Dynamics of Electron Beam and Dark Current in Photocathode RF Guns

Study of the emission mechanisms and the dynamics with experiments and numerical calculations

4. November 2005

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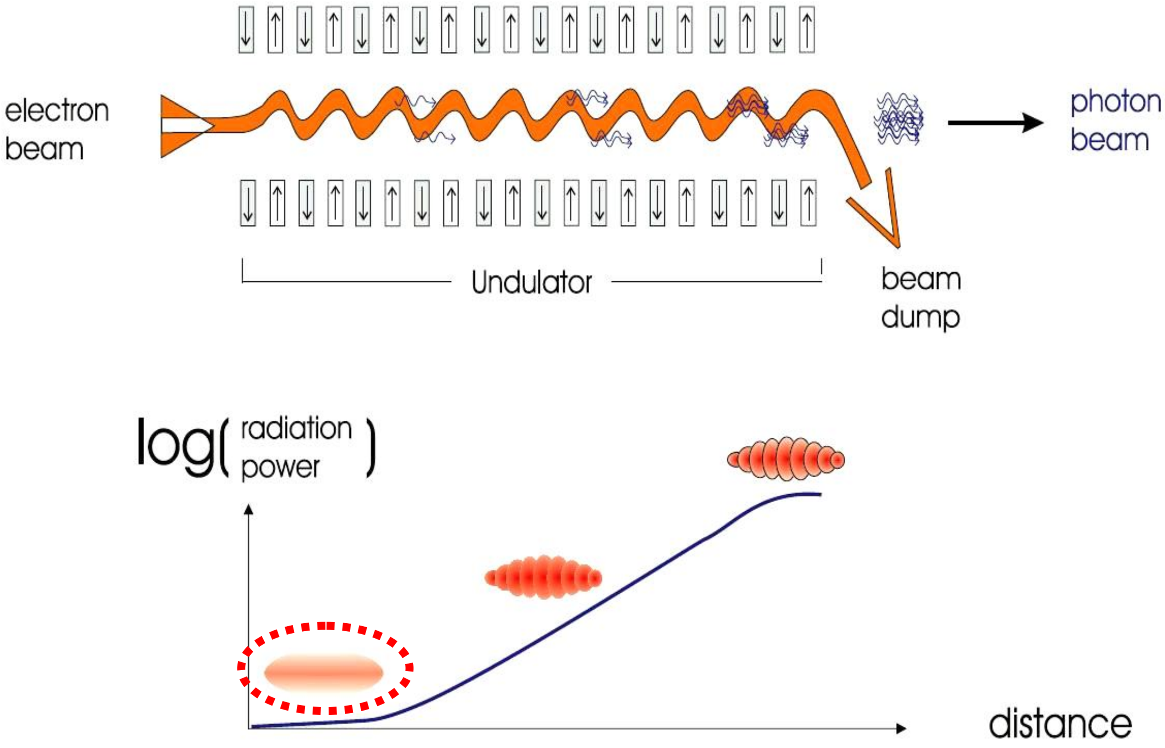
Contents

- Introduction: X-ray FEL, RF gun, photocathode
- Photoemission (electron emission by the drive-laser)
  - Thermal emittance analysis dependence on the rf gradient
- Field emission (electron emission by strong E-field)
  - Dark current source characterization and estimation for the European XFEL gun (60 MV/m)
- Secondary emission (electron emission by impacting of primary electrons)
  - Beam dynamics including secondary emission
  - Multipacting (multiple electron impacting)

X-ray FEL

External signal or spontaneous radiation interacts with the electron beam resonantly in undulator



Free Electron Laser in the Self Amplified Spontaneous Emission (SASE) mode

(From TESLA Technical Design Report Part I)

X-ray FEL

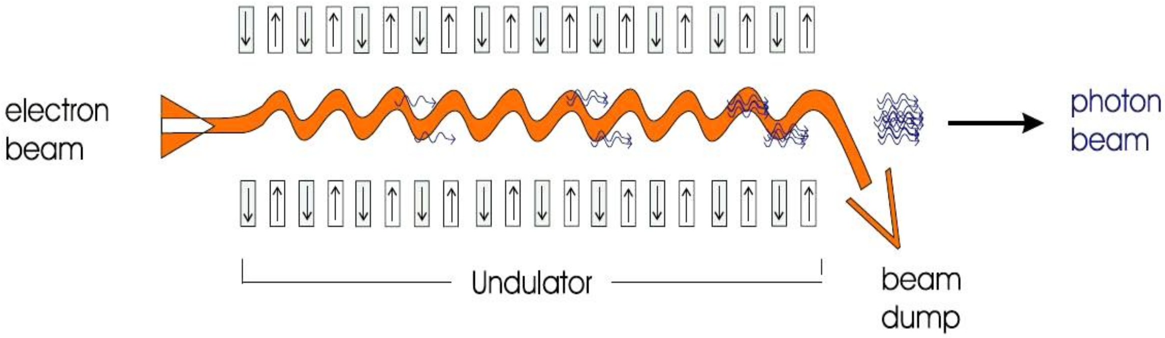
External signal or spontaneous radiation interacts with the electron beam resonantly in undulator

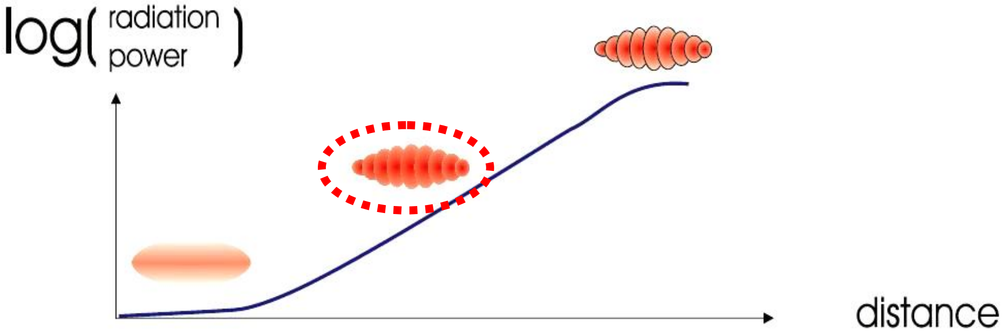
Energy modulation

Density modulation (micro-bunching)

Coherent radiation

⇨ **Exponential growth**





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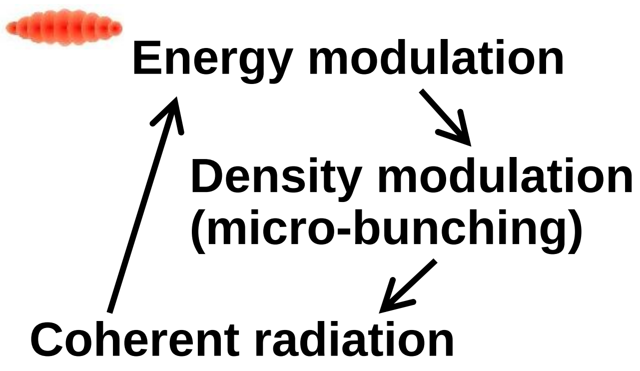


Energy modulation

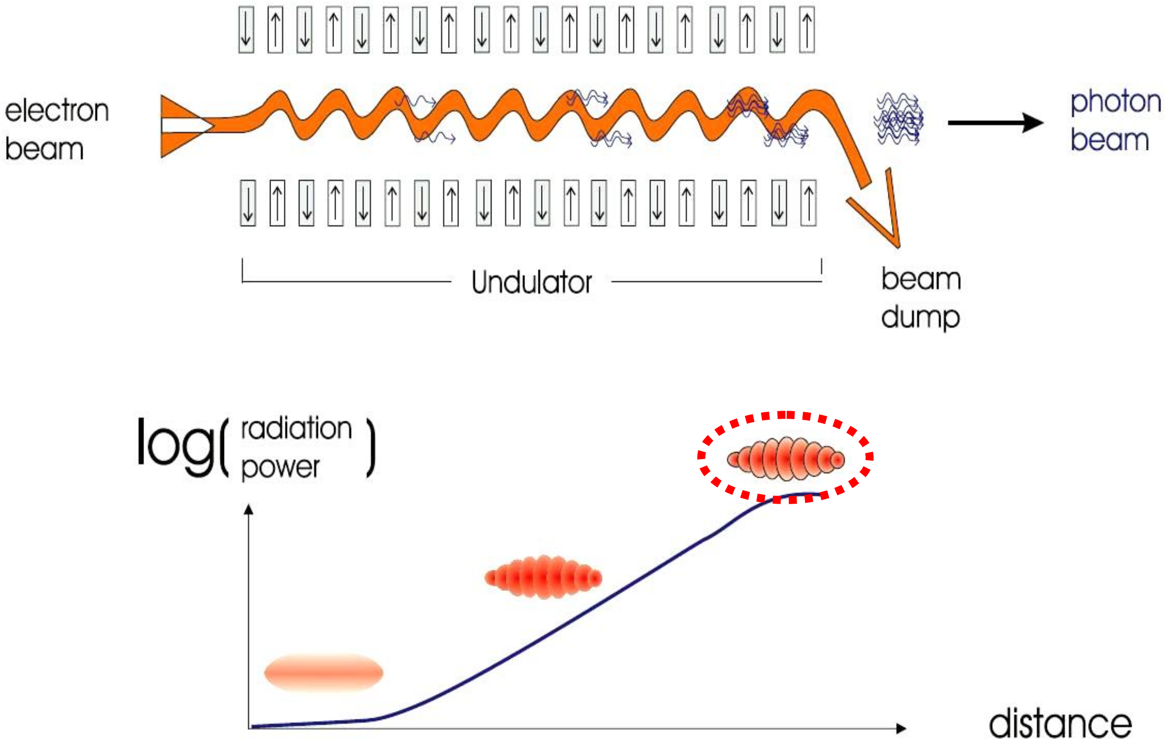
Density modulation (micro-bunching)

Coherent radiation

⇨ **Exponential growth**

At sufficiently high power, electrons are fully micro-bunched and trapped in the ponderomotive field

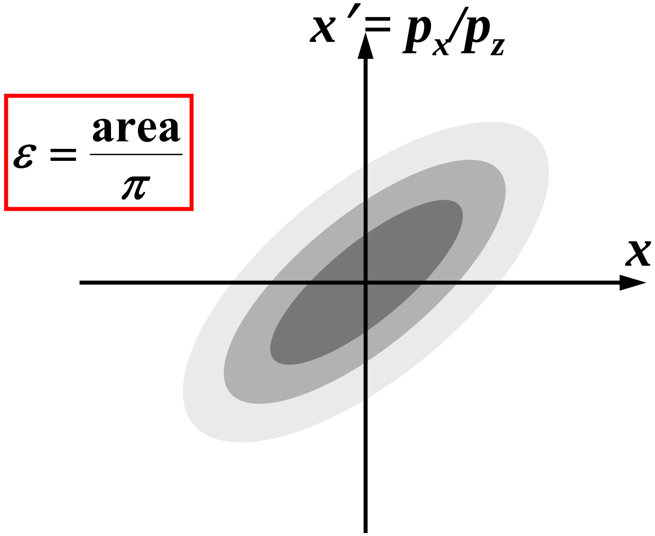
→ **saturation**



Free Electron Laser in the Self Amplified Spontaneous Emission (SASE) mode
(From TESLA Technical Design Report Part I)

Achievable shortest wavelength of the radiation is also limited by the transverse emittance.

Emittance

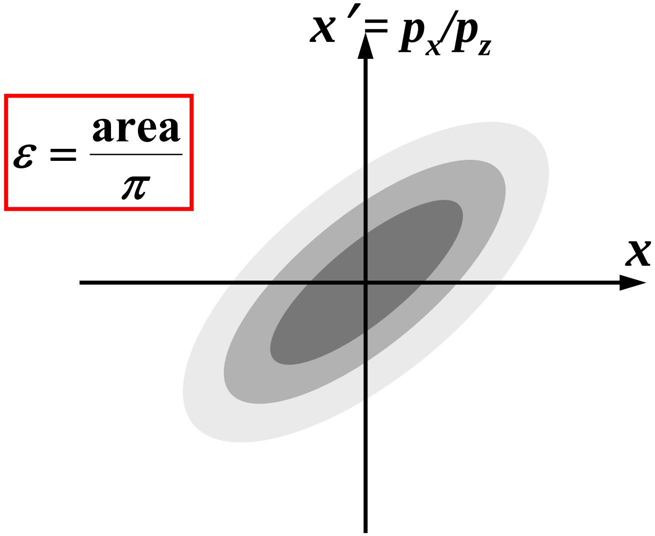


$$\varepsilon = \frac{\text{area}}{\pi}$$

Two-dimensional elliptical phase space area occupied by particle beam

According to Liouville’s theorem, the beam emittance is invariant of the particle motion
→ Good indicator of the beam quality

Emittance



$$\boxed{\varepsilon = \frac{\text{area}}{\pi}}$$

Two-dimensional elliptical phase space area occupied by particle beam

According to Liouville's theorem, the beam emittance is invariant of the particle motion
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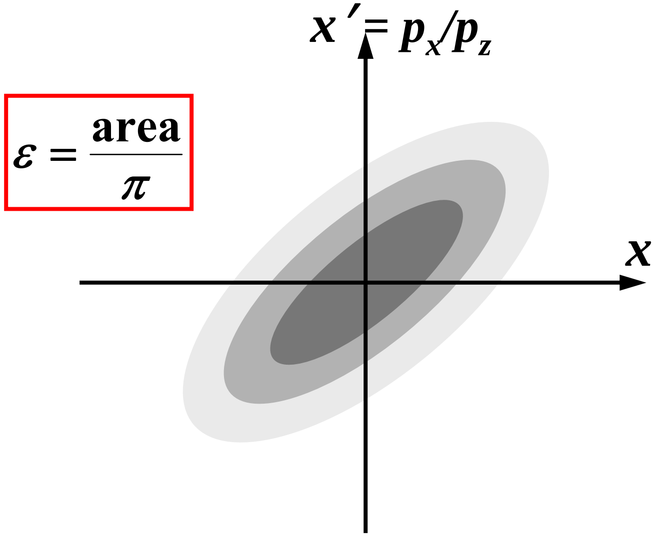
In linear accelerator (linac), the phase space area is not elliptical. Therefore, the rms emittance is useful to define the beam emittance

$$\varepsilon_{\text{rms}} = \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2}$$

Emittance



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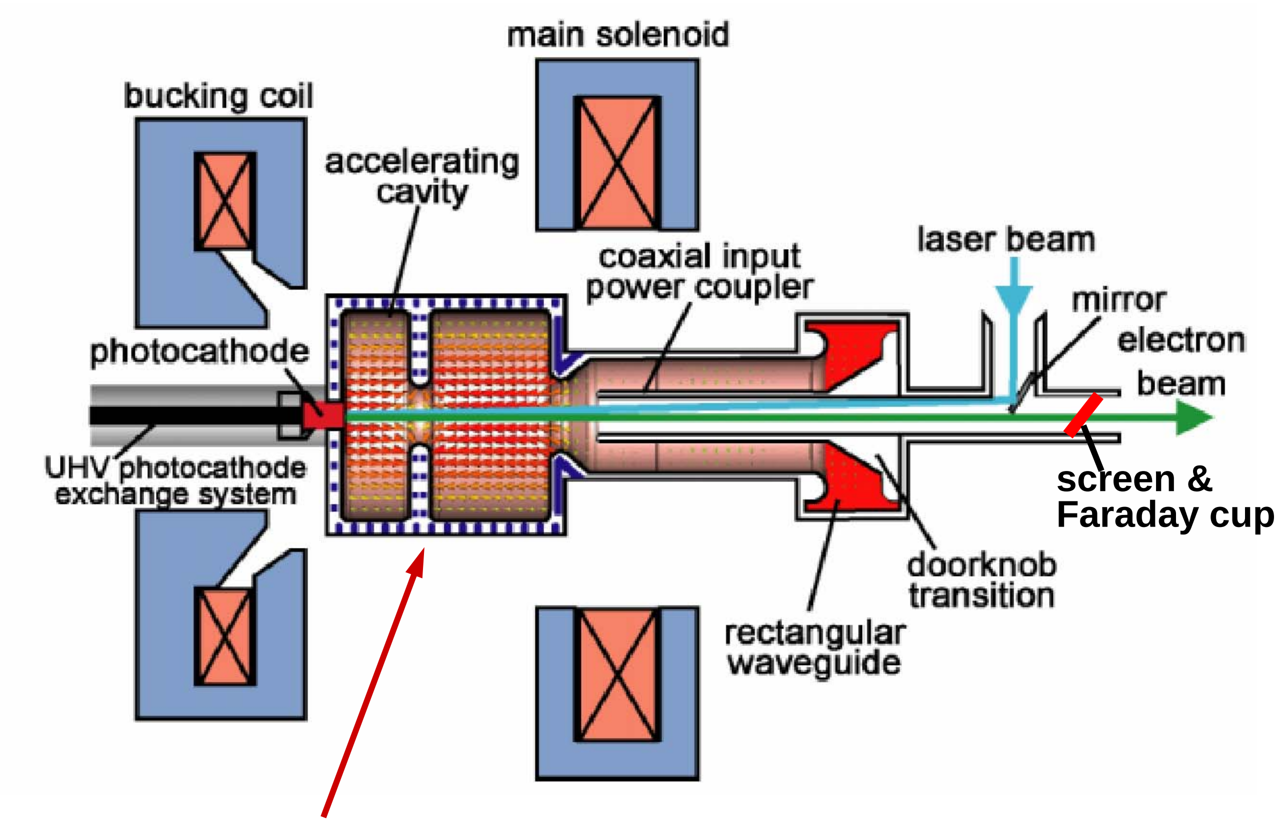
$$\varepsilon_{\text{rms}} = \sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2}$$

In linac, the beam is accelerated through the accelerator.
So, the transverse divergence is scaled with the longitudinal momentum.
In this case, the normalized rms emittance is invariant.

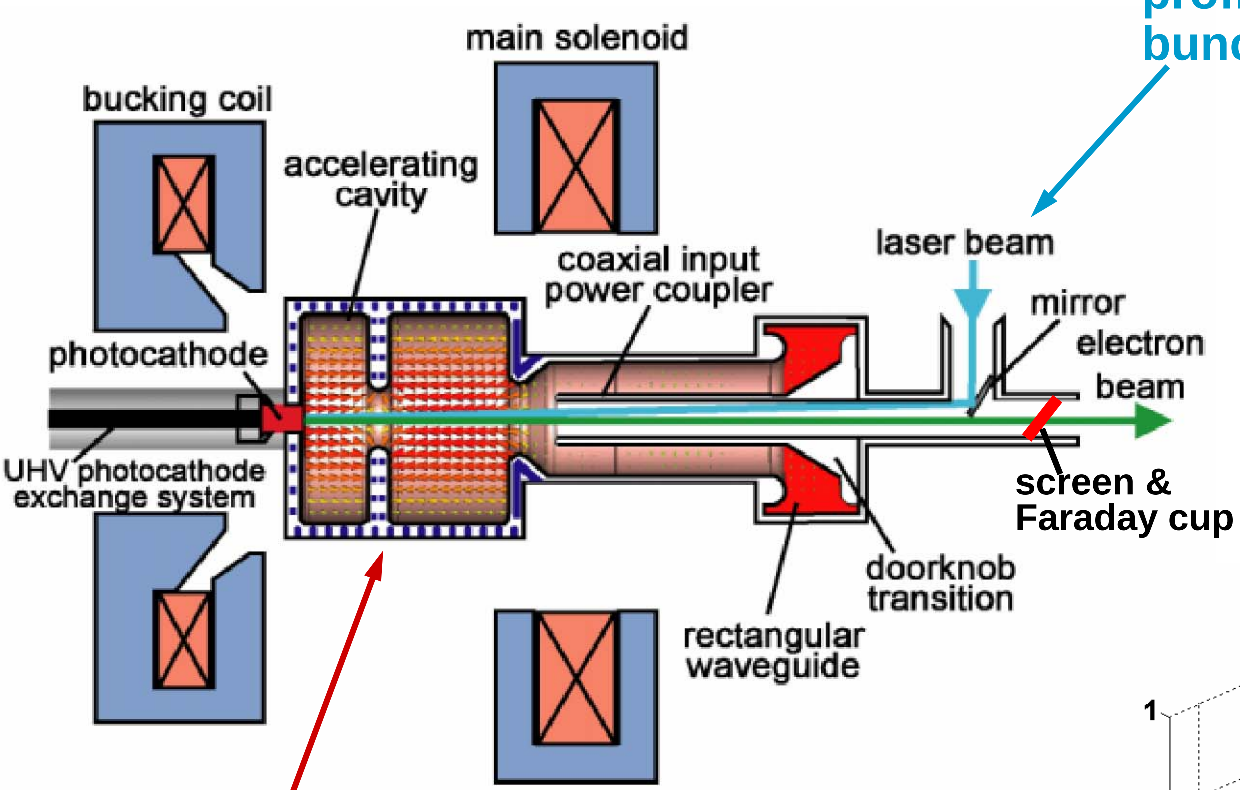
$$\varepsilon_{\text{rms}} = \sqrt{\langle x^2\rangle\langle p_x{}^2\rangle - \langle xp_x\rangle^2}$$

Photocathode RF gun

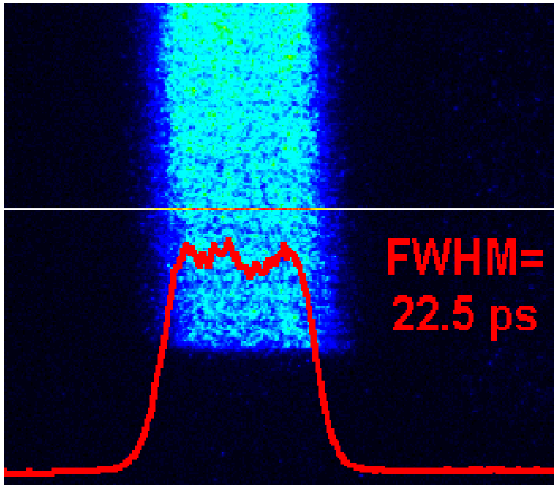


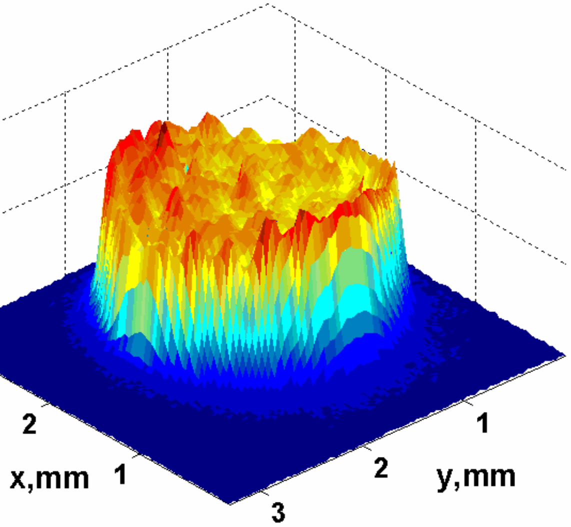
High RF field can accelerate the emitted electrons with keeping the collective effect to be small

Photocathode RF gun



With the drive-laser, the initial profile of the emitted electron bunch can be optimized

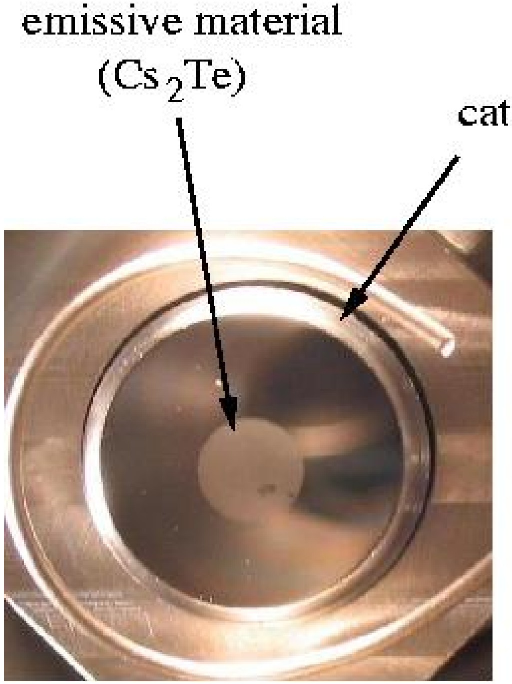




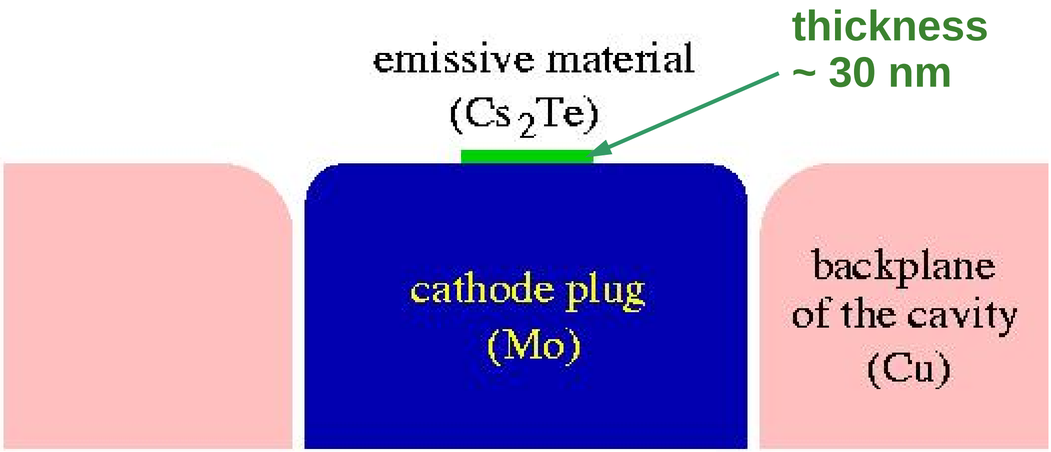
High RF field can accelerate the emitted electrons with keeping the collective effect to be small

Cs_2Te Photocathode

The figure of merit for the photocathode characterization:
operative lifetime, quantum efficiency, response time,
achievable current density, uniformity of the emissive layer
→ At present, Cs_2Te is the best solution for the XFEL gun



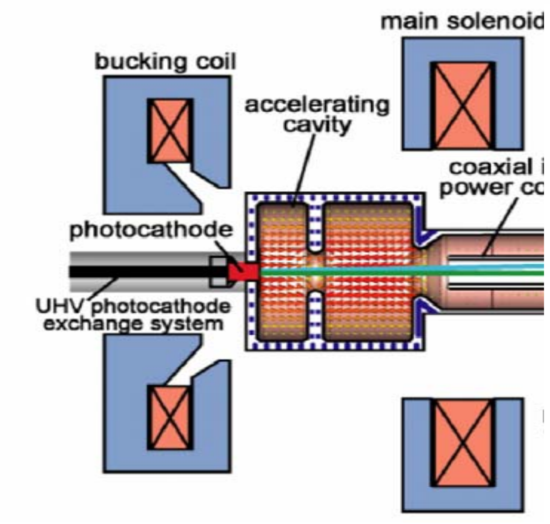
front view
in the cathode chamber

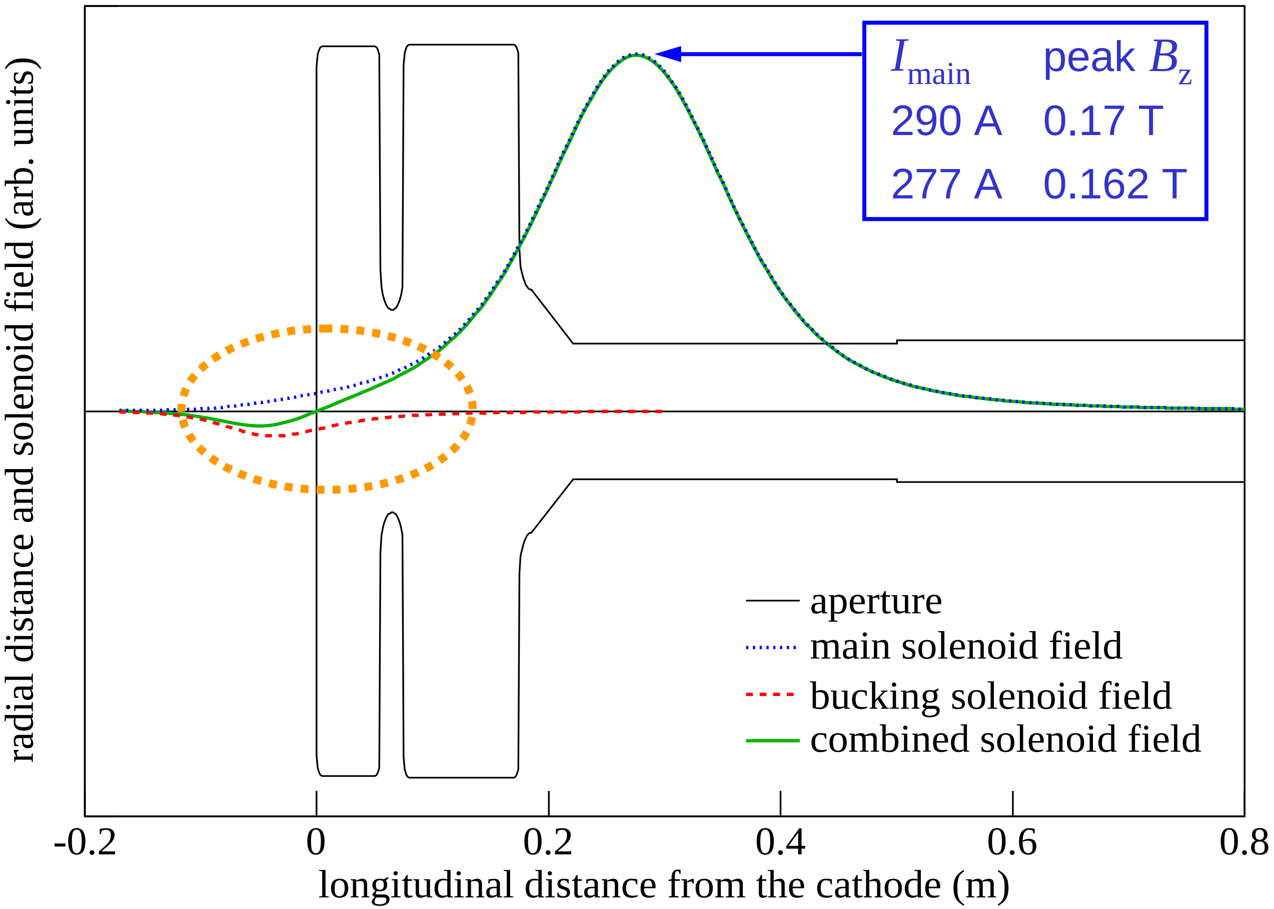


side view
in the gun cavity

Solenoids

Preservation of the emittance against the space charge force





Emittance growth due to the magnetic field at the cathode

$$\varepsilon_{n,\mathrm{rms}} = \frac{eBr_{\mathrm{rms}}^{2}}{2m_{0}c}$$

Photoinjector Test Facility at Zeuthen (PITZ)

Goal: development of electron sources required for the VUV-FEL and the European XFEL.

Measurements in this presentation have been made at PITZ.

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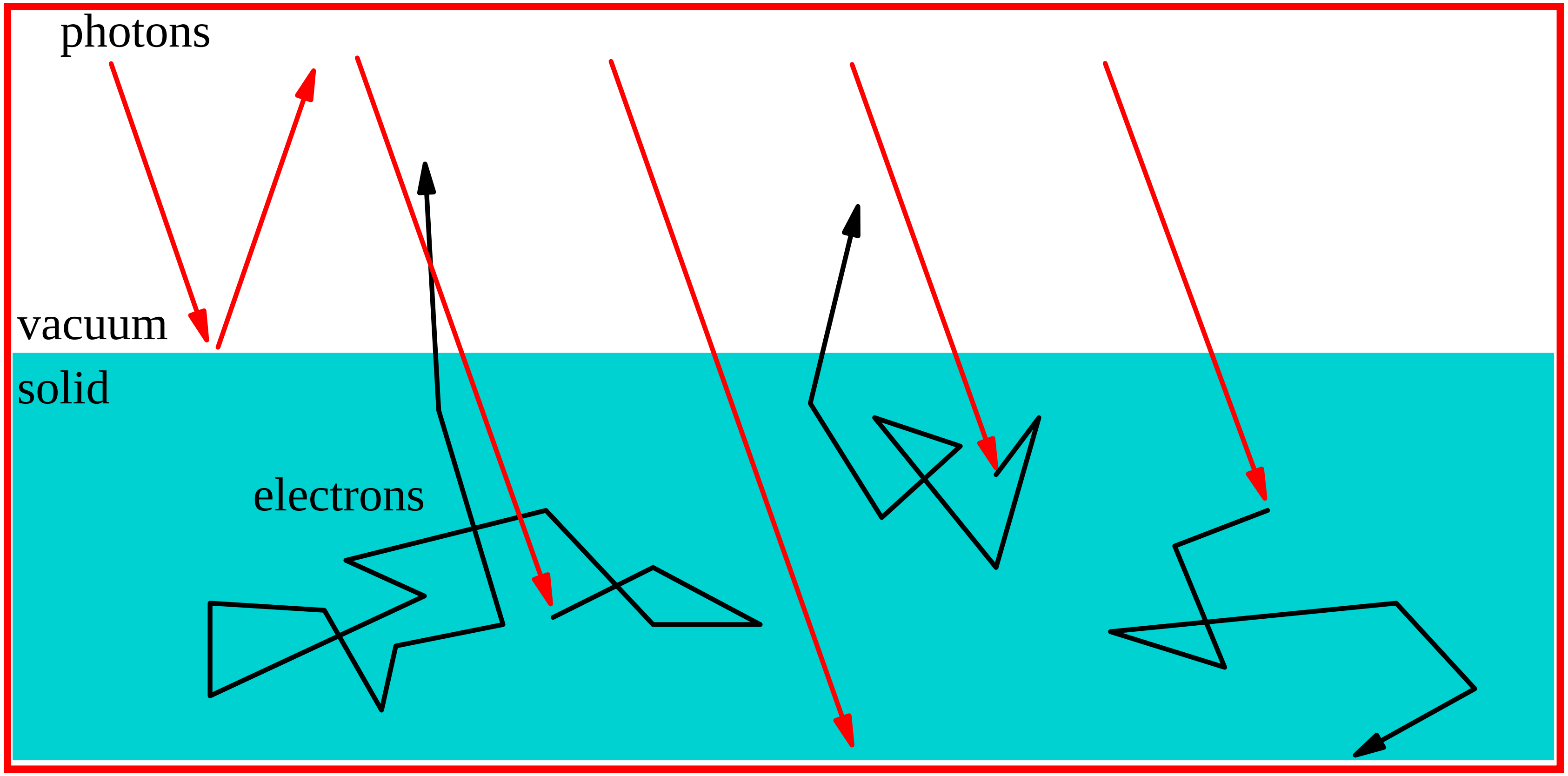
Photoemission (PE)

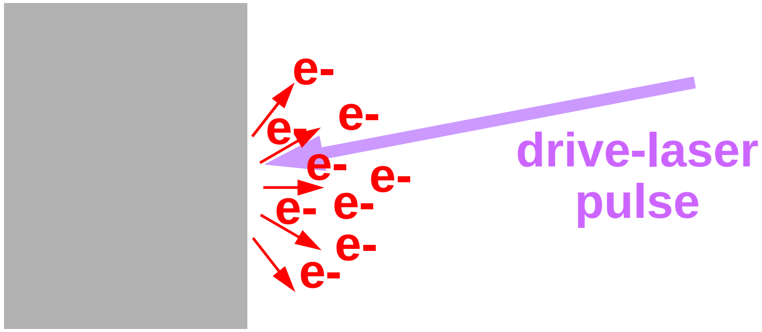
Quantum efficiency (QE)

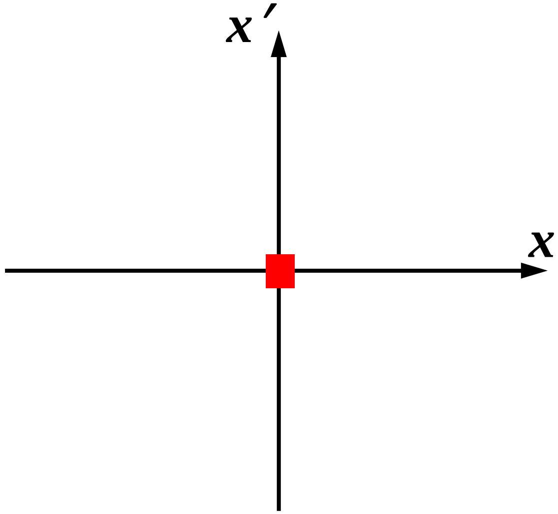
$$\mathbf{QE} = \frac{\textbf{number of emitted electrons}}{\textbf{number of irradiated photons}}$$



Thermal emittance

Thermal emittance: initial emittance of the beam, which is configured during the beam emission

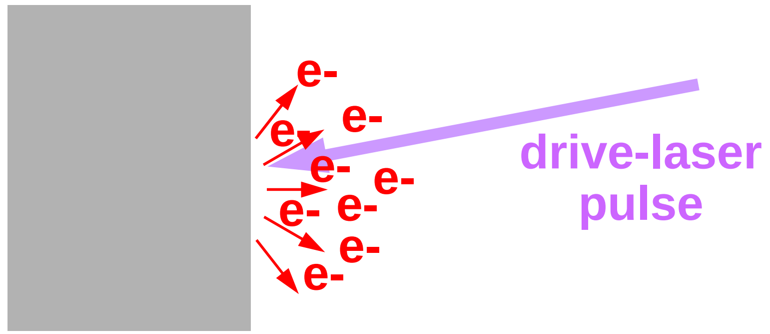


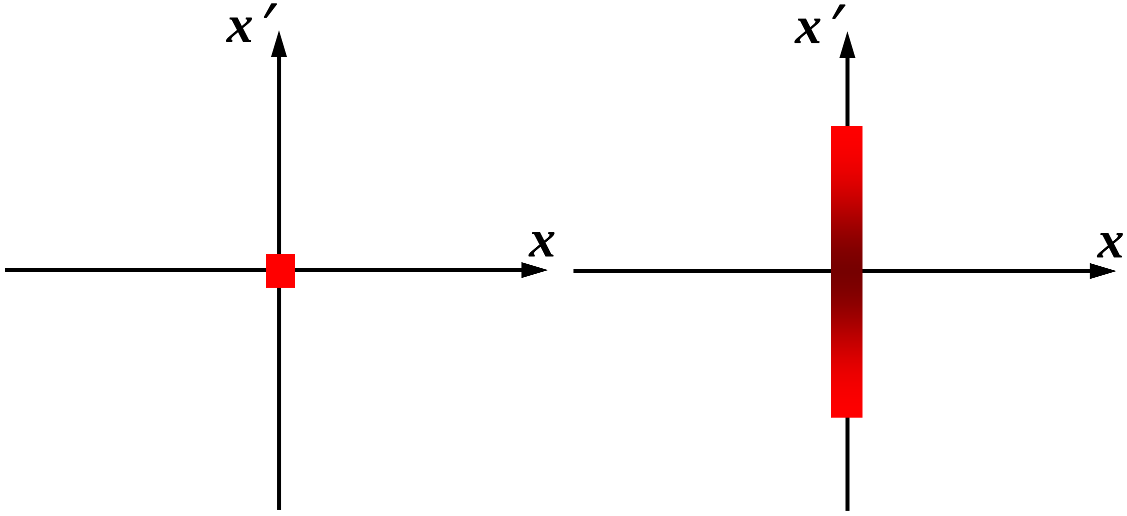


Single point
No kinetic energy

Thermal emittance

Thermal emittance: initial emittance of the beam, which is configured during the beam emission



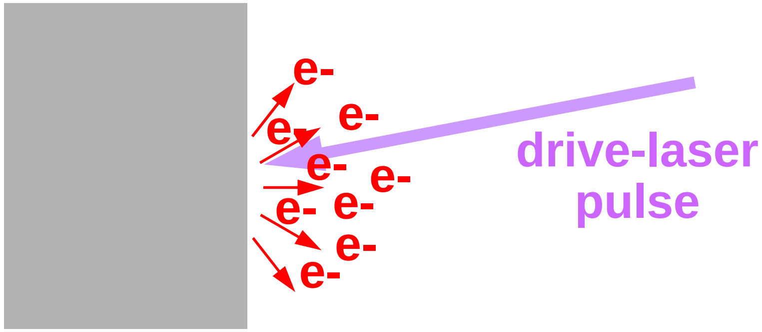


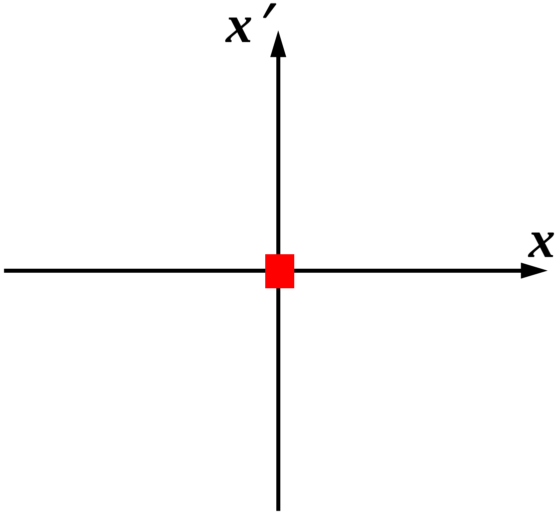
Single point
No kinetic energy

Single point
Finite kinetic energy

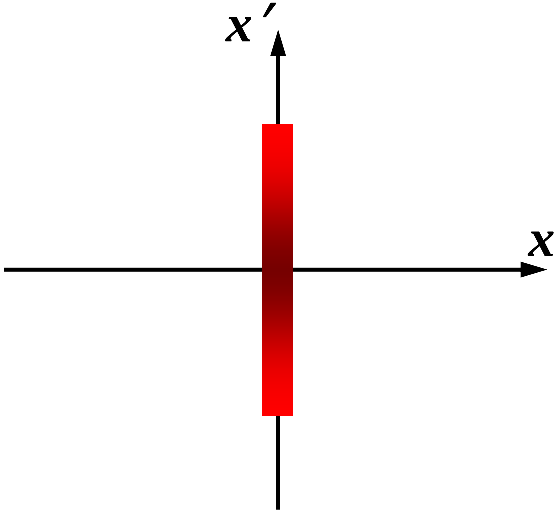
Thermal emittance

Thermal emittance: initial emittance of the beam, which is configured during the beam emission

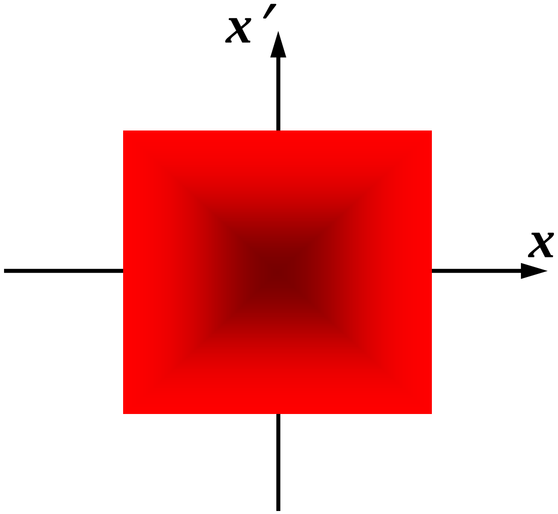




Single point
No kinetic energy

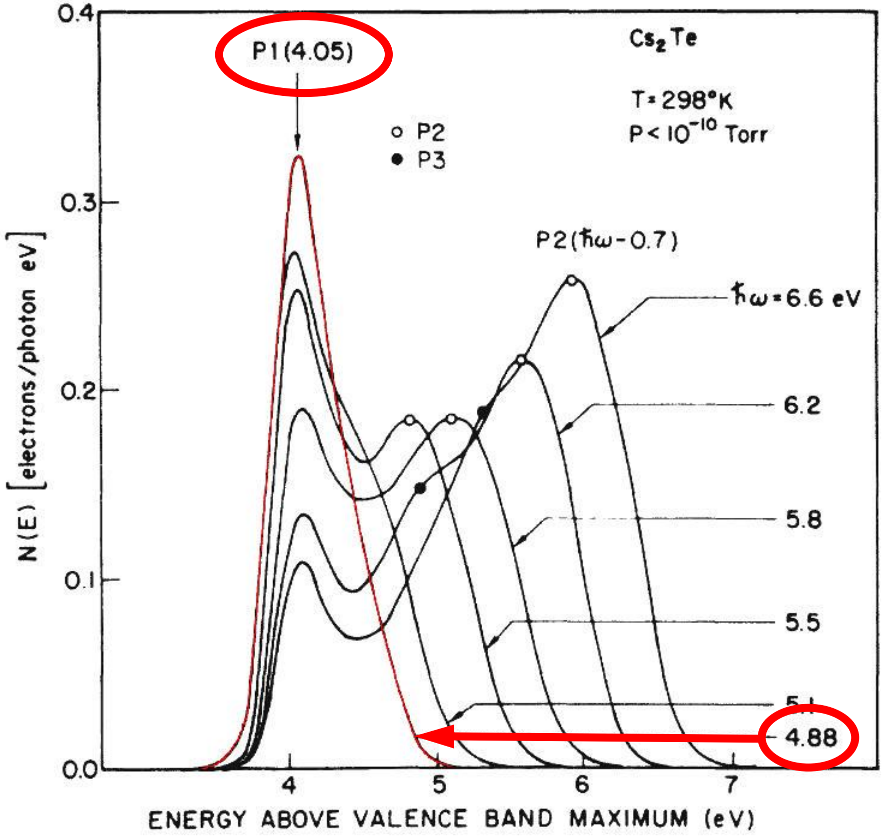


Single point
Finite kinetic energy



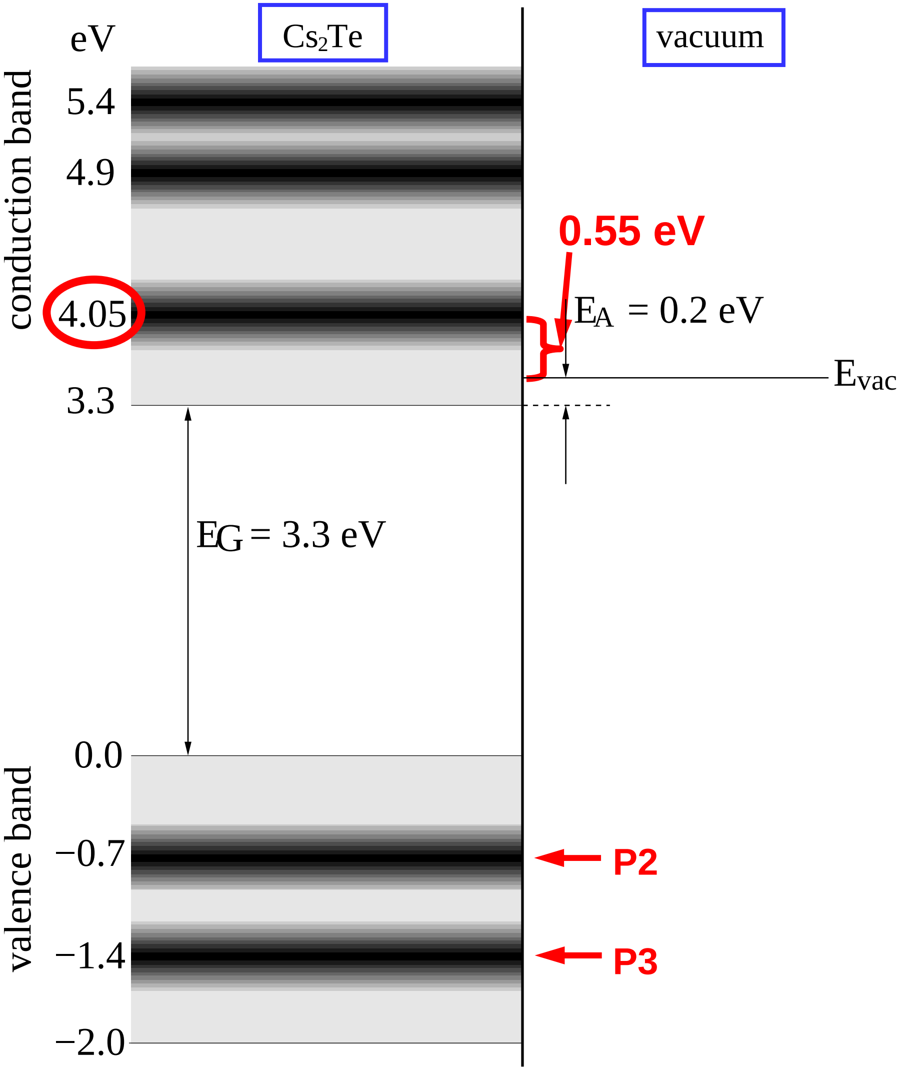
Finite beam size
Finite kinetic energy

Kinetic energy of electrons emitted from Cs_2Te cathode



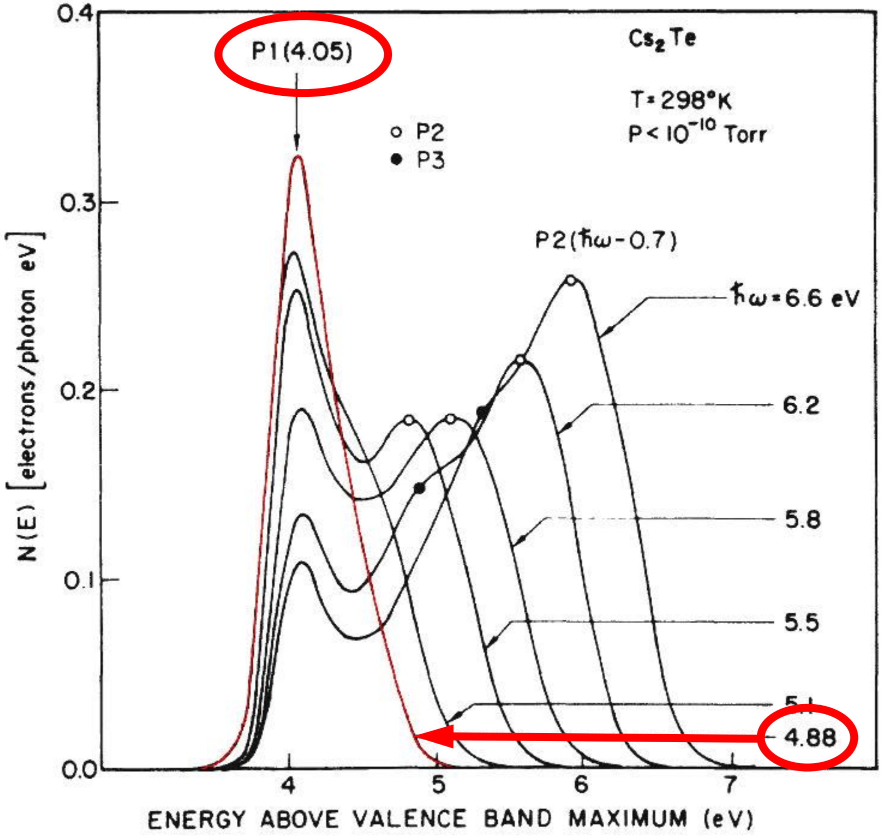
Energy distributions of the photoemitted electrons

From R. A. Powell et al., PRB 8, 3987 (1973)



From K. Floettmann, FEL1999

Kinetic energy of electrons emitted from Cs_2Te cathode



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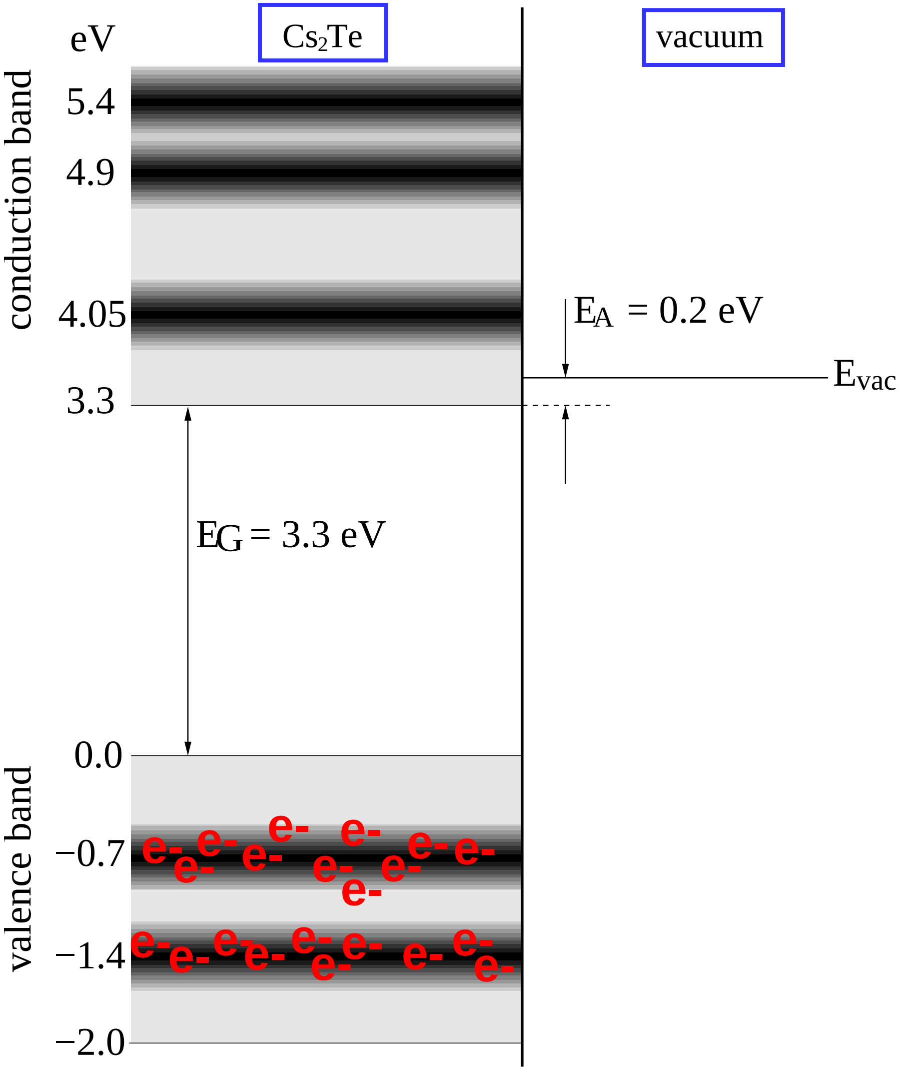

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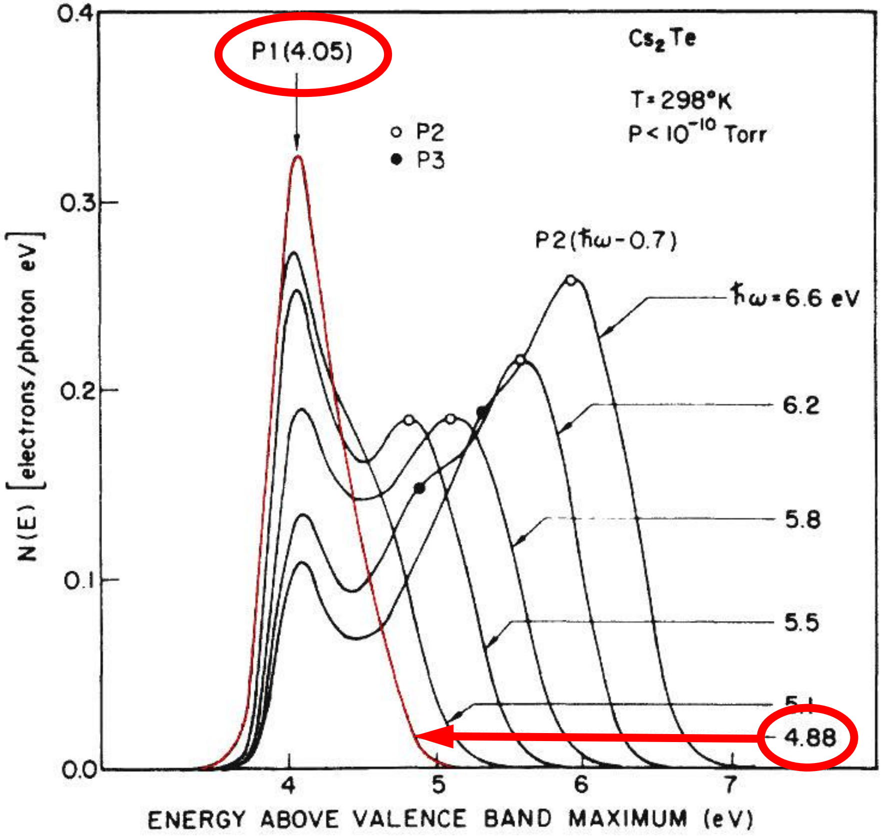

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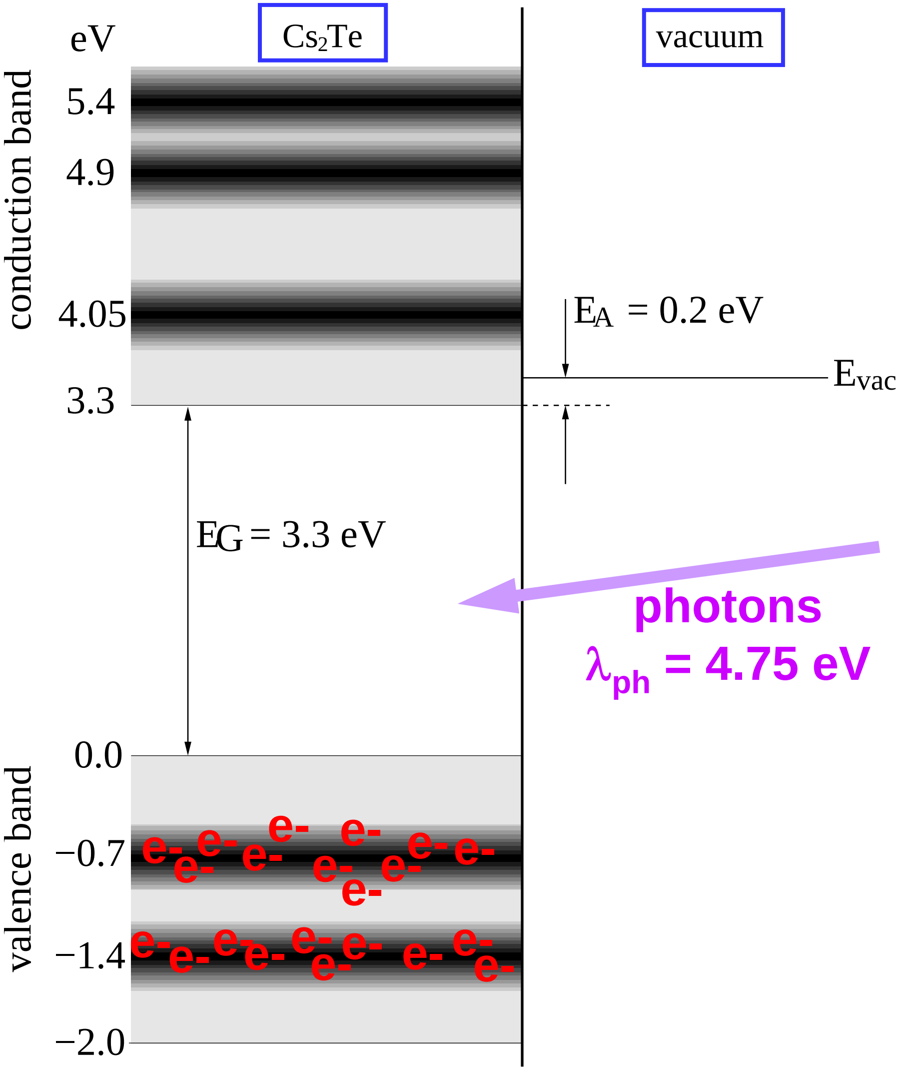

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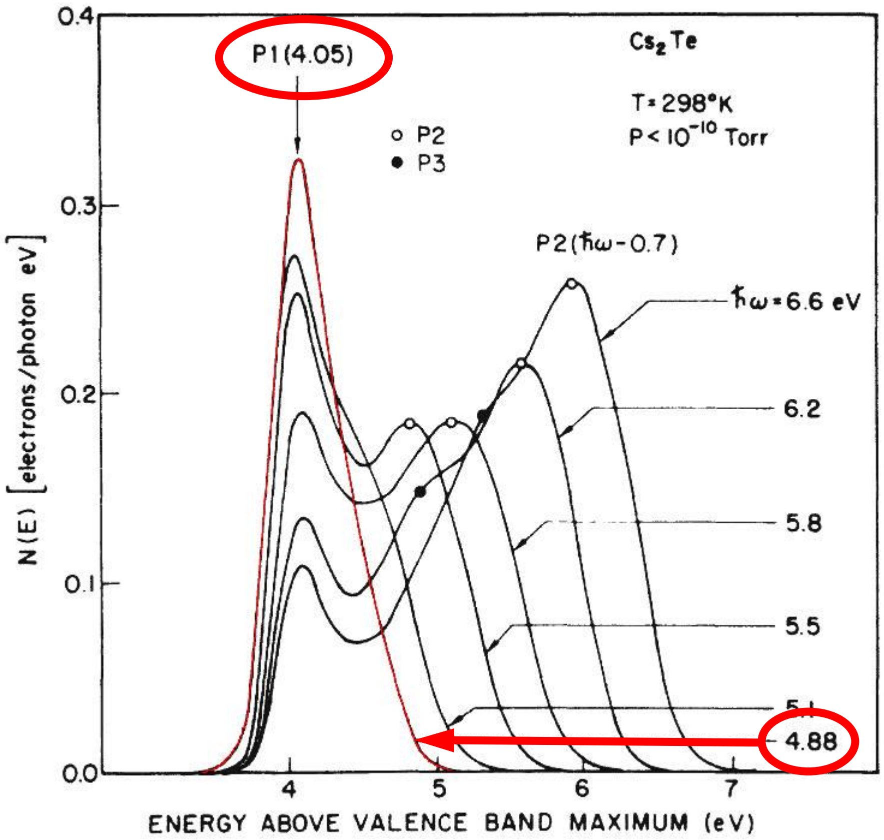

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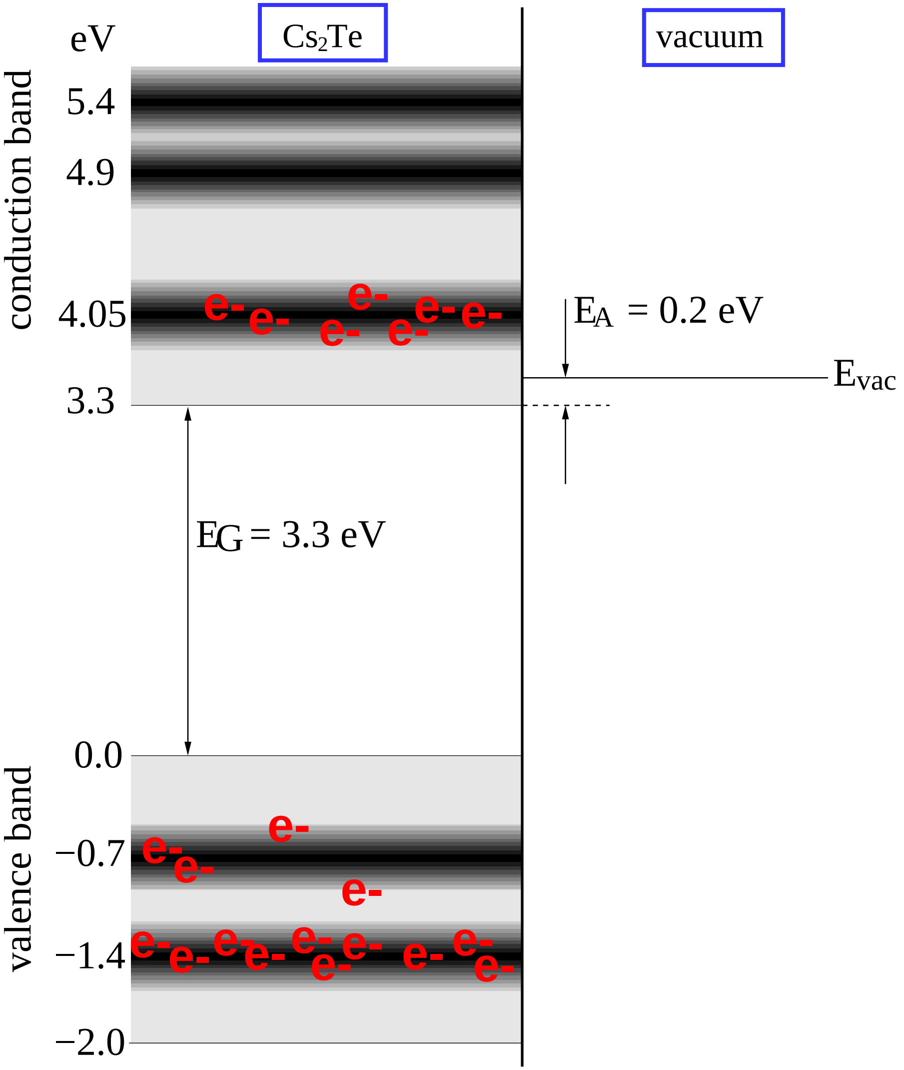

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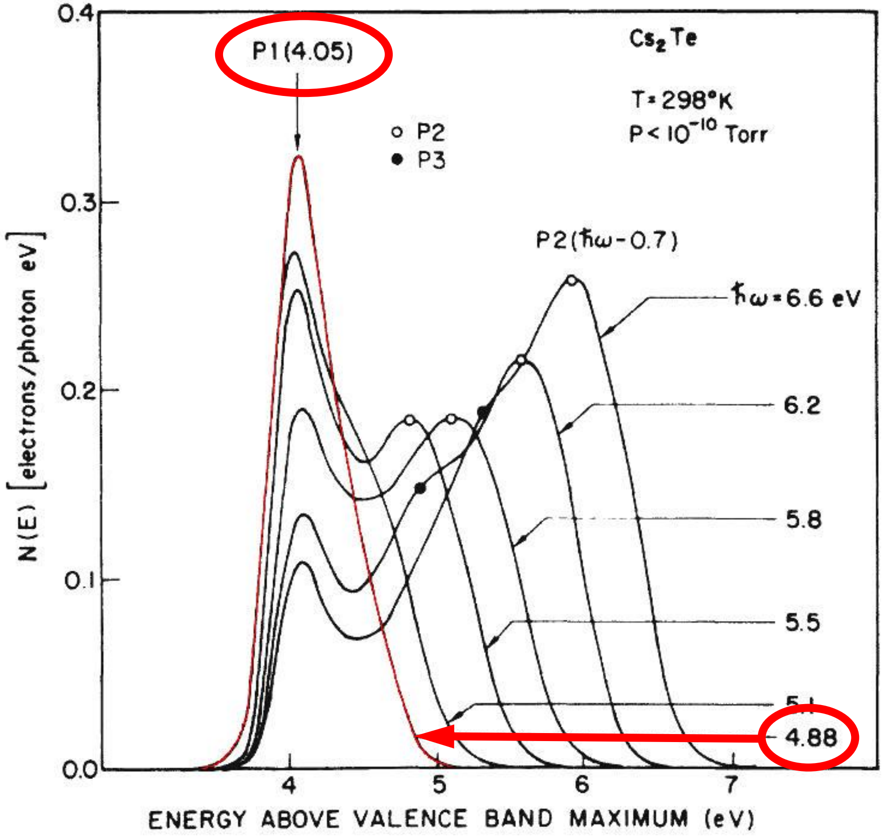

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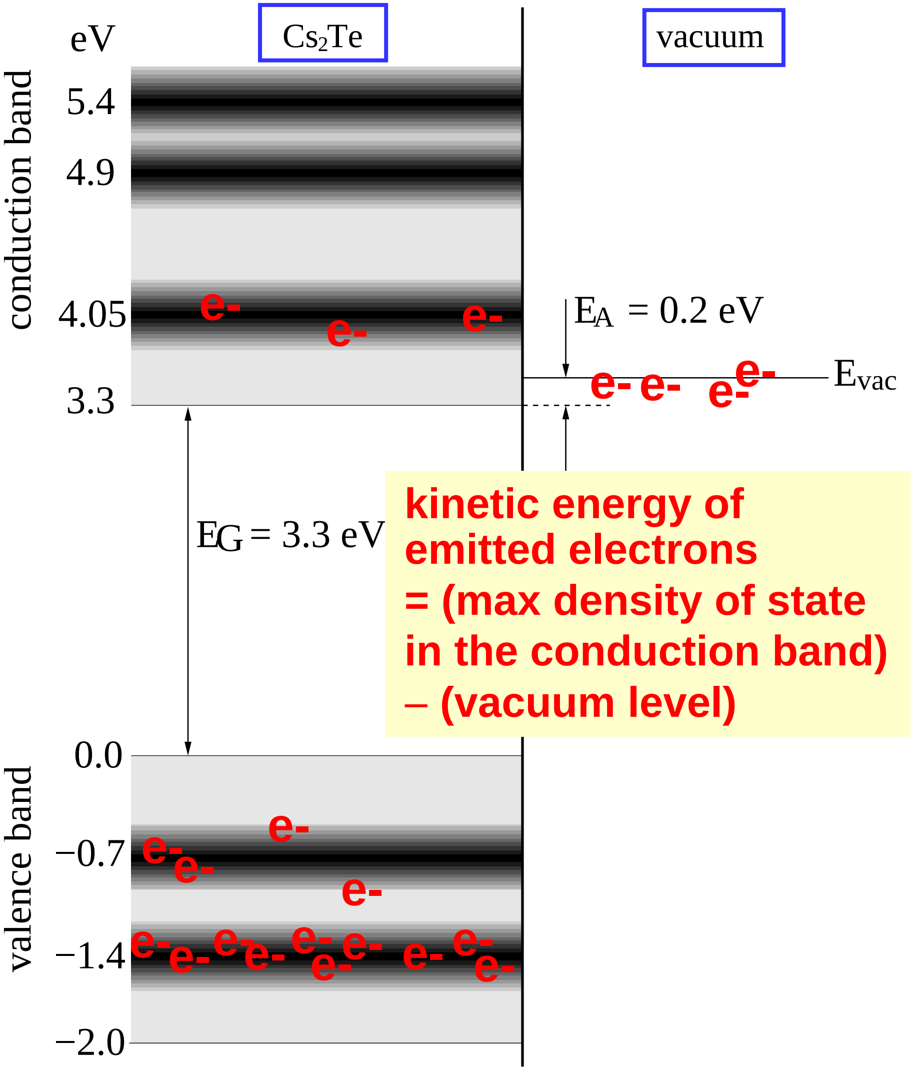
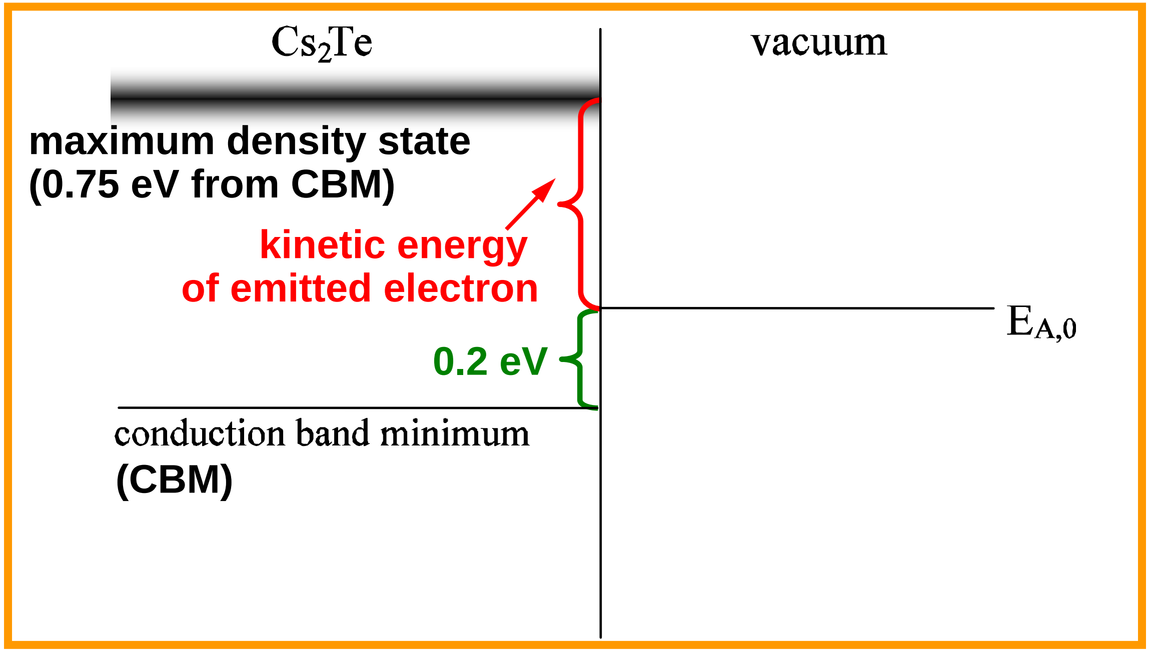


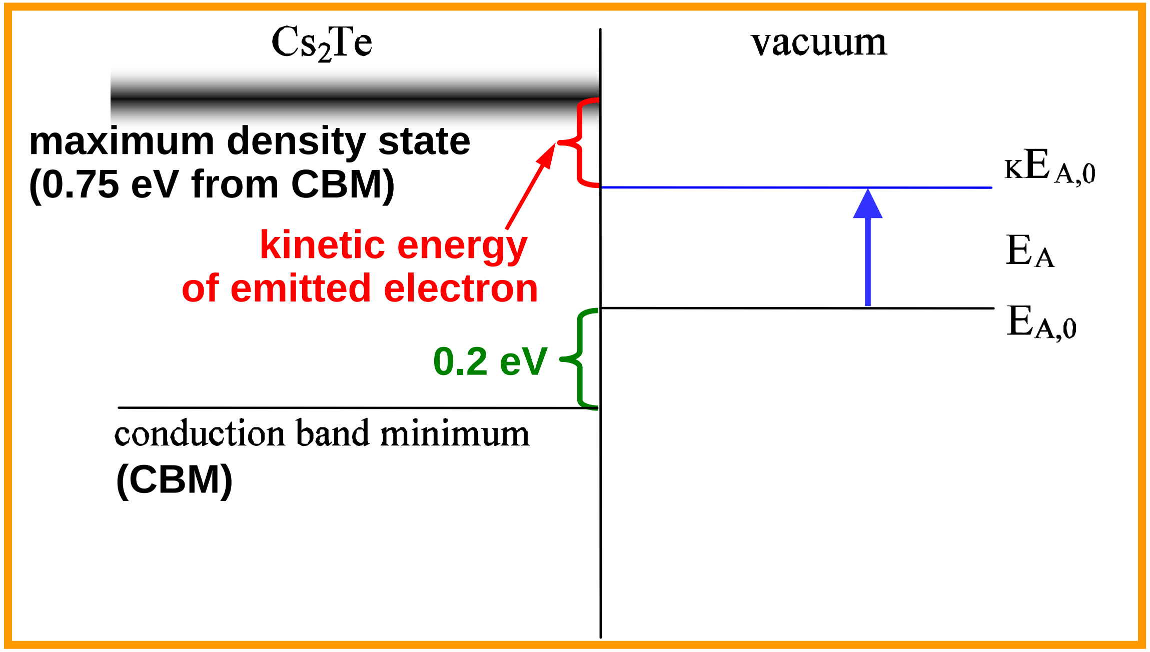
kinetic energy of emitted electrons = (max density of state in the conduction band) – (vacuum level)

From K. Floettmann, FEL1999

Effective electron affinity



Effective electron affinity



Cs_2Te

vacuum

maximum density state (0.75 eV from CBM)

kinetic energy of emitted electron

$\kappa E_{A,0}$

E_A

$E_{A,0}$

0.2 eV

conduction band minimum

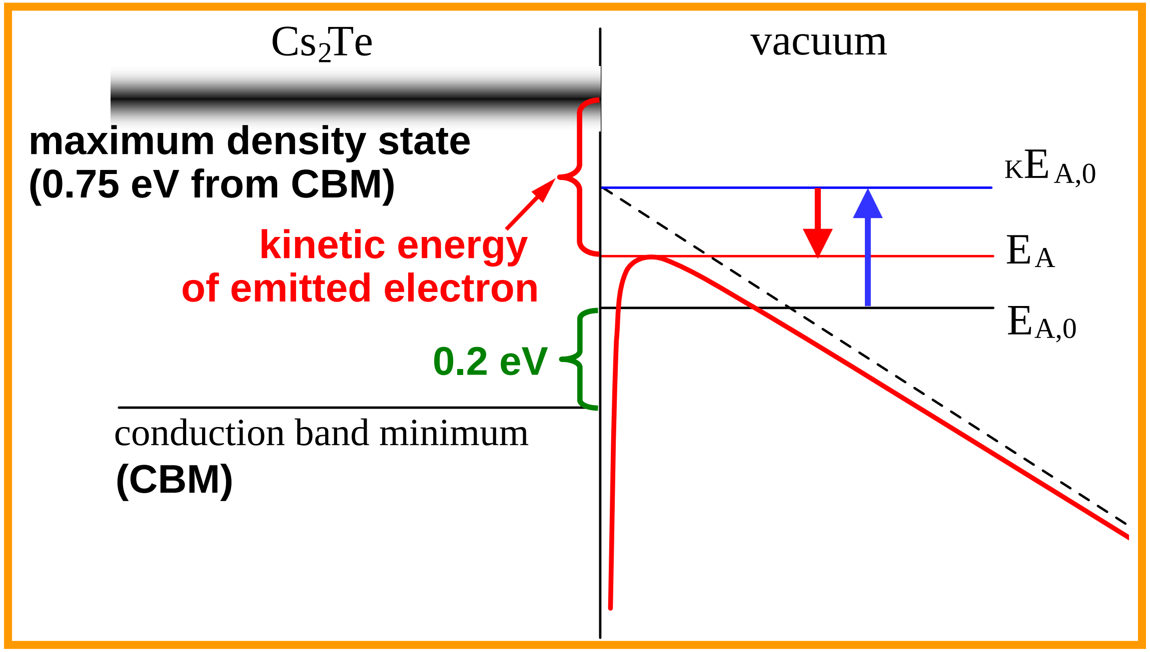
(CBM)

electron affinity increase due to surface contamination

$$E_A = \kappa E_{A,0} - \sqrt{\frac{e^3}{4\pi\varepsilon_0}\beta_{ph} E_{emit}}$$

κ : surface contamination factor

Effective electron affinity



electron affinity increase due to surface contamination

$$E_A = \kappa E_{A,0} - \sqrt{\frac{e^3}{4\pi\varepsilon_0}\beta_{ph} E_{emit}}$$

electron affinity decrease due to the Schottky effect

Potential barrier decrease by the electric field

Electron affinity variation results in

1. Bunch charge increase
2. Kinetic energy increase of emitted electrons (thermal emittance)

κ : surface contamination factor
β_{ph}: field enhancement factor
E_{emit}: electric field at emission

Thermal emittace: measurement & theory

<measurement>

1. x_{rms} of the beam
2. x_{rms} of the beamlet → $p_{x,\mathrm{rms}}$

low charge density bunch

short pulse length

$$\varepsilon_{\mathrm{meas}} = \sqrt{\left(\varepsilon^{\mathrm{therm}}\right)^2 + \cancel{\left(\varepsilon^{\mathrm{SC}}\right)^2} + \cancel{\left(\varepsilon^{\mathrm{rf}}\right)^2} + \left(\varepsilon^{\mathrm{sys.error}}_{\mathrm{meas}}\right)^2}$$

$$\varepsilon_{n,\mathrm{rms}} = x_{\mathrm{rms}} \frac{p_{x,\mathrm{rms}}}{m_0 c}$$

<theoretical estimation>

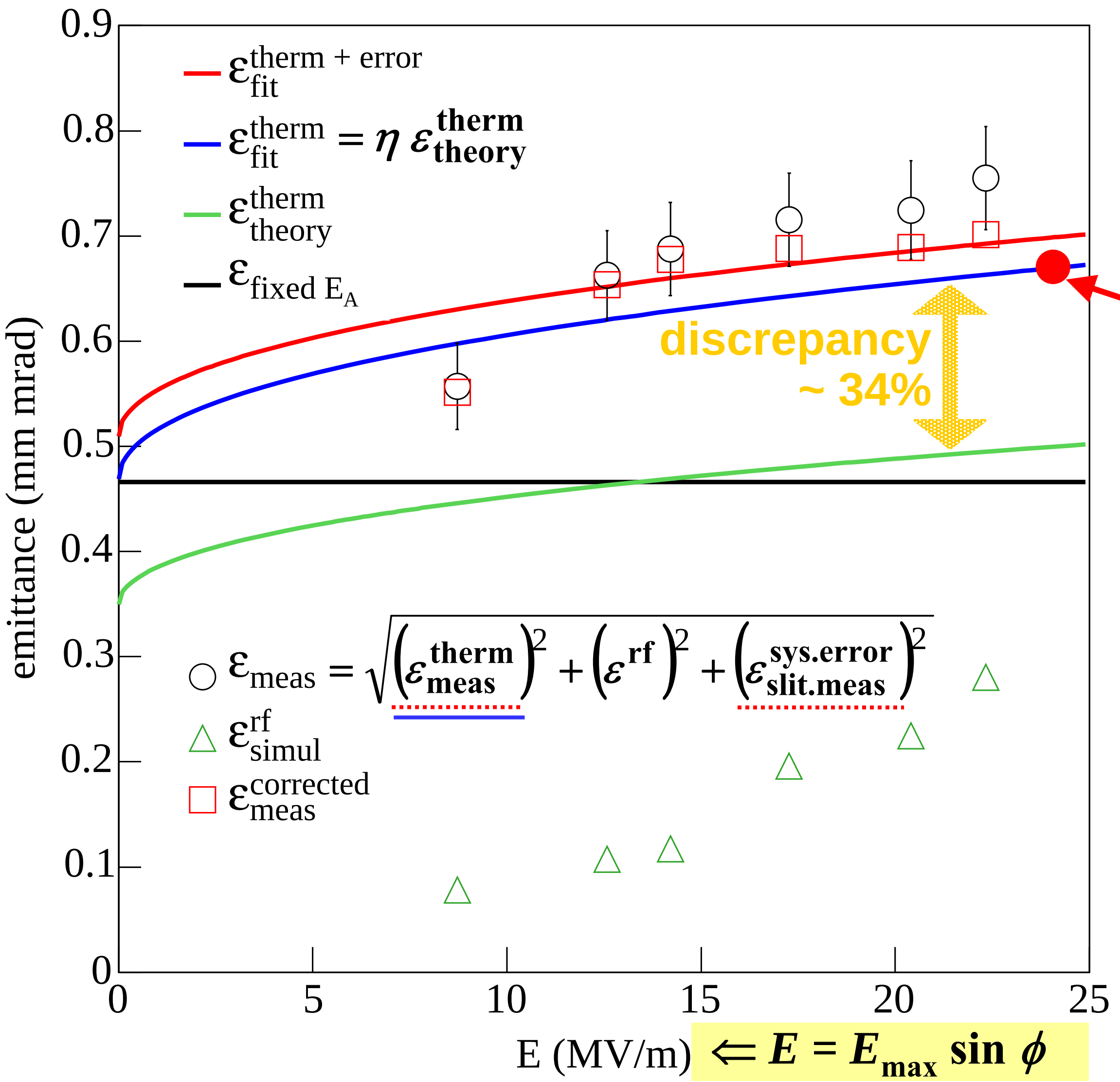
1. x_{rms} of the laser spot
2. E_{emit} (rf field at the emission)

→ effective electron affinity

→ kinetic energy of emitted electron

$$\varepsilon^{\mathrm{therm}}_{n,\mathrm{rms}} = x_{\mathrm{rms}} \sqrt{\frac{2E_{\mathrm{kin}}}{m_0 c^2}} \frac{1}{\sqrt{3}}$$

Analysis of measurement



$\Leftarrow E = E_{max} \sin \phi$

laser spot size ~ 0.55 mm
bunch charge ~ 3 pC

$\varepsilon_{fit}^{therm}$ ~ 0.68 mm mrad
(r_{rms} = 0.55 mm)

$\varepsilon_{fit}^{therm}$ / laser size rms
~1.24 mm mrad / mm

at PITZ1 & VUV-FEL (TTF2) operating condition
E_{emit} ~ sin 35° x 42 (MV/m)
~ 24 MV/m

European XFEL
E_{emit} ~ sin 44° x 60 (MV/m)
~ 42 MV/m
$\varepsilon_{fit}^{therm}$ / laser size rms
~ 1.37 mm mrad / mm

Summary for photoemission study

- The kinetic energy of emitted electron varies with the applied RF field strength at the cathode.
- Thermal emittance measurement as a function of the RF gradient has been analyzed.
- A discrepancy between the measurement and the theory has to be studied.
  - Roughness and inhomogeneous QE of the cathode surface
  - Jitters in the RF or in the laser

  → Theoretical model is to be improved!
- In parameter optimization for the electron beam of the XFEL, the thermal emittance increase with the RF field strength has to be considered.

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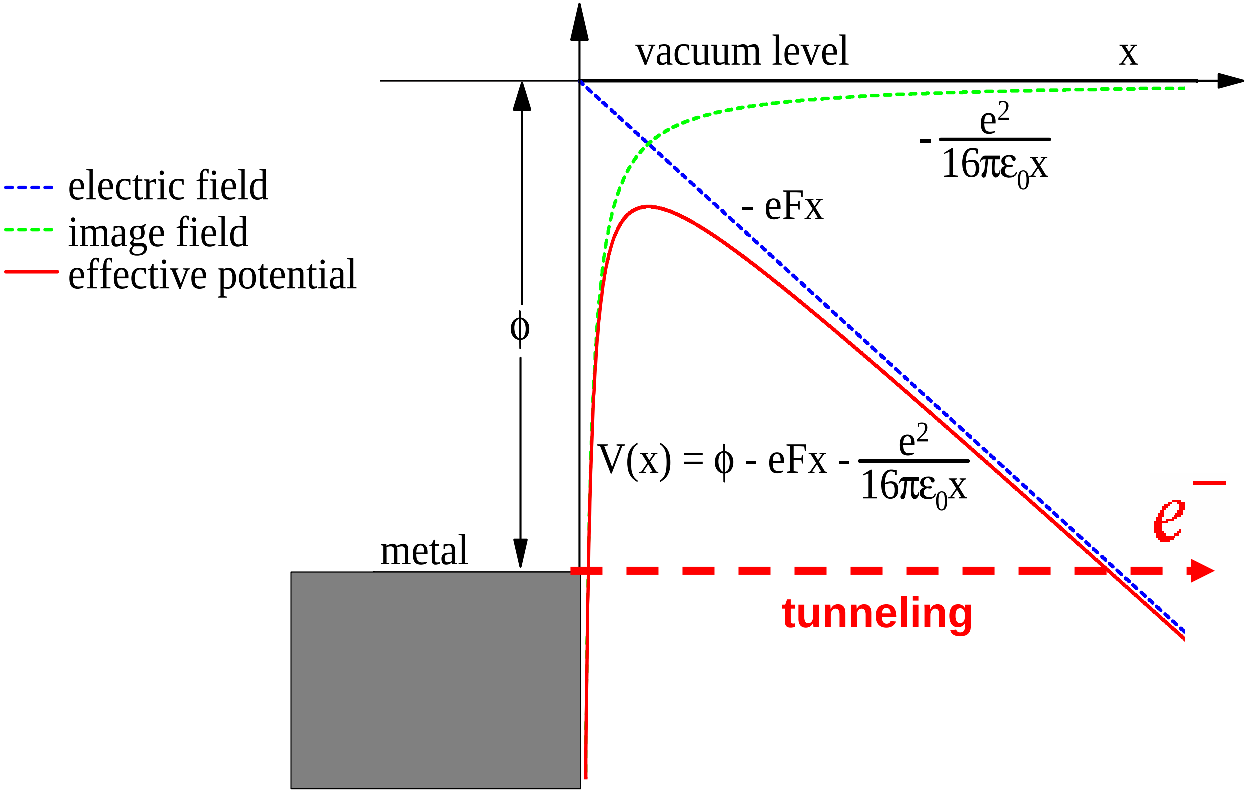
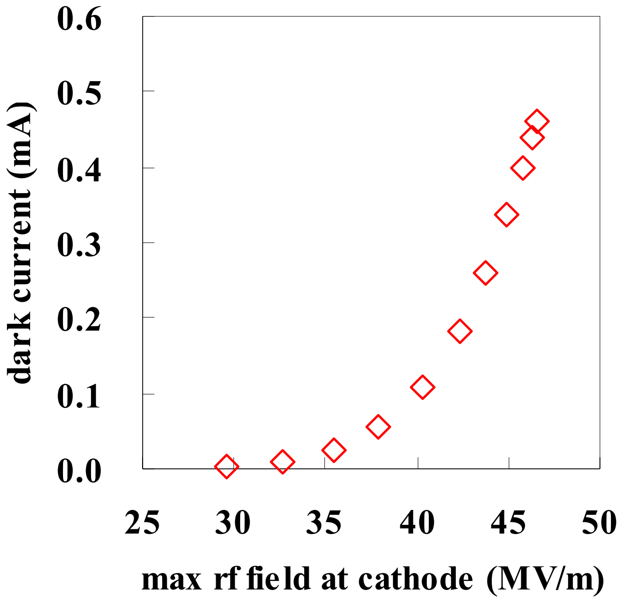
Field emission (FE): Dark current

Dark current in photocathode RF guns:
unwanted current generated in the absence of the drive-laser pulse

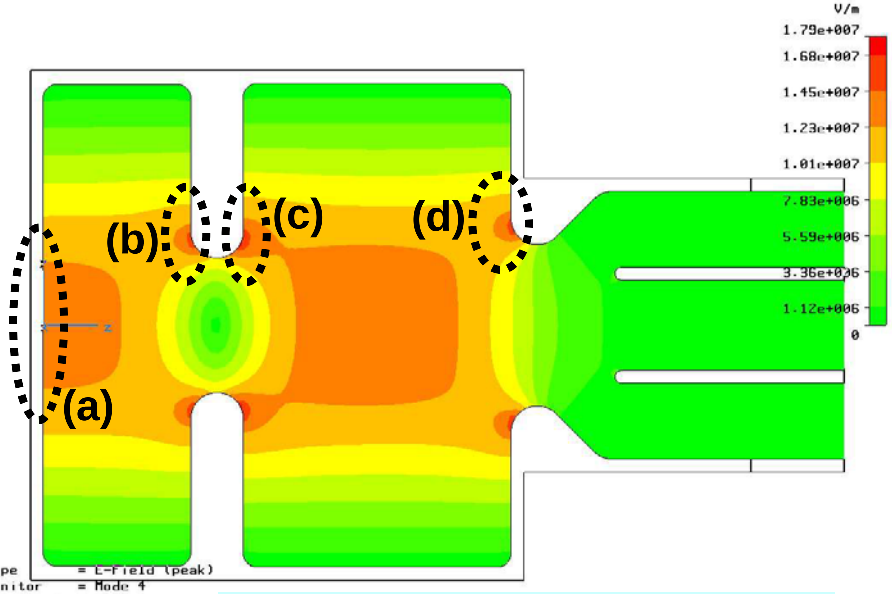


(Fowler-Nordheim equation)

$$\bar{I}_{FE} = C_1 E^{2.5} \exp(-C_2 / E)$$

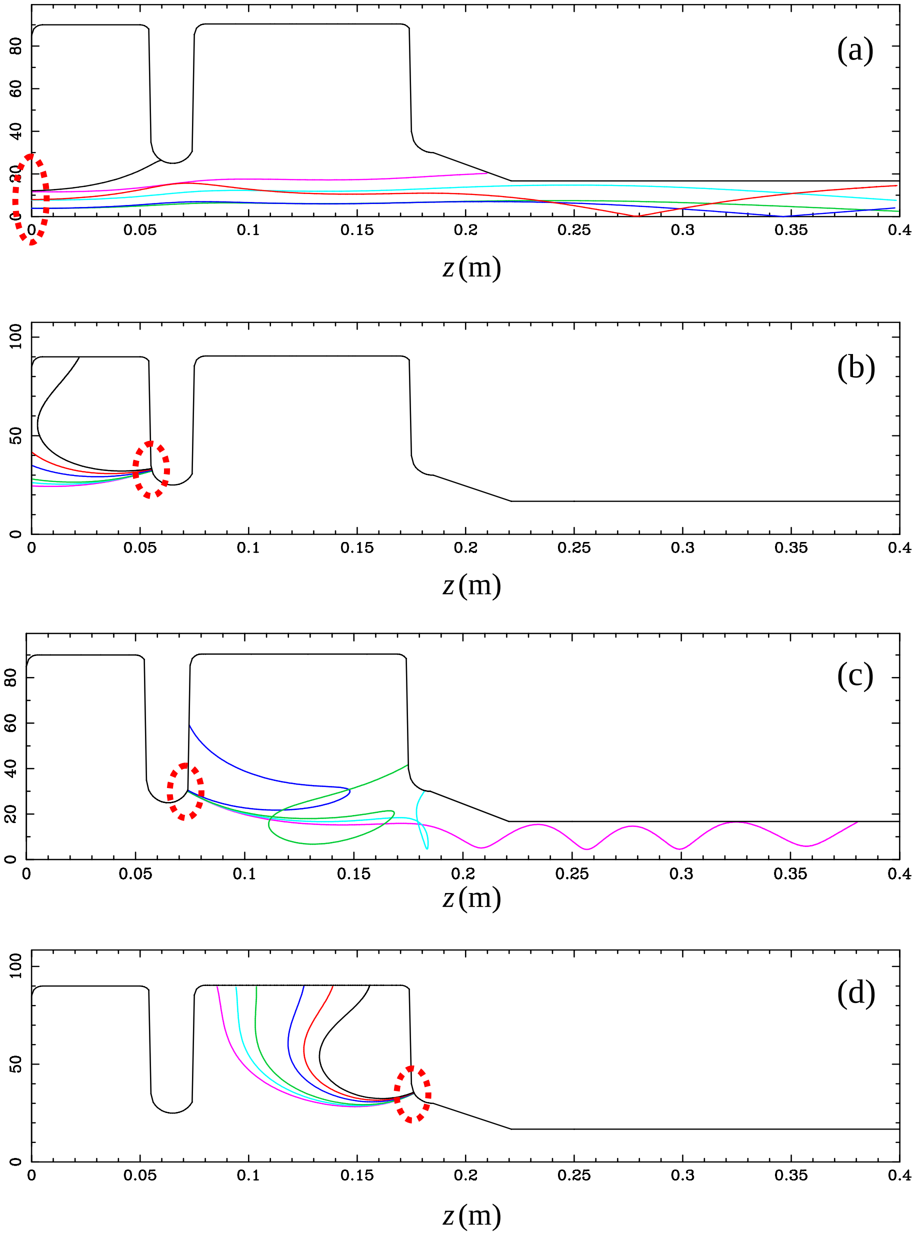


Dark current trajectories



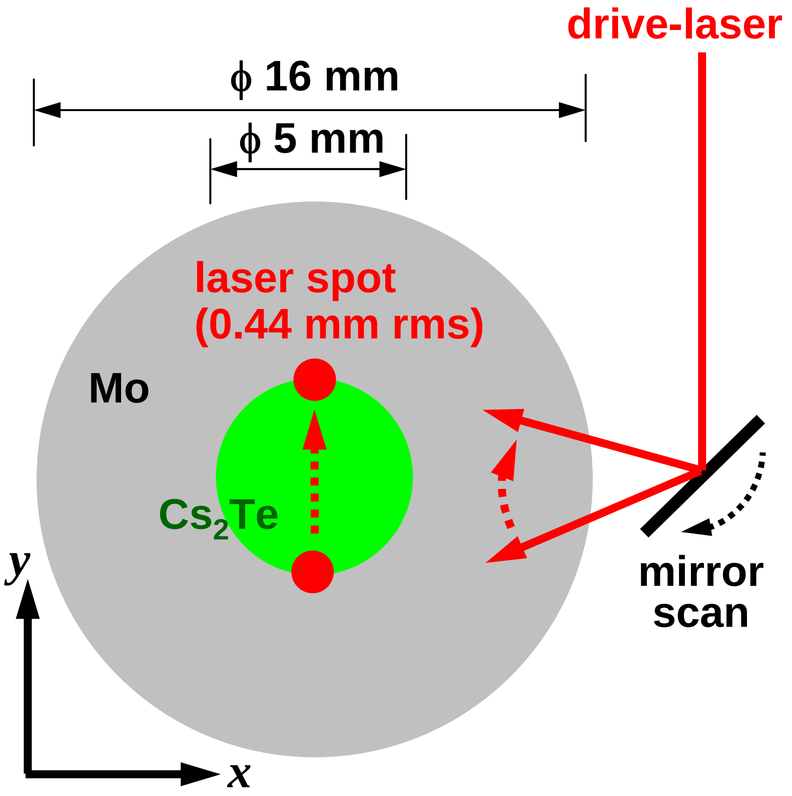
Type = E-Field (peak)
Monitor = Mode 4
Component = Abs
Plane at x = 0
Frequency = 1.29998
Phase = 0 degrees

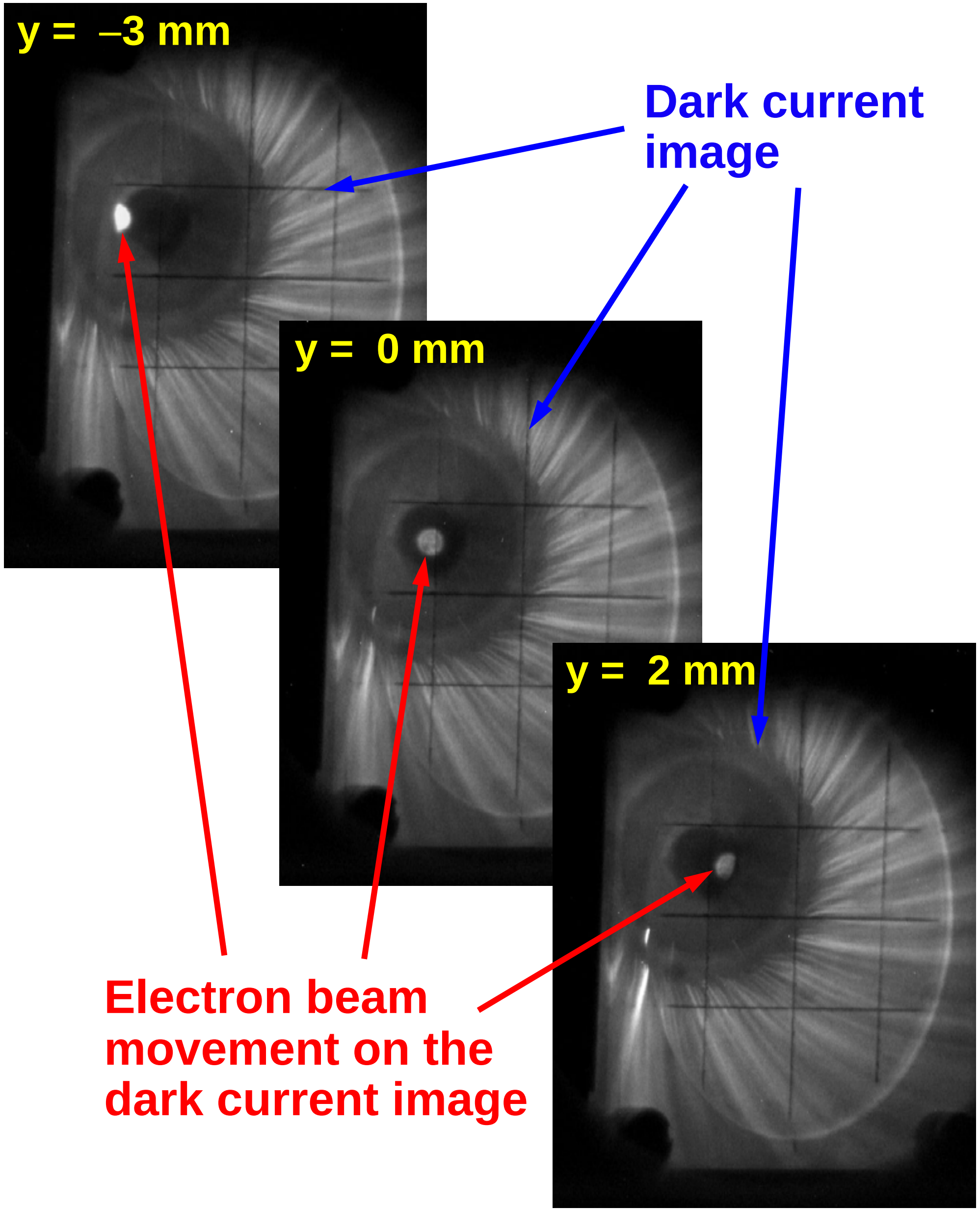
The maxima of the RF field strength can be the major source of dark current



ASTRA simulation at 40 MV/m gradient and 300 A main solenoid current

Images of dark current + beam



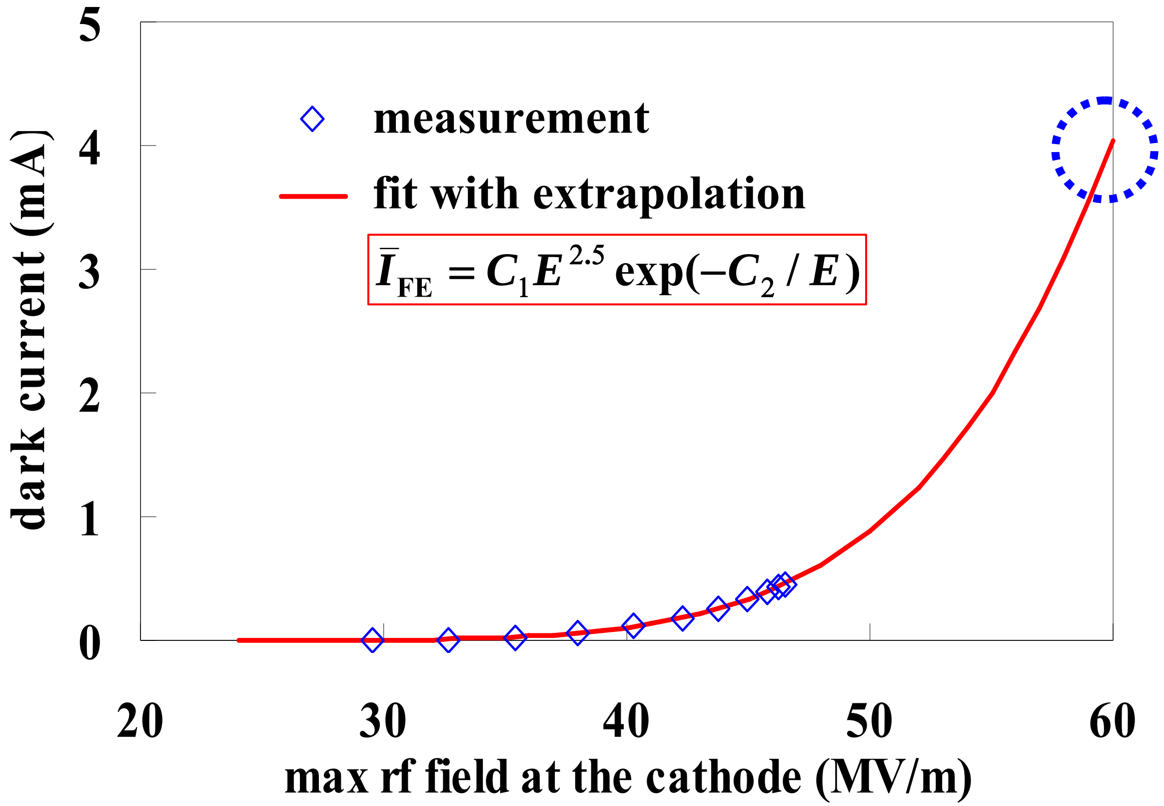


Dark current image

Electron beam movement on the dark current image

By the influence of the solenoid field the trajectory of the beam rotates by ~90°.

Estimation of dark current for the XFEL



European XFEL gun

In this extension, possible decrease of the dark current with RF conditioning was not considered.

Summary for field emission study

- In the RF photocathode gun, the major dark current sources are the photocathode and the surrounding backplane of the gun cavity.
- Dark current for the XFEL gun is estimated to be order of mA.
- More study on the photocathode and the gun cavity is crucial in order to reduce the dark current.

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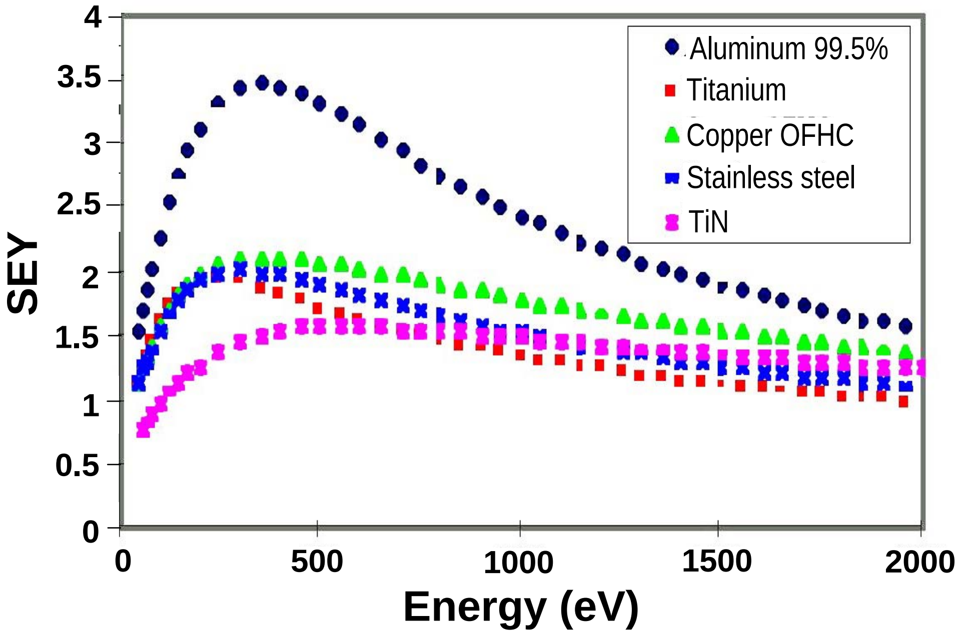
Secondary emission (SE)

When a primary electron strikes a solid material, it may penetrate the surface and generate secondary electrons.

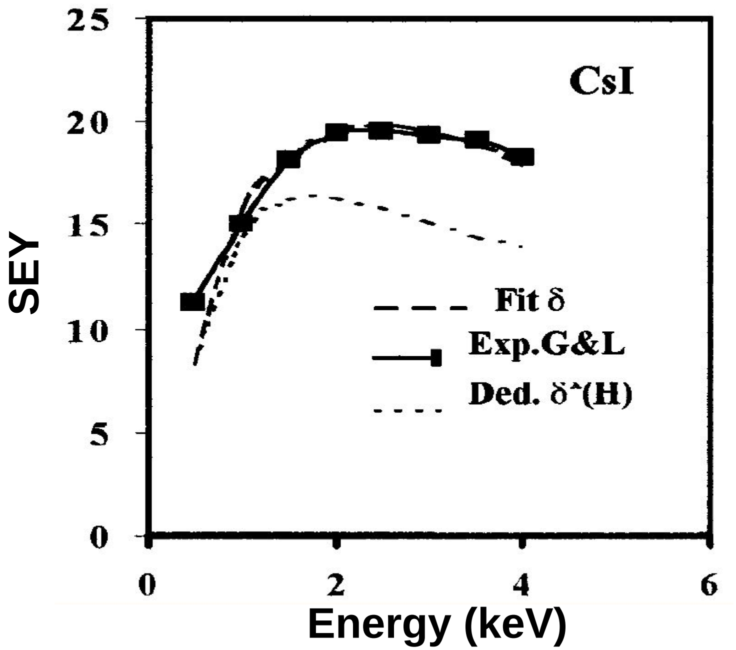
Secondary emission yield, SEY (δ)

$$\delta = \frac{\text{number of emitted electrons}}{\text{number of irradiated electrons}}$$

Secondary emission process has a great similarity to photoemission process.
In general, good photoemitters are good secondary electron emiters.



From N. Hilleret et.al., EPAC2000

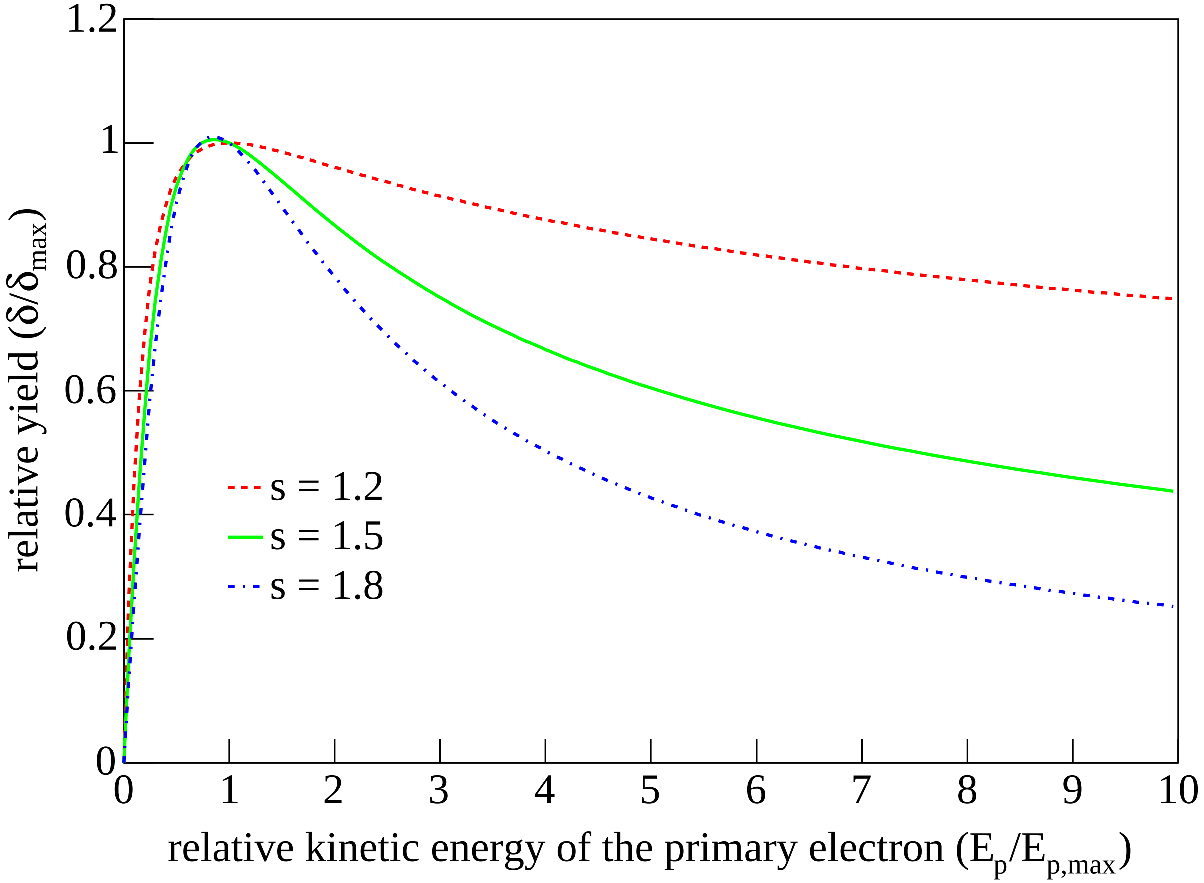


From J. Cazaux, JAP89, 8265 (2001)

Secondary emission (SE) – modeling

A SE model has been implemented into ASTRA

$$\delta(E_p) = \delta_{\max} \frac{E_p}{E_{p,\max}} \cdot \frac{s}{s-1+\left(E_p / E_{p,\max}\right)^s}$$



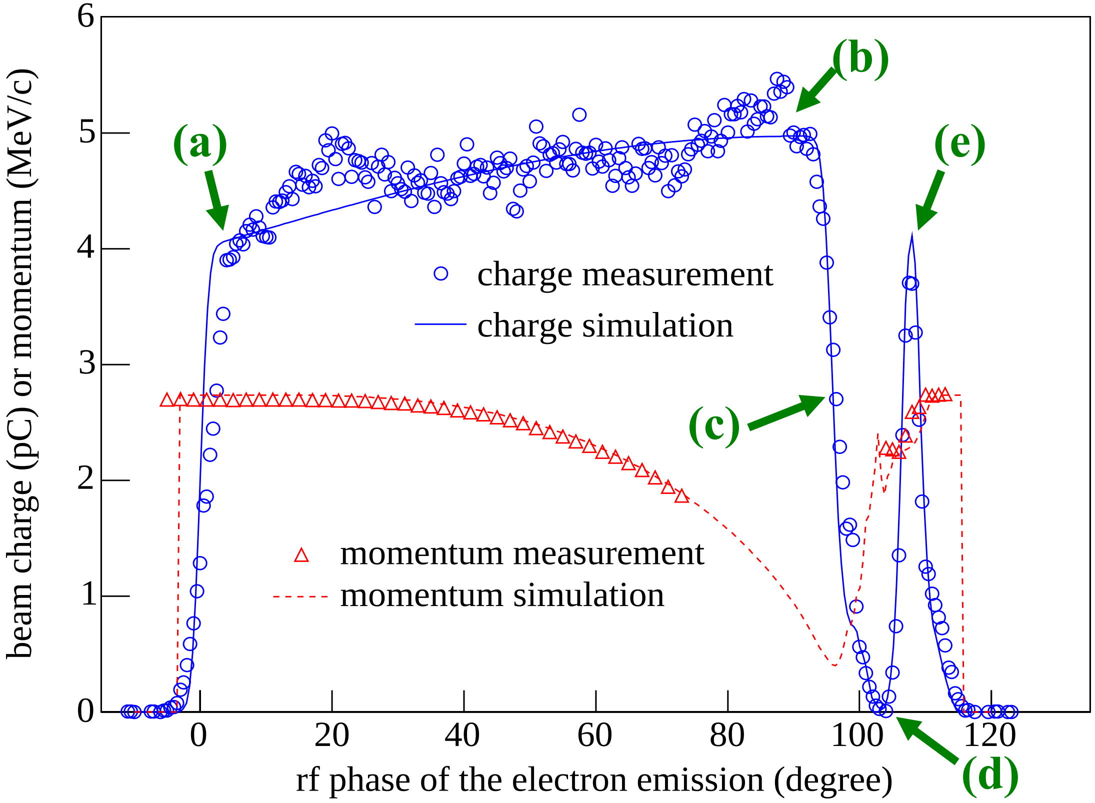
Q_{bunch} & p_{mean} vs. ϕ_{emit}

Max. Q_{bunch} ~ 5 pC

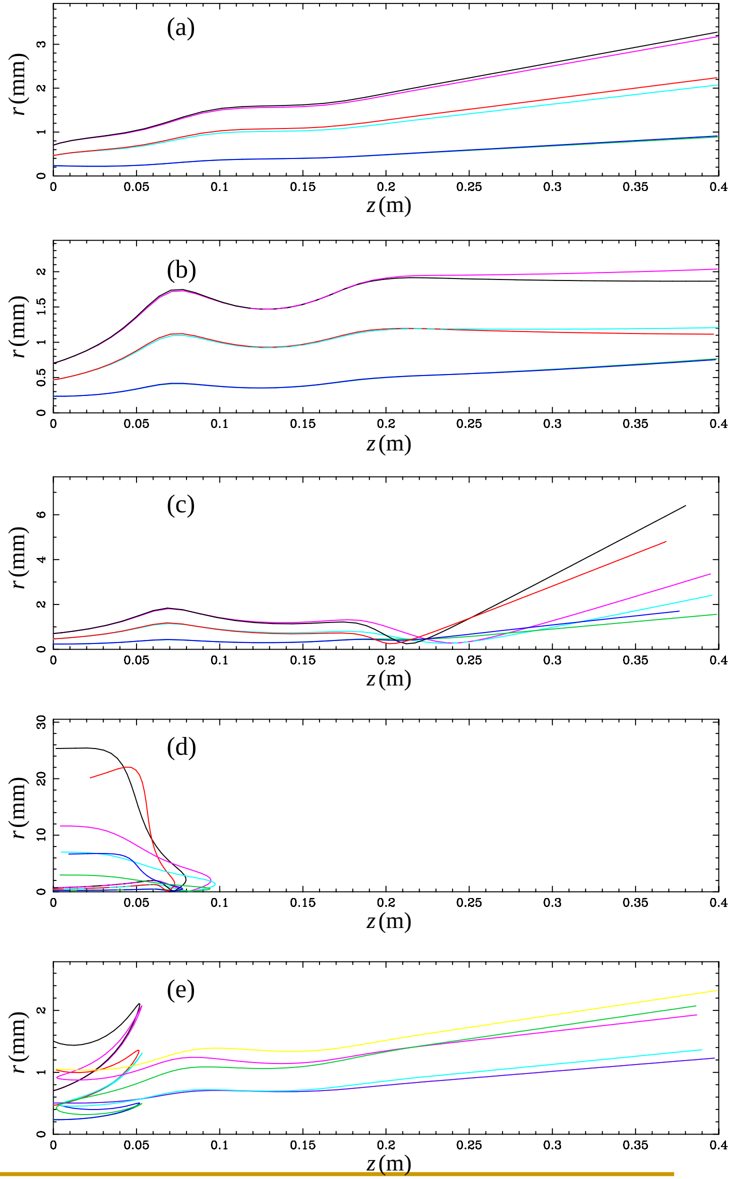
Max. RF field: ~22 MV/m (negligible dark current)

Laser profile: [temporal] **~2.3 ps rms** Gaussian

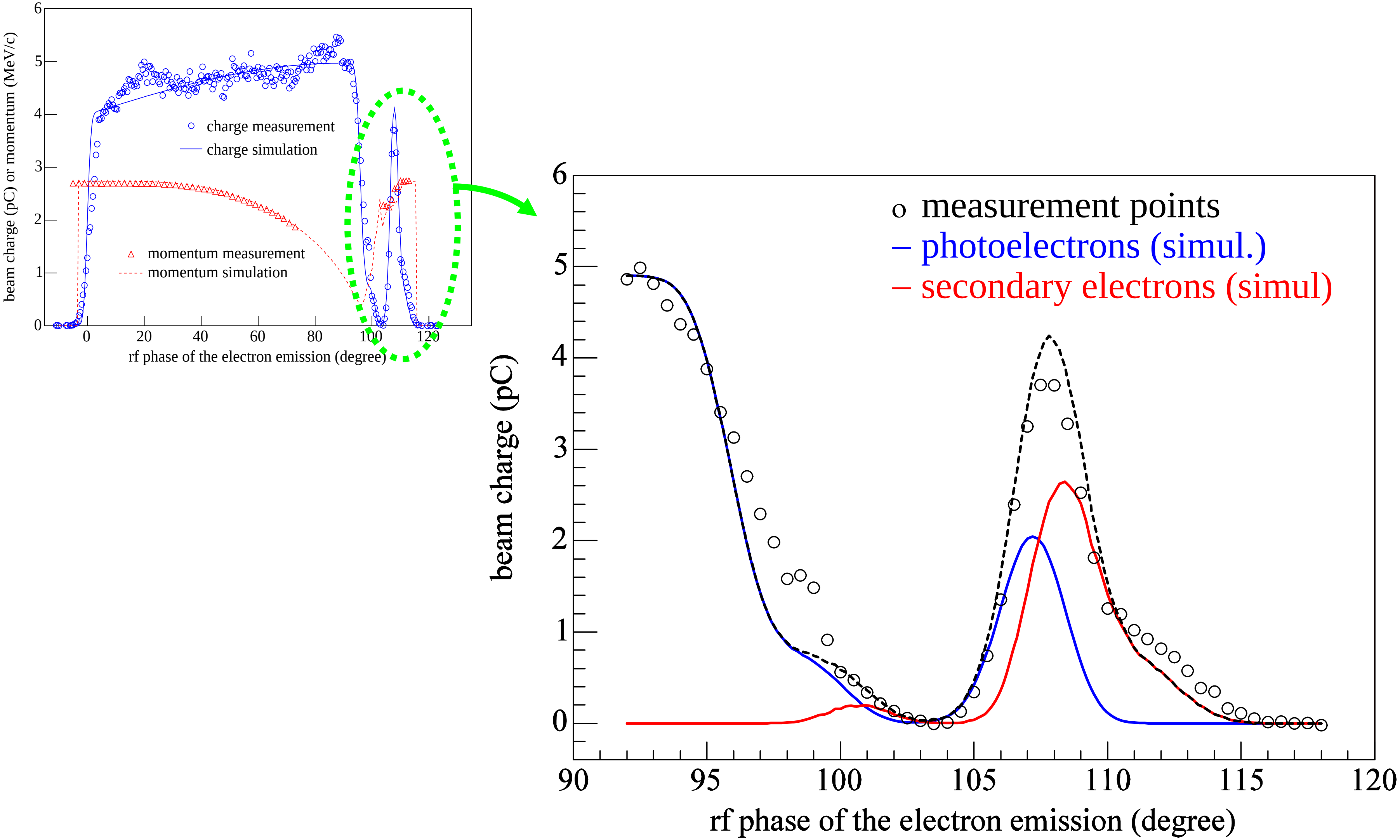
[transverse] **~0.5 mm rms**



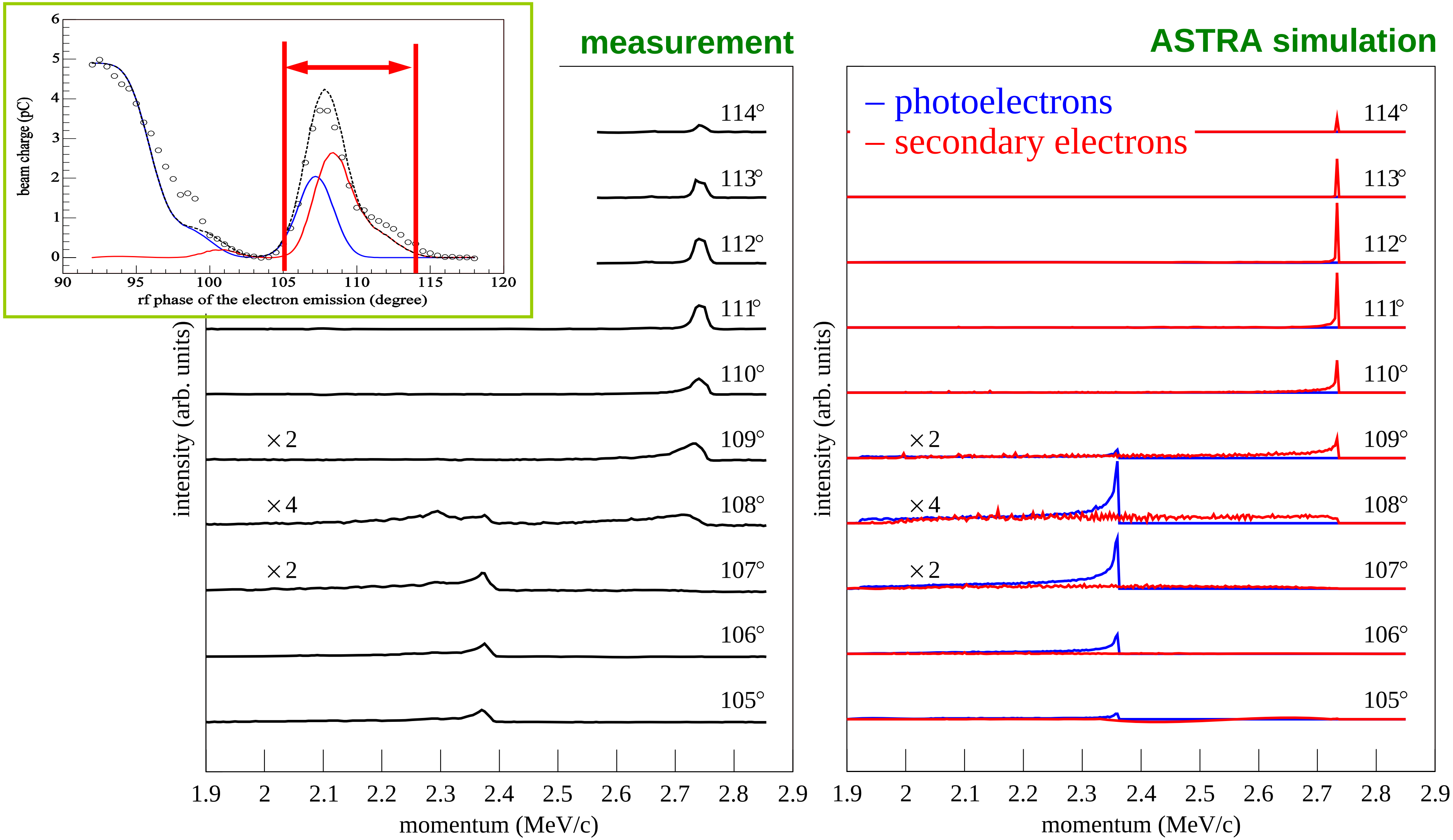
simulated trajectories



SE dependence on emission phase



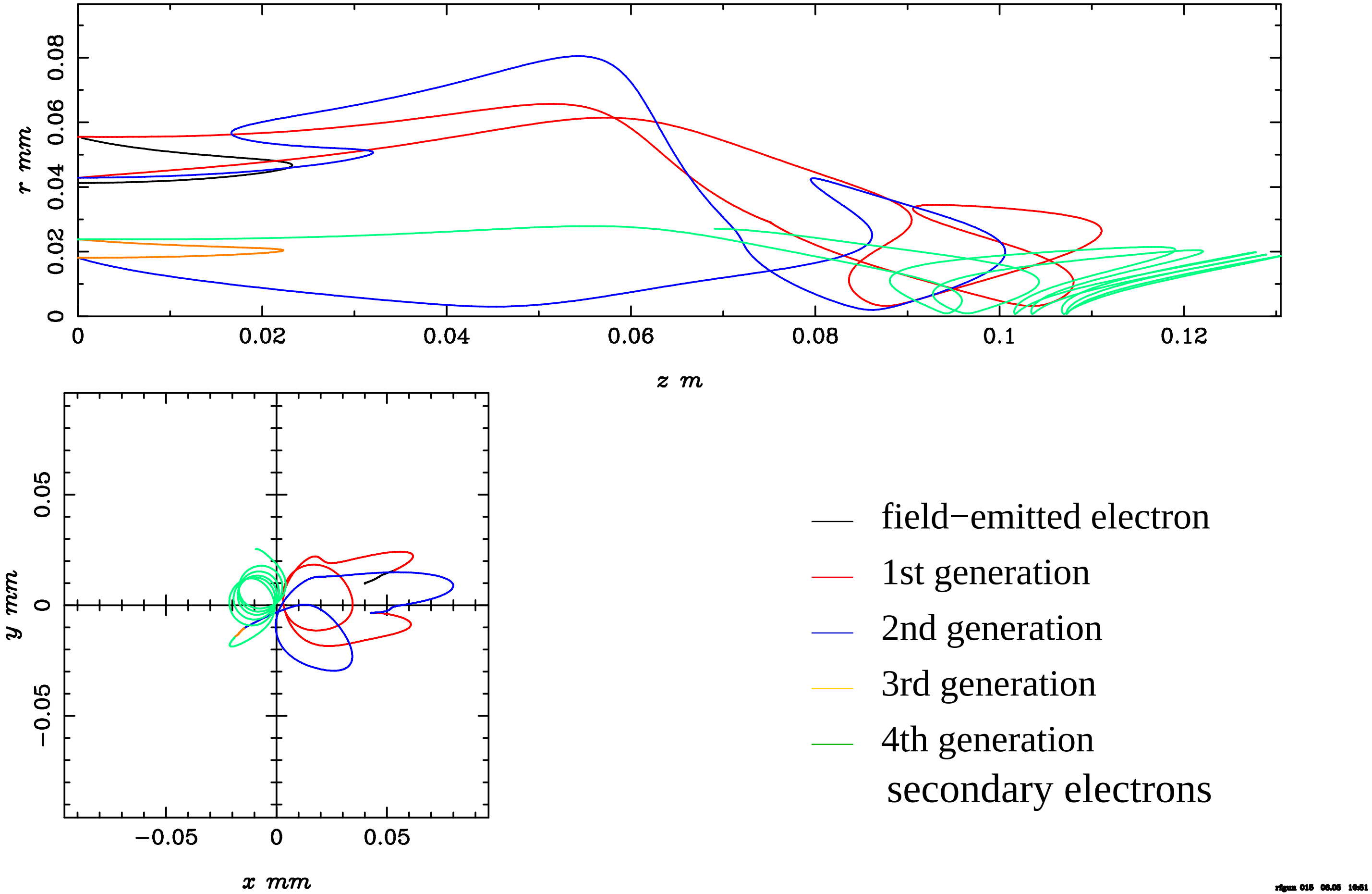
SE dependence on emission phase



Multipacting: electron multiple impacting

Undesired explosive increase of the number of electrons

Multipacting may cause RF power loss, lead to vacuum breakdown, and even damage the surface inside the cavity.

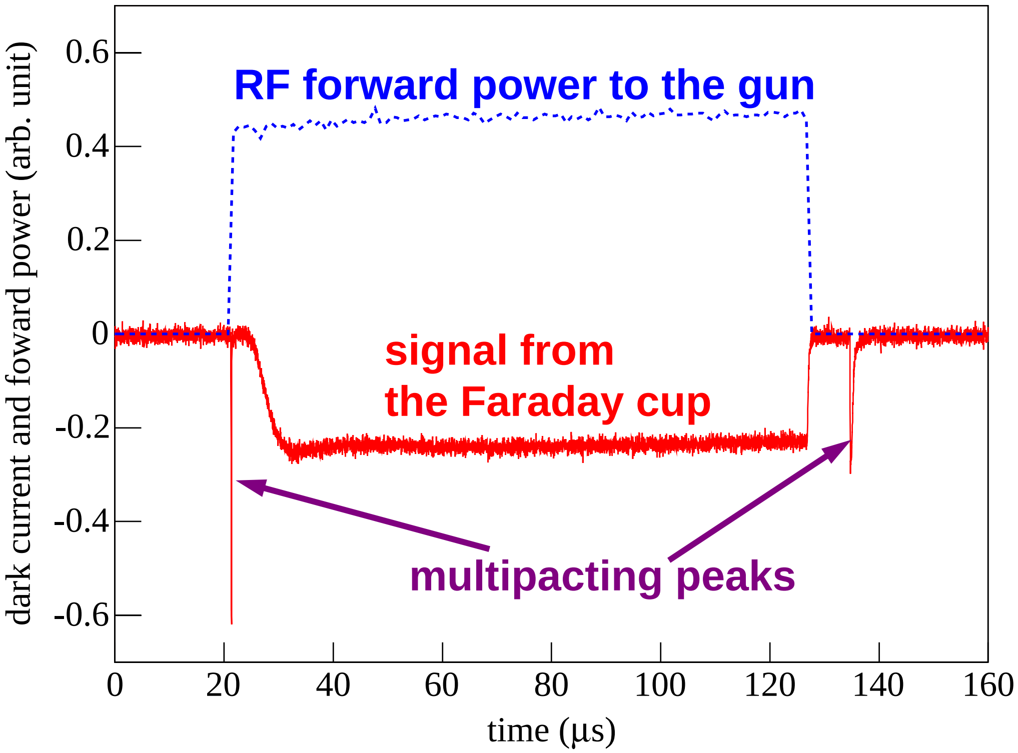


Observation at PITZ and TTF phase 1

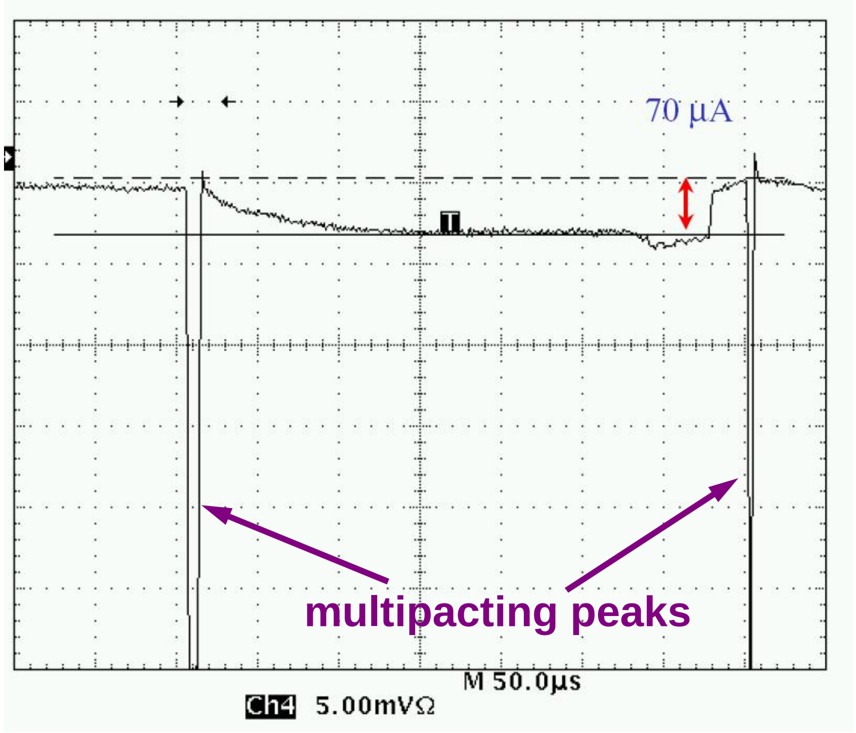
This multipacting has not been observed with Mo cathodes except for the case of very bad vacuum in the gun cavity.

→ Multipacting at the Cs_2Te photocathode

From D. Setore *et.al*., FEL2000

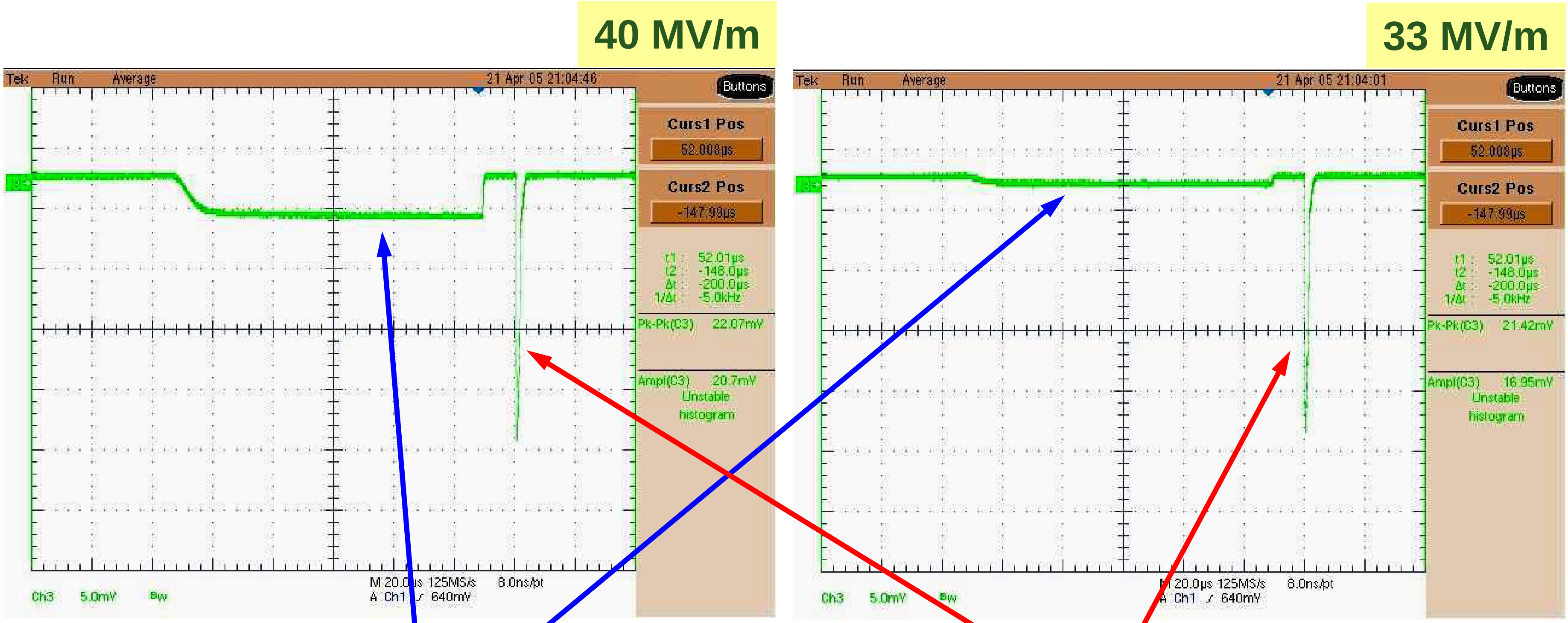


PITZ



TTF phase1

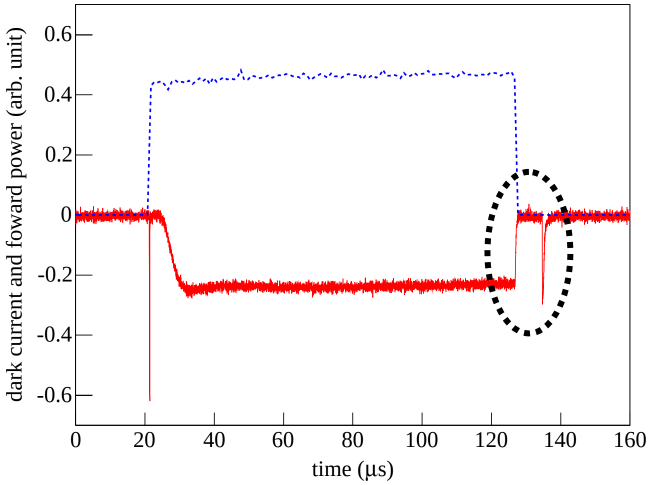
DC and multipacting vs. max RF gradient

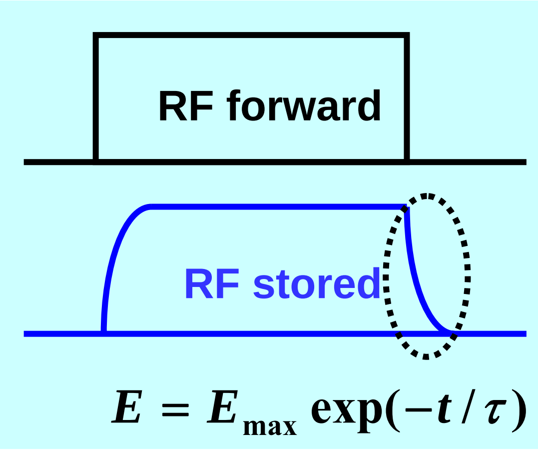


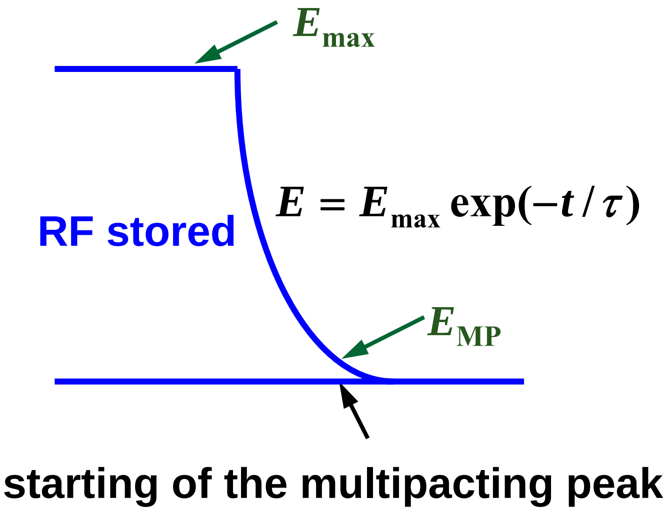
**Dark current following
the Fowler-Nordeim relation**

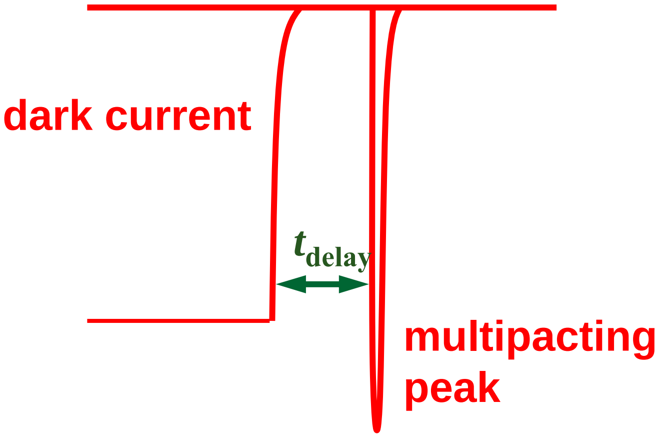
**Multipacting peak
Independent of the gradient**

Description of multipacting peak





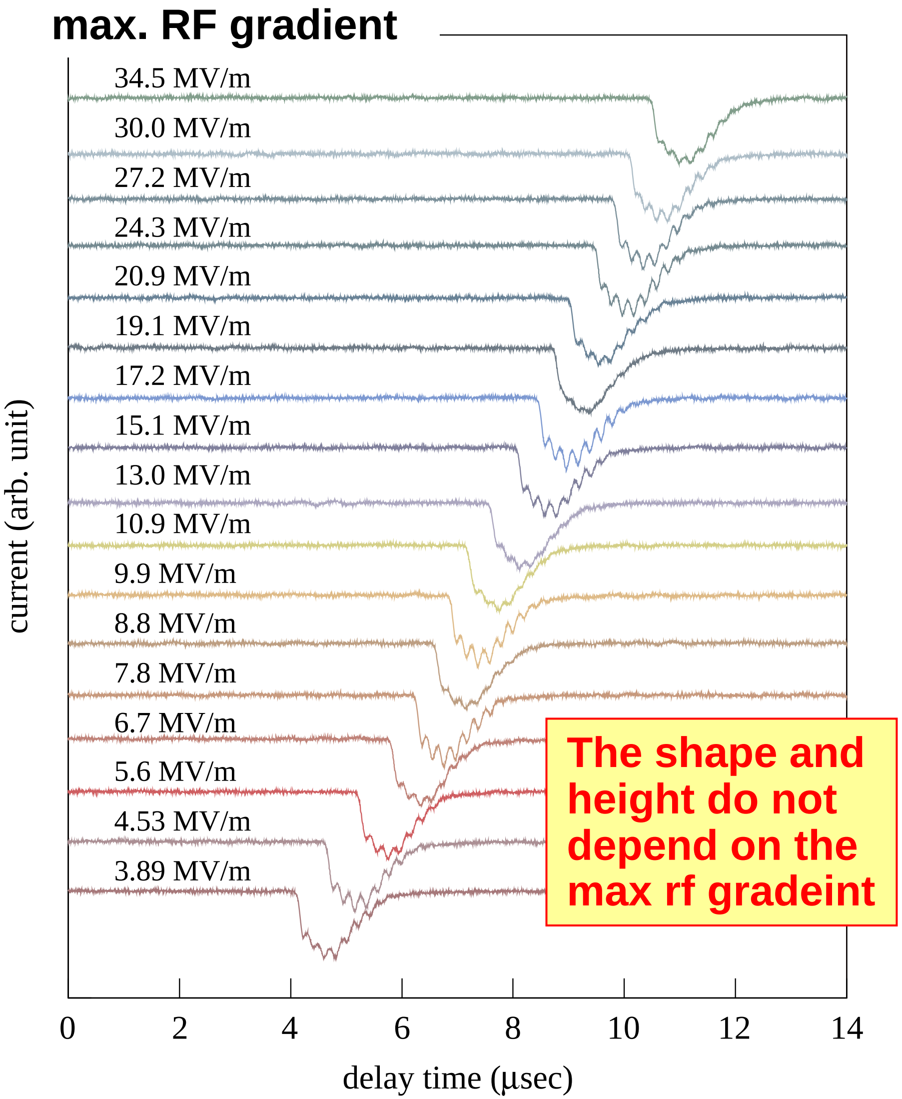




$$\boxed{\begin{aligned} E_{\mathrm{MP}} &= E_{\max} \exp(-t_{\mathrm{delay}}/\tau) \\ t_{\mathrm{delay}} &= \tau \ln E_{\max} - \tau \ln E_{\mathrm{MP}} \end{aligned}}$$

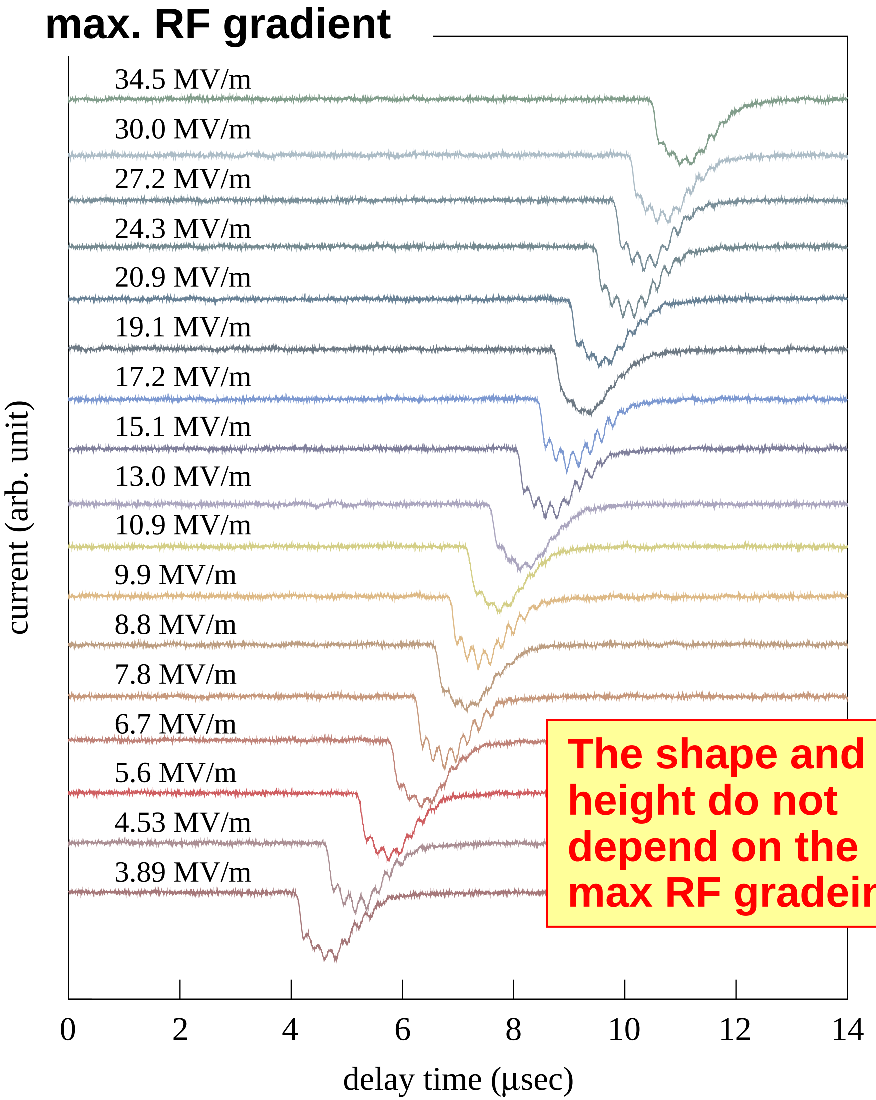
E_{MP}: RF field when the multipacting starts
$E_{\max}$: maximum field of the RF pulse
t_{delay} : the delay between the RF pulse and the multipacting peak
τ : fill/decay time of the RF field in the cavity

Delay time vs. max RF gradient

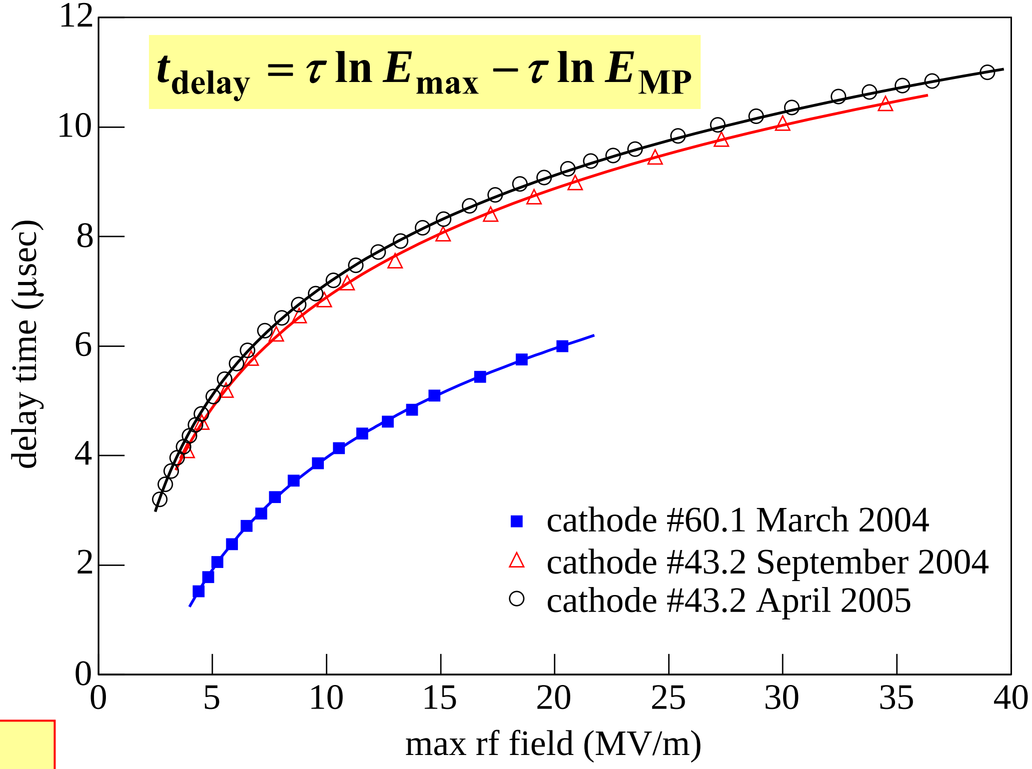


The shape and height do not depend on the max rf gradeint

Delay time vs. max RF gradient



The shape and height do not depend on the max RF gradeint

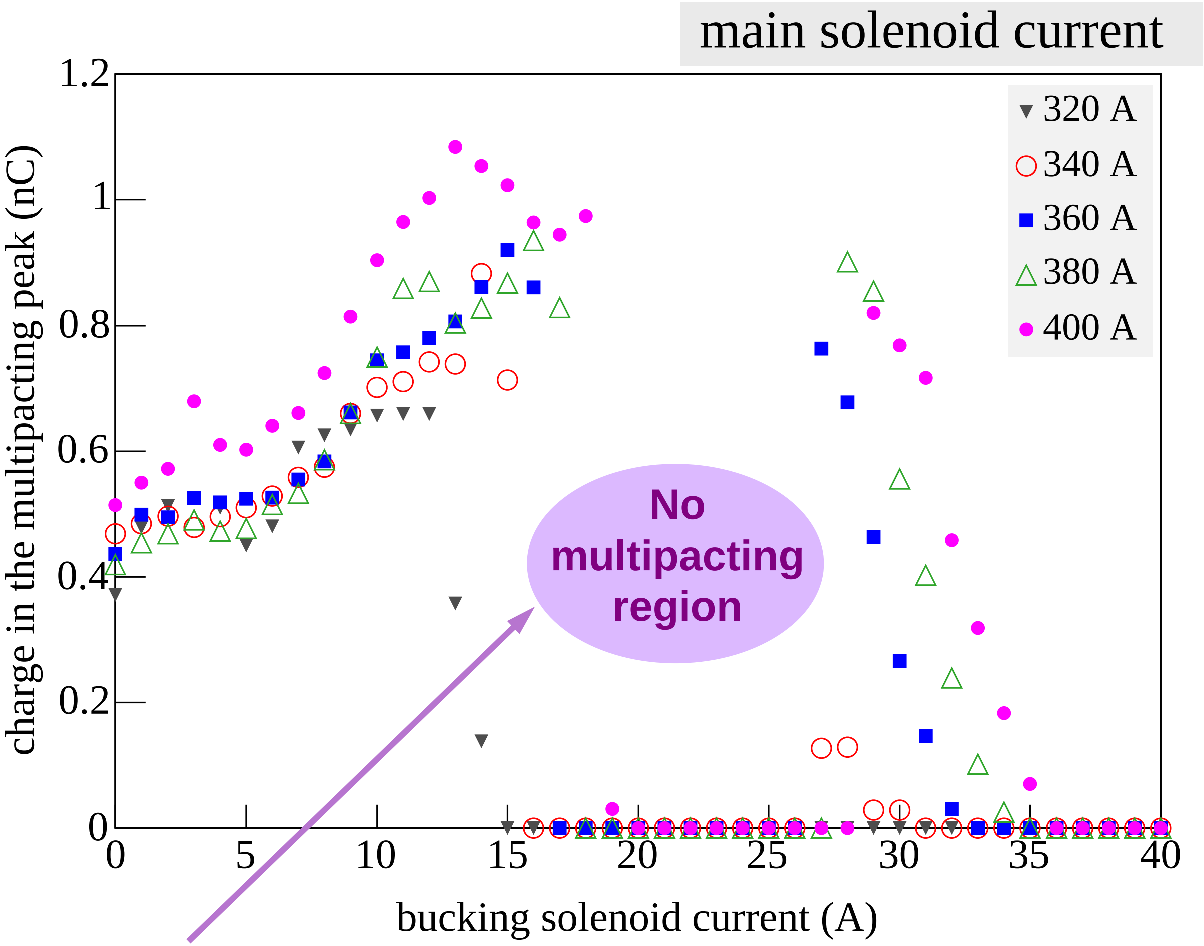


$$t_{\mathrm{delay}} = \tau \ln E_{\mathrm{max}} - \tau \ln E_{\mathrm{MP}}$$

cathode	#60.1	#43.2	
Meas. time	Mar.04	Sep.04	Apr.05
E_{MP} (MV/m)	2.70	1.04	1.07
τ (μs)	2.80	2.83	2.83

RF measurement in the cavity: 2.78 (μs)

Dependence on solenoid field profile

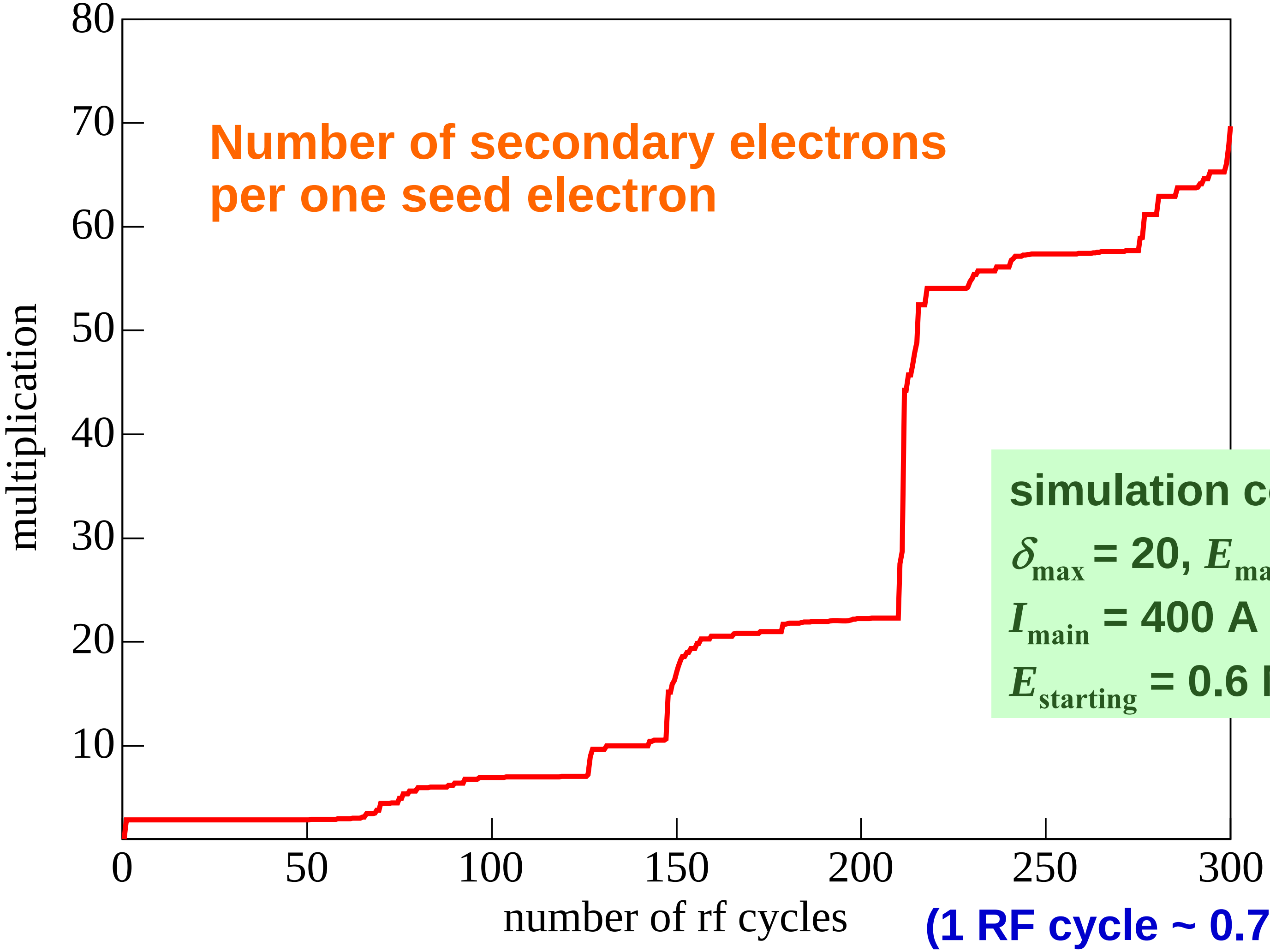


Strong dependence on the solenoid field profile

→ Magnetic mirror configured by the solenoid field plays a crucial role in generation of the multipacting.

Multipacting sometimes takes place in the region according to the cathode parameter and vacuum condition

ASTRA simulation of multiplication process



simulation conditions:

δ_{max} = 20, E_{max} = 1 keV, s = 2.2

I_{main} = 400 A & $I_{bucking}$ = 30.5 A

$E_{starting}$ = 0.6 MV/m, τ = 2.78 μs

(1 RF cycle ~ 0.77 ns)

Summary of secondary emission study

- The model implemented in ASTRA can simulate electron beam dynamics including secondary emission
- Multipacting takes place at the Cs_2Te photocathode at a low RF gradient (~1 MV/m) with a strong influence of the solenoid field configuration.
- For the typical operation conditions of the PITZ or VUV-FEL guns, multipacing does not take place.
- For the XFEL gun, the main solenoid will be located farther, therefore weaker multipacting is expected.
- RF guns using cathodes with higher secondary emission yield might have a serious problem of multipacting generation.

Conclusion

- The dark current at the photocathode RF guns has the main origin in field emission from the photocathode and the surrounding backplane.
- For the XFEL much higher dark current is estimated, therefore further study for reducing the amount is crucial.

- Since the strong RF field decreases the potential barrier for the electron emission, the kinetic energy of the emitted electrons increase with the RF strength.
- The thermal emittance for the PITZ gun has been analyzed and that for the XFEL gun has been estimated.

- A secondary emission model simulates successfully the beam dynamics for electron bunches with low charge and short length.
- The multipacting at the cathode has been measured systematically and analyzed with ASTRA simulation.

Outlook

- Since a transverse emittance lower than 1.0 mm mrad is required for the XFEL gun, a study in order to decrease thermal emittance at the high RF gradient is necessary.
- More study in order to reduce strong dark current, which is estimated at the high RF gradient (60 MV/m) in the XFEL gun, has to be made.