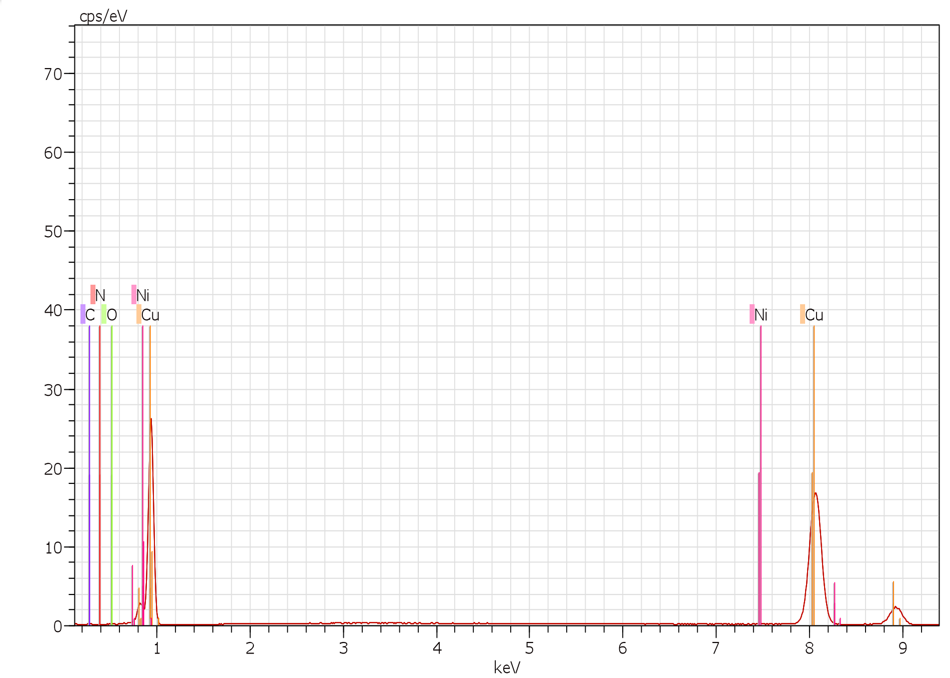


Spectrum: Acquisition 862 - particella.spx

El	AN	Series	unn. C [wt.%]	norm. C [wt.%]	Atom. C [at.%]	Error (1 Sigma) [wt.%]	K fact.	Z corr.	A corr.	F corr.
Cu	29	K-series	62.20	63.79	34.62	1.72	0.548	1.114	1.000	1.044
O	8	K-series	17.08	17.51	37.76	2.31	0.377	0.464	1.000	1.000
Si	14	K-series	15.46	15.86	19.47	0.69	0.131	1.203	1.000	1.004
C	6	K-series	2.77	2.84	8.15	0.76	0.077	0.369	1.000	1.000
		Total:	97.51	100.00	100.00					

Chemical composition after machining



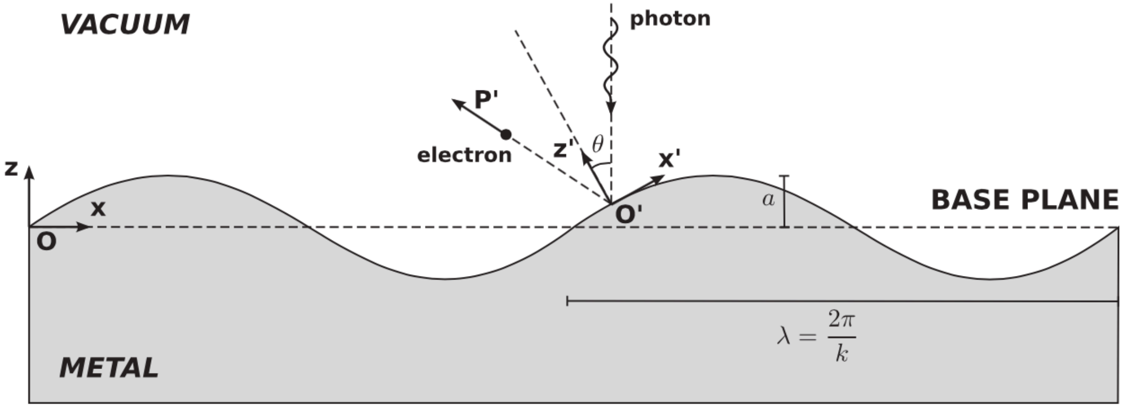


Spectrum: Acquisition 877

El	AN	Series	Net	unn. C [wt.%]	norm. C [wt.%]	Atom. C [at.%]	Error (1 Sigma) [wt.%]
Cu	29	L-series	289089	98.81	98.81	95.69	10.64
C	6	K-series	1280	0.47	0.47	2.39	0.12
Ni	28	L-series	1453	0.34	0.34	0.35	0.09
O	8	K-series	1150	0.22	0.22	0.86	0.07
N	7	K-series	466	0.16	0.16	0.71	0.07
			Total:	100.00	100.00	100.00	

Surface roughness induced emittance

- Surface roughness on cathode introduces a transverse electric field that increases the transverse momentum, causing emittance growth.

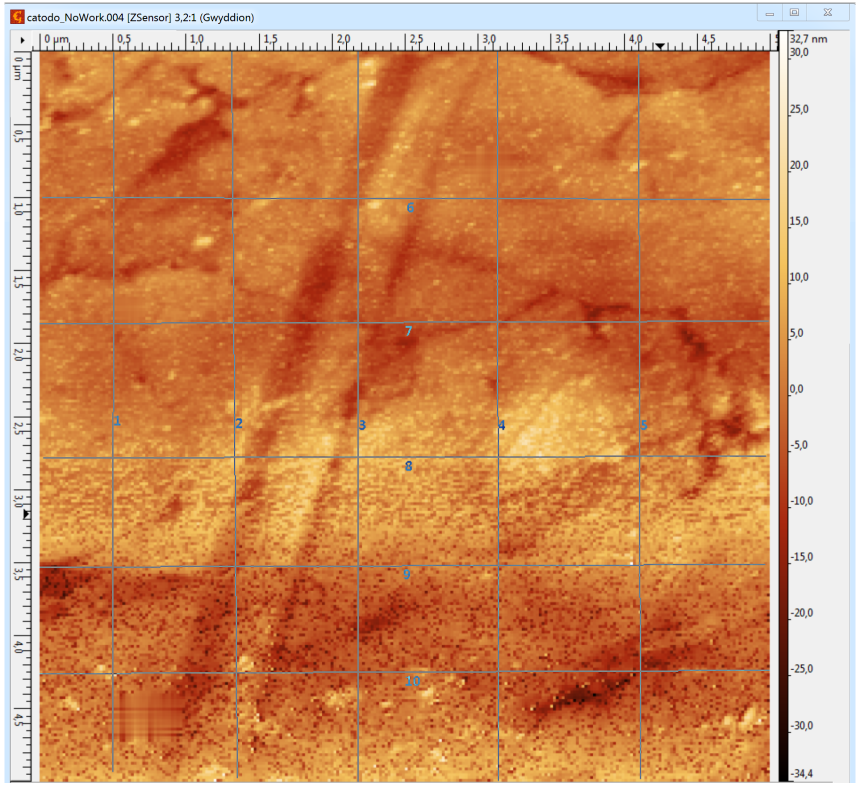


- z=a cos ((2π/λ)x), surface morphology function
- **a,** amplitude of the uneven surface
- **λ,** period of fluctuation

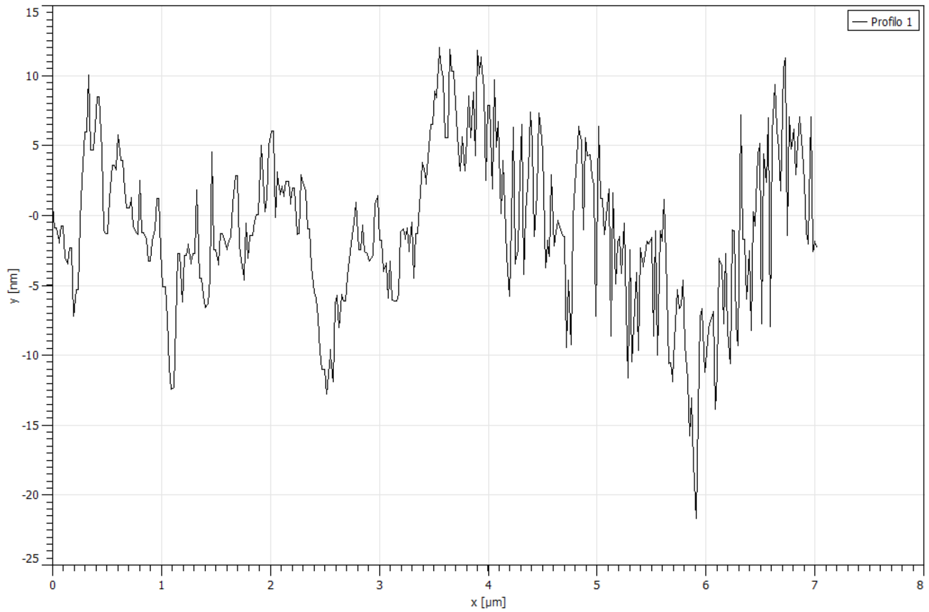
$$\varepsilon_{roughness} = \sigma_x \sqrt{\frac{e\pi^2 a^2 E_{rf} \sin\vartheta_{rf}}{2 m_0 c^2 \lambda}}$$

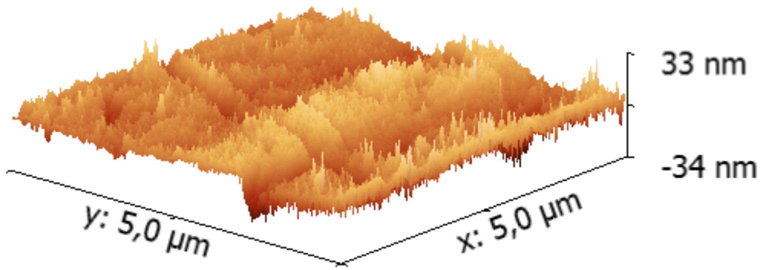
Z. Zhang and C. Tang, *Analytical study on emittance growth caused by roughness of a metallic photocathode*, PRST-AB 18, 053401 (2015)
D. Xiang et al., *First principle measurements of thermal emittance for copper and magnesium*, Proc. of PAC07, Albuquerque, New Mexico, USA

Activity at SPARC_LAB test facility: Cu photocathode surface analysis with AFM before machining



Profile of images





Statistical parameters:

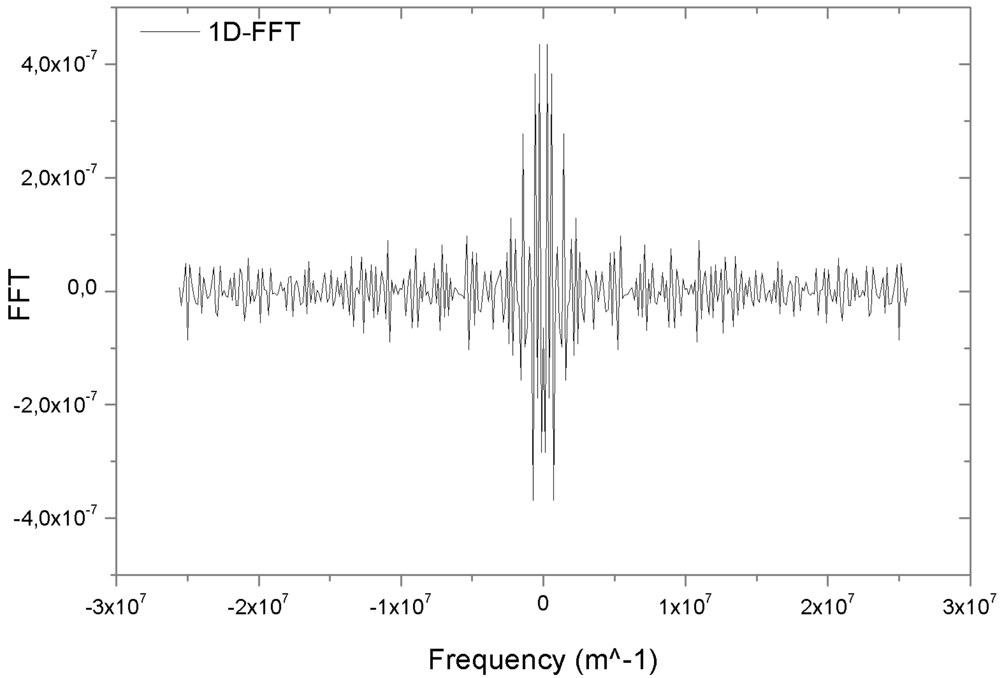
Min_value:	-34,4 nm
Max_value:	32,6 nm
Ra (Sa):	4,3 nm
Rms (Sq):	5,7 nm

J. Scifo

Fourier transform of AFM image

$$\boxed{Re\,\{F[l]\} = \frac{1}{N}\sum_{n=0}^{N-1} Re\,\{f[n]\}\cos 2\pi \frac{n}{N} l}$$

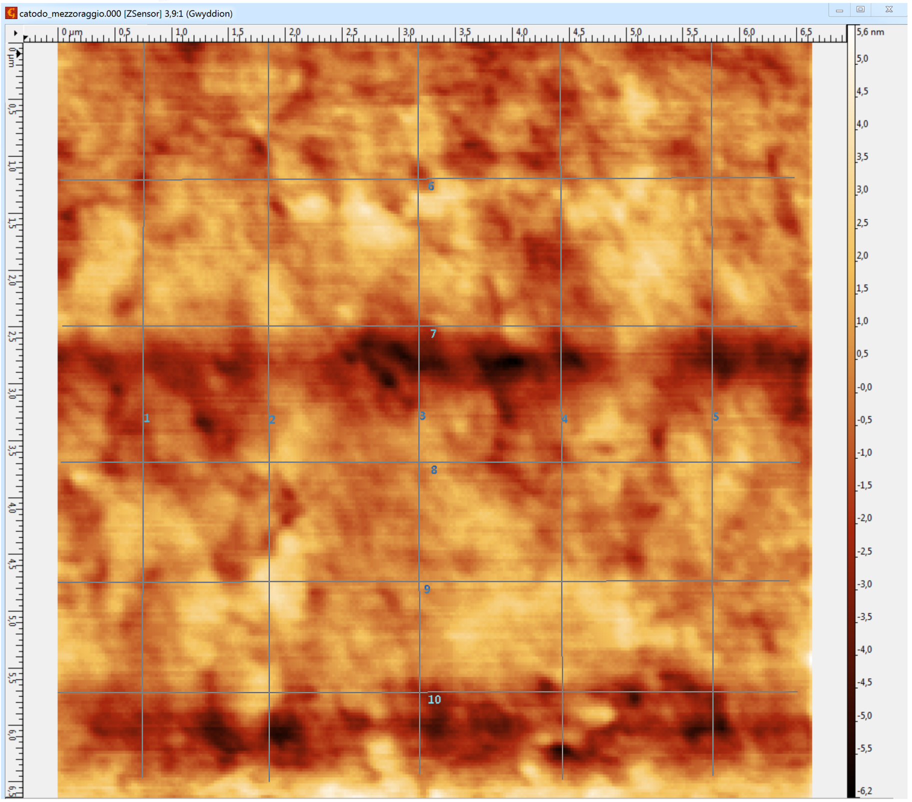
1D-DFT



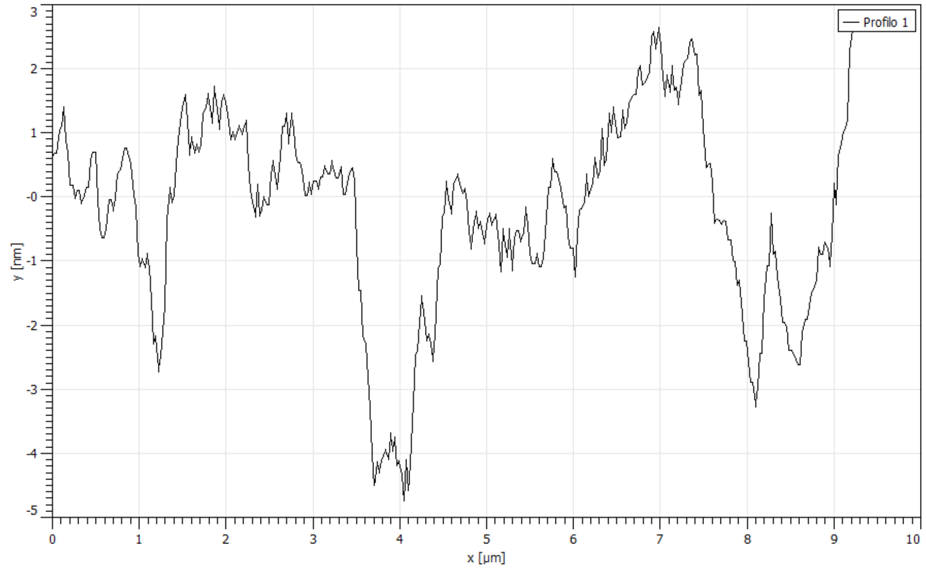
$$\left[\begin{aligned} a_n &= \mathrm{Re}\{f[n]\} \\ \lambda_n &= \frac{L_{cathode}}{n} \end{aligned}\right]$$

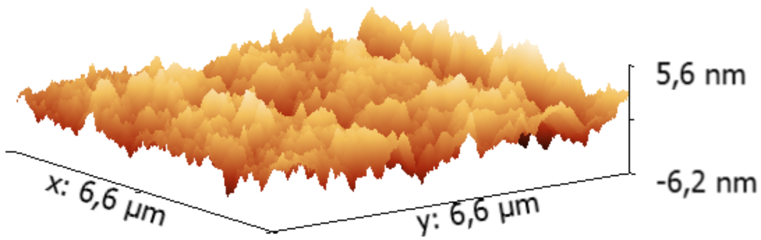
$$\sum_{n=0}^{N-1} \frac{a_n^2}{\lambda_n} = \underline{3.13e-11m}$$

Activity at SPARC_LAB test facility: Cu photocathode surface analysis with AFM after machining



Profile of images





Statistical parameters:

Min_value:	-6,16 nm
Max_value:	5,60 nm
Ra (Sa):	1,18 nm
Rms (Sq):	1,501nm

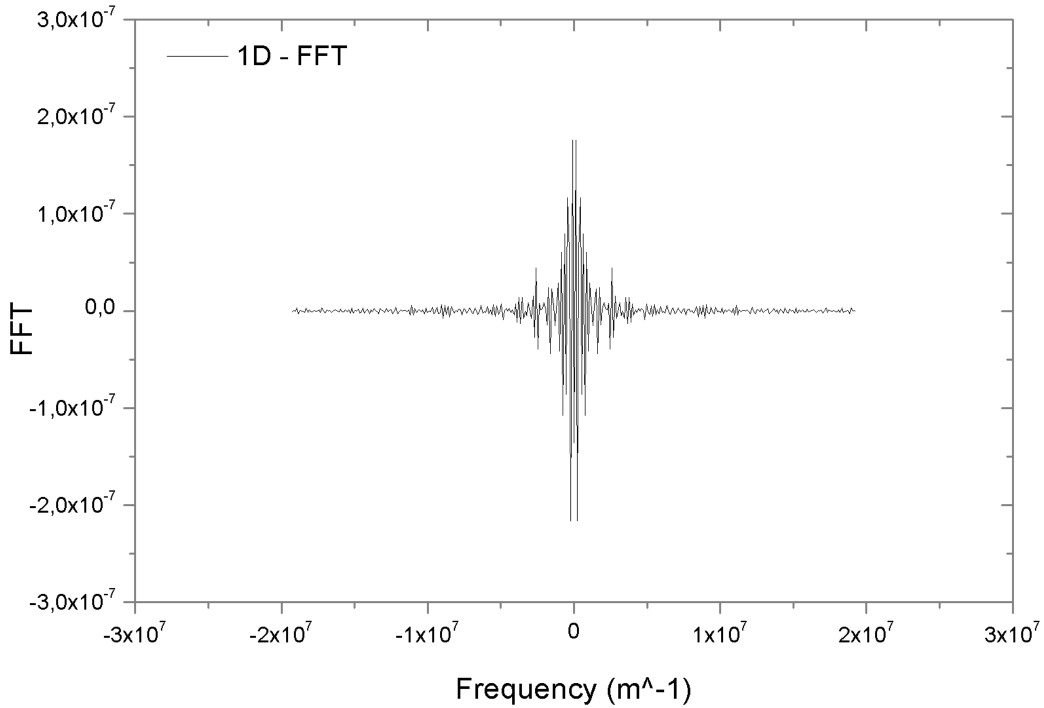
J. Scifo

Fourier transform of AFM image

$$\boxed{Re\,\{F[l]\} = \frac{1}{N}\sum_{n=0}^{N-1} Re\,\{f[n]\}\cos 2\pi \frac{n}{N} l}$$

1D-DFT

$$\left[\begin{array}{l} a_n = \mathrm{Re}\{f[n]\} \\ \lambda_n = \dfrac{L_{cathode}}{n} \end{array}\right]$$



$$\sum_{n=0}^{N-1} \frac{a_n^2}{\lambda_n} = \underline{4e-13m}$$

Surface roughness induced emittance and Fourier transform of AFM image

$$\varepsilon_{roughness}^2 = \sum_{n=0}^{N-1} \varepsilon^2(a_n, k_n) = \sigma_x^2 \frac{\pi^2 e E_{rf} \sin\theta_{rf}}{2mc^2} \sum_{n=0}^{N-1} \frac{a_n^2}{\lambda_n}$$

$$\begin{cases} E_{rf} = 91 MV/m \\ \vartheta_{rf} = 30° \\ \sigma_x = 0.19 mm \end{cases}$$

Before n-machining

$$\sum_{n=0}^{N-1} \frac{a_n^2}{\lambda_n} = 3.13e - 11m$$

$$\sqrt{\varepsilon_{roughness}^2} = 0.022 \mu m$$

After n-machining

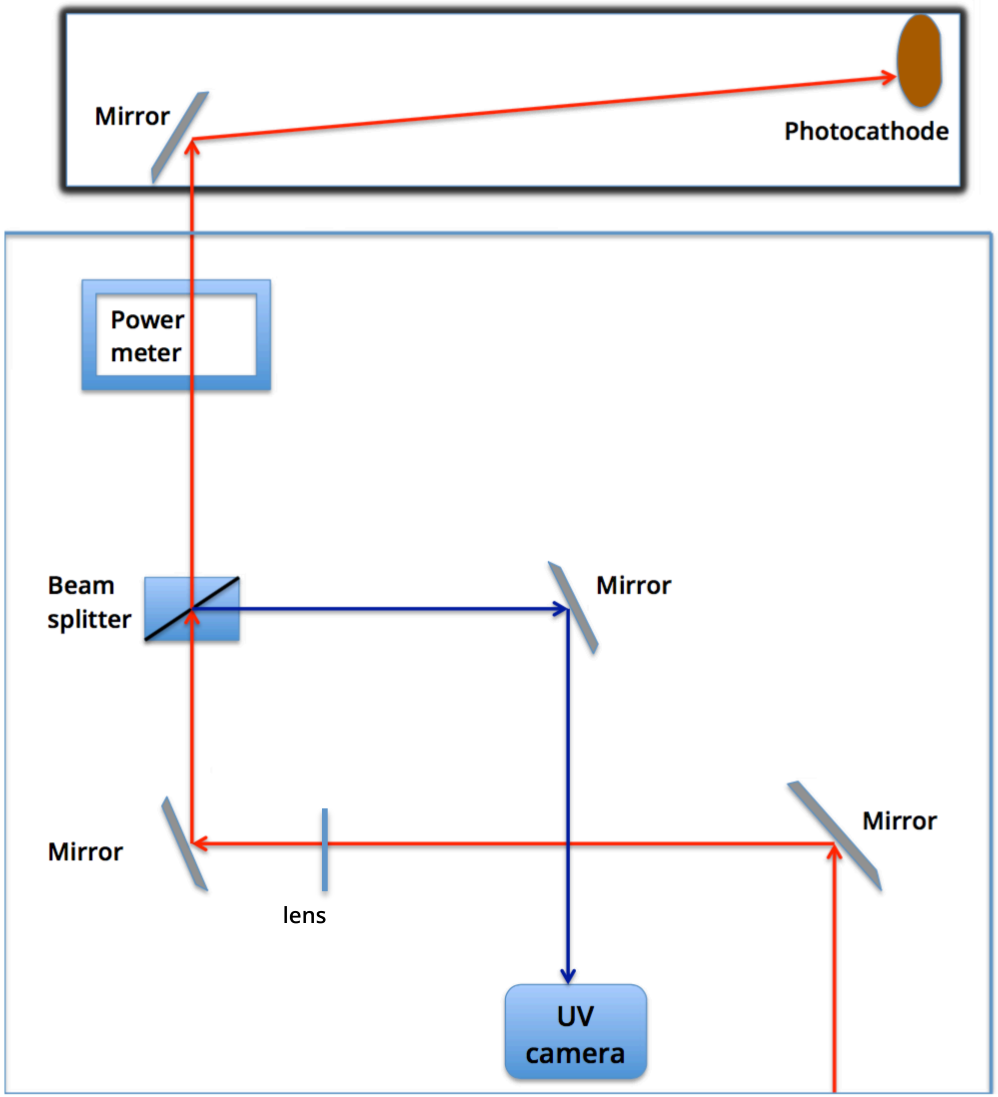
$$\sum_{n=0}^{N-1} \frac{a_n^2}{\lambda_n} = 4e - 13m$$

$$\sqrt{\varepsilon_{roughness}^2} = 0.0025 \mu m$$!!!

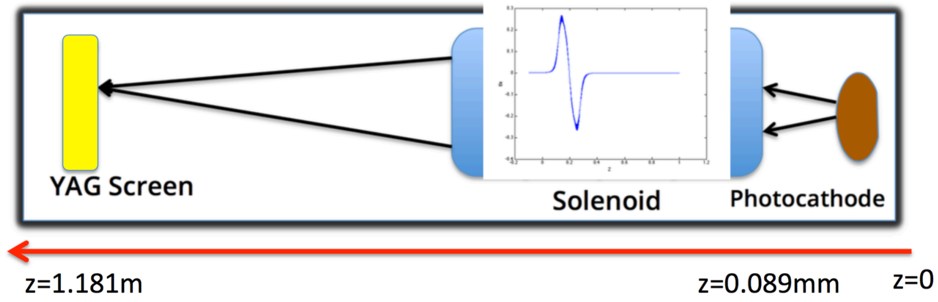
Private communication with David H. Dowell

Emittance measurements: experimental set up

- Photocathode laser



- Beam line



<u>Solenoid is in not-rotating configuration, that is no x/y coupling</u>

Emittance measurements at SPARC_LAB test facility: measurements method

Solenoid Scan Technique:

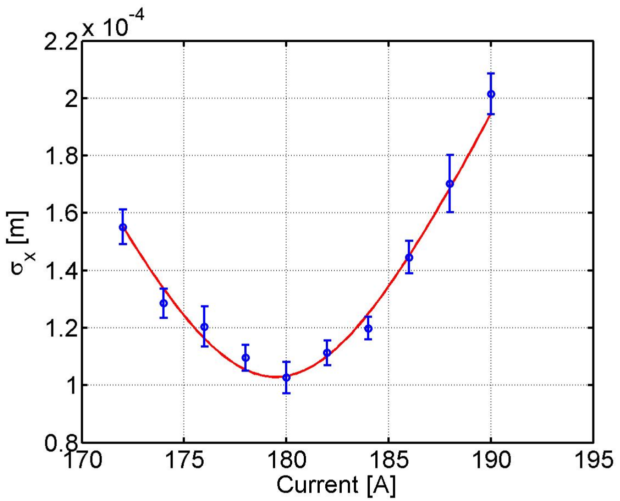
1. Calculation of beam size squared on YAG Screen for different solenoid field is given by:

$$\langle x_i \rangle^2 = R_{11}^{(i)^2} \langle x_0^2 \rangle + 2R_{11}^{(i)} R_{12}^{(i)} \langle x_0 x_0^{'} \rangle + R_{12}^{(i)^2} \langle x_0^{'2} \rangle$$

Where the coefficients R_{11} and R_{12} are the elements of beam line transfer matrix.

2. Total normalized emittance has been computed at the entrance of gun solenoid:

$$\varepsilon_{nx,rms} = \gamma\beta\sqrt{\langle x_0{}^2 \rangle \langle x_0{}^{'2} \rangle - \langle x_0 x_0^{'} \rangle^2}$$



At the entrance of gun solenoid:

$$\varepsilon_{nx} = 0.16 \pm 0.01 mmmrad$$

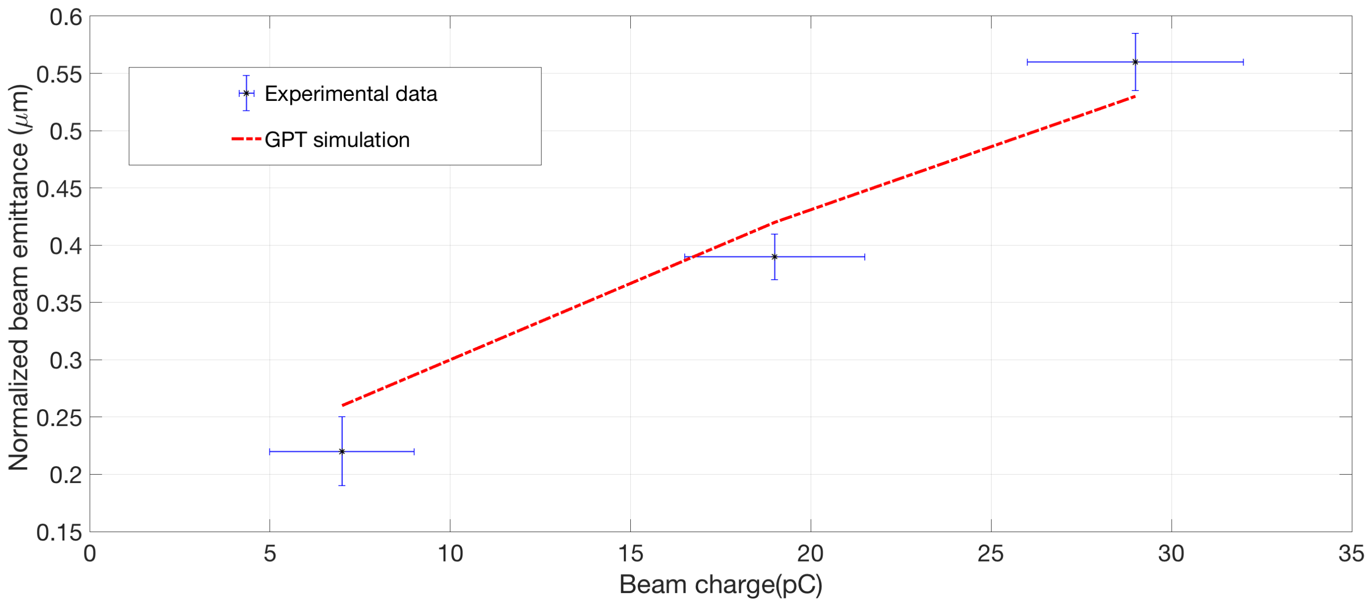
$$\beta x\_in = 0.38 \pm 0.04 m$$

$$\alpha x\_in = -6.8 \pm 0.8$$

Emittance measurements at SPARC_LAB test facility: scaling of emittance with e- beam charge

Parameters:

- E_{RF}= 102 MV/m
- Working RF phase≈24°
- Laser pulse length =4.7 ps - FWHM (Gaussian profile)
- E= 4.53±0.05MeV - Energy at the gun exit
- $\sigma_{x,yrms}$ (Laser spot)=0.24mm (Flat top profile)



Intrinsic emittance evaluation

From the beam emittance measurements as function of the beam charge, in which the applied RF field was E_{RF} = 102 MV/m, the intrinsic emittance value is given from:

$$\varepsilon_{TOT} \approx \sqrt{\varepsilon^2_{chromatic} + \varepsilon^2_{RF} + \varepsilon^2_{roughness} + \varepsilon^2_{SC} + \varepsilon^2_{\text{int}} + \varepsilon^2_{Busch}}$$

$$\varepsilon_{chromatic} = \sigma^2_{x,sol}\sigma_p \left| \frac{d}{dp}\left(\frac{1}{f_{sol}}\right) \right|$$

$$\varepsilon_{first} = \frac{k_{RF}\alpha sin(\phi_0)}{\sqrt{2}}\sigma^2_x\sigma_z,$$

$$\varepsilon_{second} = \frac{k^3_{RF}\alpha cos(\phi_0)}{\sqrt{2}}\sigma^2_x\sigma^2_z$$

$$\varepsilon_{RF} = \sqrt{\varepsilon^2_{first} + \varepsilon^2_{second}}$$

$$\varepsilon_{SC} = \frac{c^2}{8\alpha f sin\phi_0}\frac{I}{I_A}\frac{\sigma_z}{\mu(A)}$$

$$\varepsilon_{Busch} \sim \frac{eB_0}{2mc}\sigma^2_x \sim 0.3B[mT]\sigma_x[mm]^2$$

Contributions to the beam emittance	Value (μm)
$\varepsilon_{roughness}$	0.022
ε_{RF}	0.0054
ε_{SC}	0.1025
$\varepsilon_{chromatic}$	0.0053
ε_{Busch}	0.061

Experimental values

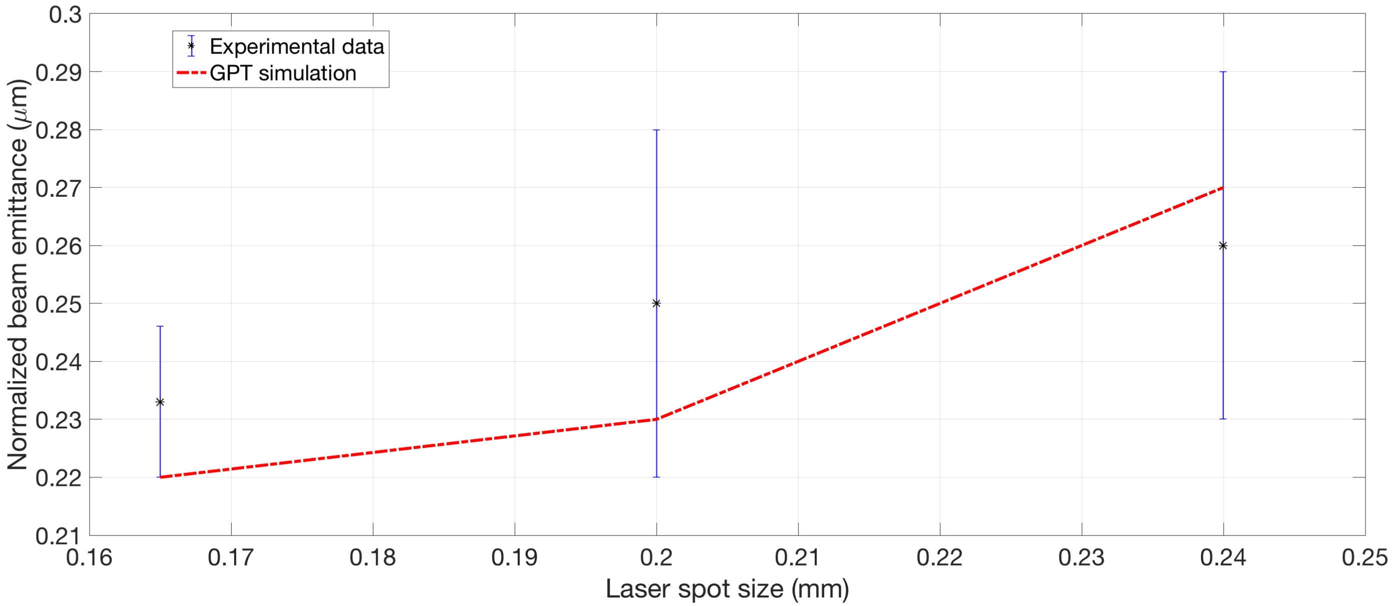
- ε_{TOT} = 0.22±0.06μm
- ε_{int} = 0.20±0.07μm
- **$\varepsilon_{int/mm}$ = 0.80±0.07μm/mm**

$\varepsilon_{int/mm\ (theoretical)}$ = 0.7μm/mm

Emittance measurements at SPARC_LAB test facility: scaling of emittance with laser spot size

Parameters:

- E_{RF}= 91MV/m
- Working RF phase=30°
- Laser pulse length =4.7 ps - FWHM (Gaussian profile)
- E= 4.10±0.05MeV - Energy at the gun exit
- Beam charge≈10 pC



Intrinsic emittance evaluation

From the beam emittance measurements as function of the beam charge, in which the applied RF field was ERF = 91 MV/m, the intrinsic emittance value is given from:

$$\varepsilon_{TOT} \approx \sqrt{\varepsilon^2_{chromatic} + \varepsilon^2_{RF} + \varepsilon^2_{roughness} + \varepsilon^2_{SC} + \varepsilon^2_{\text{int}} + \varepsilon^2_{Busch}}$$

Contributions to the beam emittance	Value (μm)
$\varepsilon_{roughness}$	0.0025
ε_{RF}	0.0022
ε_{SC}	0.090
$\varepsilon_{chromatic}$	0.030
ε_{Busch}	0.061

Experimental values

- ε_{TOT} = 0.26±0.03μm
- ε_{int} = 0.23±0.03μm
- **$\varepsilon_{int/mm}$ = 0.90±0.03μm/mm**

$\varepsilon_{int/mm\ (theoretical)}$ = 0.6μm/mm

Emittance measurements before and after n-machining

***Parameters*:**
- Epeak= 91MV/m
- Working RF phase=30°
- $\sigma_{x,yrms}$ (Laser spot)=0.19mm (Flat top profile)
- E= 4.10±0.05MeV - Energy at the gun exit
- Laser pulse length =4.7ps - FWHM (Gaussian profile)
- Bunch charge≅ 6pC

	Before n-machining		***After n-machining***	
E_acc (MV/m)	**ε_x(mm mrad)**	**ε_y(mm mrad)**	**ε_x(mm mrad)**	**ε_y(mm mrad)**
91	0.37±0.07	0.43±0.05	0.21±0.02	0.22±0.03

J. Scifo, et al., Nano-machining, surface analysis and emittance measurements of a copper photocathode at SPARC_LAB, Nuclear Inst. and Methods in Physics Research, A (2018),https://doi.org/10.1016/j.nima.2018.01.041

Intrinsic emittance evaluation

From the beam emittance measurements as function of the beam charge, in which the applied RF field was ERF = 91 MV/m, the intrinsic emittance value is given from:

$$\varepsilon_{TOT} \approx \sqrt{\varepsilon^2_{chromatic} + \varepsilon^2_{RF} + \varepsilon^2_{roughness} + \varepsilon^2_{SC} + \varepsilon^2_{\text{int}} + \varepsilon^2_{Busch}}$$

Before n-machining

Contributions to the beam emittance	Value (μm)
$\varepsilon_{roughness}$	0.022
ε_{RF}	0.0029
ε_{SC}	0.063
$\varepsilon_{chromatic}$	0.030
ε_{Busch}	0.061

Experimental values

- ε_{TOT} = 0.37±0.07μm
- ε_{int} = 0.357±0.05μm

After n-machining

Contributions to the beam emittance	Value (μm)
$\varepsilon_{roughness}$	0.0025
ε_{RF}	0.0029
ε_{SC}	0.063
$\varepsilon_{chromatic}$	0.030
ε_{Busch}	0.061

Experimental values

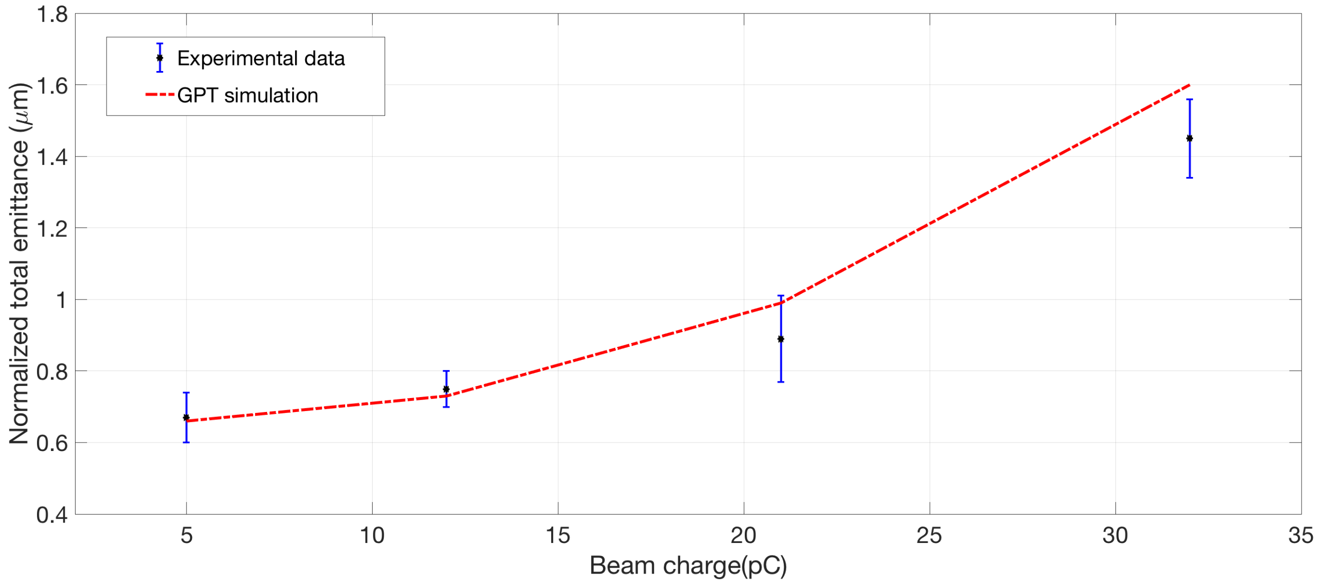
- ε_{TOT} = 0.21±0.02μm
- **ε_{int} = 0.20±0.03μm**

$\varepsilon_{TOT\ (GPT)}$ = 0.196μm

Yttrium preliminary results at Cavity Test Facility (CTF) at Elettra-Sicrotrone Trieste: emittance measurements

***Parameters*:**

- **Epeak= 107MV/m**
- **Working RF phase=30°**
- **Laser pulse length =5.3ps - FWHM (Gaussian profile)**
- **E= 4.66MeV - Energy at the gun exit**
- **$\sigma_{x,yrms}$ (Laser spot)≅0.11mm (Gaussian profile)**



J. Scifo, et al., Nano-machining, surface analysis and emittance measurements of a copper photocathode at SPARC_LAB, Nuclear Inst. and Methods in Physics Research, A (2018),https://doi.org/10.1016/j.nima.2018.01.041

Intrinsic emittance evaluation

From the beam emittance measurements as function of the beam charge, in which the applied RF field was E_{RF} = 107 MV/m, the intrinsic emittance value is given from:

$$\varepsilon_{TOT} \approx \sqrt{\varepsilon^2_{chromatic} + \varepsilon^2_{RF} + \varepsilon^2_{roughness} + \varepsilon^2_{SC} + \varepsilon^2_{\text{int}} + \varepsilon^2_{Busch}}$$

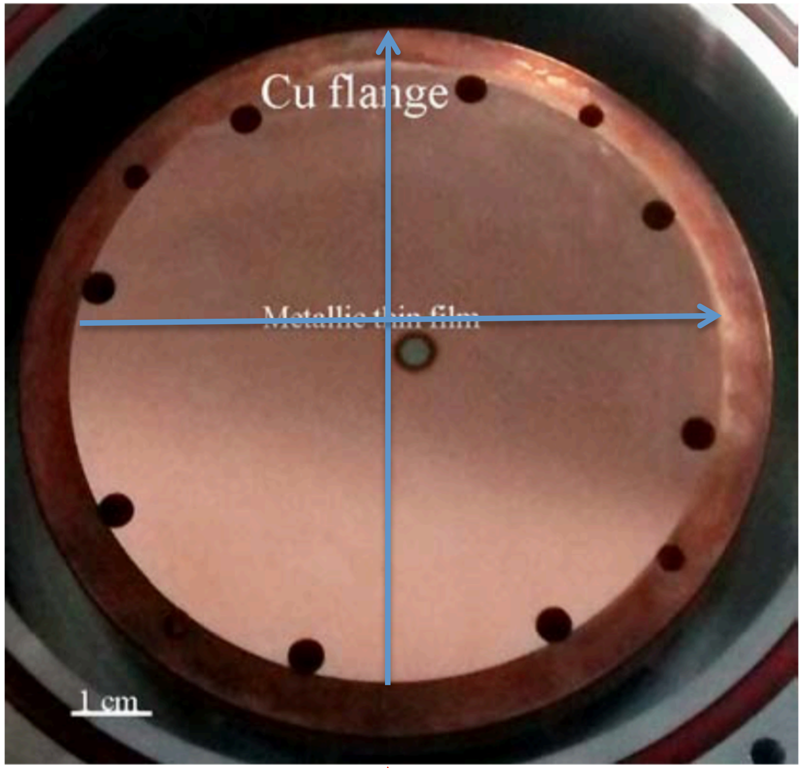
Experimental values

- ε_{TOT} = 0.66±0.07μm
- ε_{int} = 0.64±0.13μm
- **$\varepsilon_{int/mm}$ = 5±1μm/mm** ***???***

Contributions to the beam emittance	Value (μm)
ε_{RF}	0.0014
ε_{SC}	0.14
$\varepsilon_{chromatic}$	0.050
ε_{Busch}	0.003

$\varepsilon_{int/mm\ (theoretical)}$ = 1.57μm/mm

Intrinsic emittance evaluation



- X_{offset} = 0.7mm
- Y_{offset} =- 0.5mm

Experimental values

- ε_{TOT} = 0.66±0.07μm
- ε_{int} = 0.64±0.13μm
- **$\varepsilon_{int/mm}$ = 5±1μm/mm** ***???***

$\varepsilon_{int/mm\ (theoretical)}$ = 1.57μm/mm

From GPT simulation:

- ε_{int} = 0.178μm
- **$\varepsilon_{int/mm}$ = 1.6μm/mm ($\sigma_{x,yrms}$≅0.11mm)**

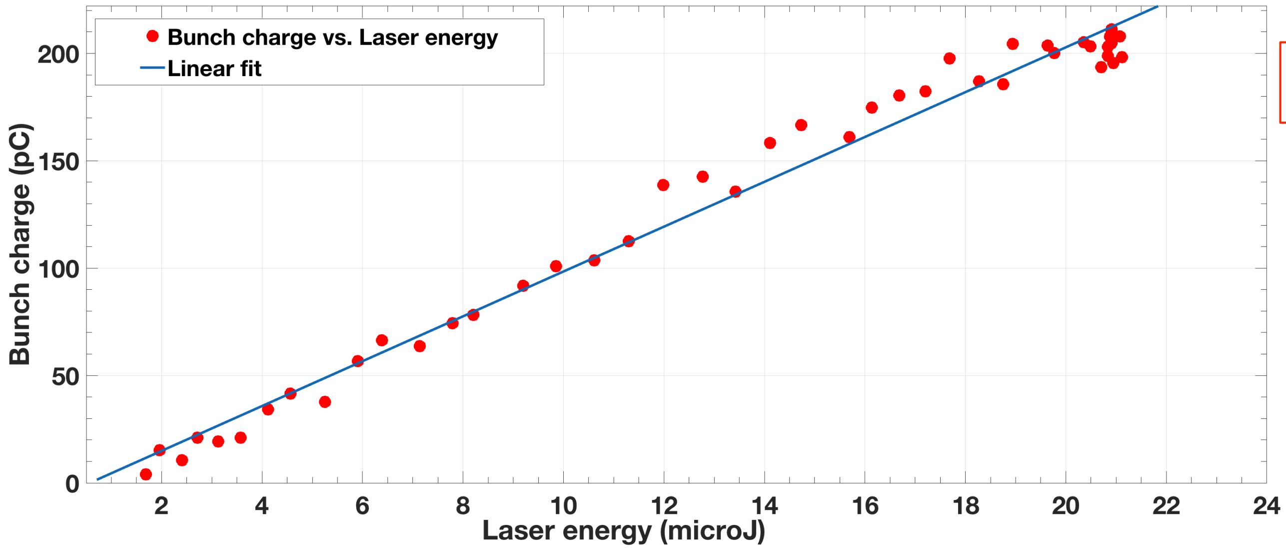
N-machined Cu photocathode QE measurements at Cavity Test Facility (CTF) at Elettra-Sicrotrone Trieste

***Parameters*:**

- Epeak≈ 62MV/m
- Working RF phase=30°
- λlaser= 262nm
- Laser pulse length =4.2ps - FWHM (Gaussian profile)
- E= 2.63MeV - Energy at the gun exit
- σ_{xrms} (Laser spot)≅0.182mm
- σ_{yrms} (Laser spot)≅0.172mm
- Gun solenoid configuration: ++--
- Solenoid current value= 87 A

Experimental values

QE=4.9e-05



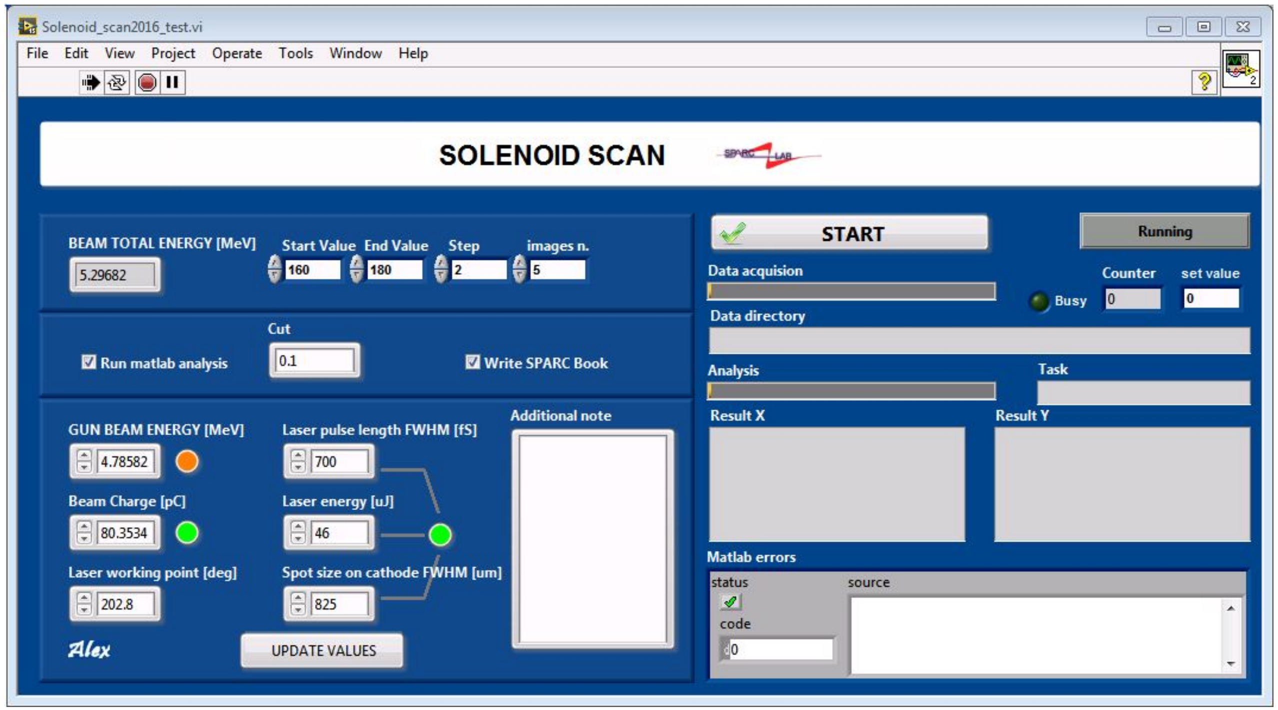
$QE_{(theoretical)}$ = 4e-05

Conclusions

- For our applications the dry machining is a good procedure because we don't have residual of diamond paste or oil

- We obtain an excellent roughness (≤ 2nm) typical of monocrystalline copper cathode

- Emittance measurements at the gun solenoid entry with the solenoid scan technique



Conclusions

- With the n-machining we improved of a factor 2 the total beam emittance

- Preliminary measurements of total beam emittance for the Y-film on Cu photocathode

- Collaboration with other facilities in order to create a network for the R&D activity on photocathodes

Future work

◆ Systematic studies (power, beam charge, laser parameters,..).

◆ Full characterization of Y-film on Cu photocathodes at Cavity Test Facility (CTF) at Elettra-Sicrotrone Trieste.

◆The effects of the discharge to ionize the gas inside the capillary on photocathode.

Finally it's over

Thank you for your attention