Emission mechanisms in photocathode RF guns

Jang-Hui Han (DESY)

3 June 2005

Research seminar, Experimental high energy physics,
Humboldt university

Motivation

- Electron beam quality in linear accelerators is determined at the gun.
- The emission processes in the gun limits the highest performance of the accelerator.
- Present understanding on the emission mechanisms is not sufficient to explain all empirical observations.

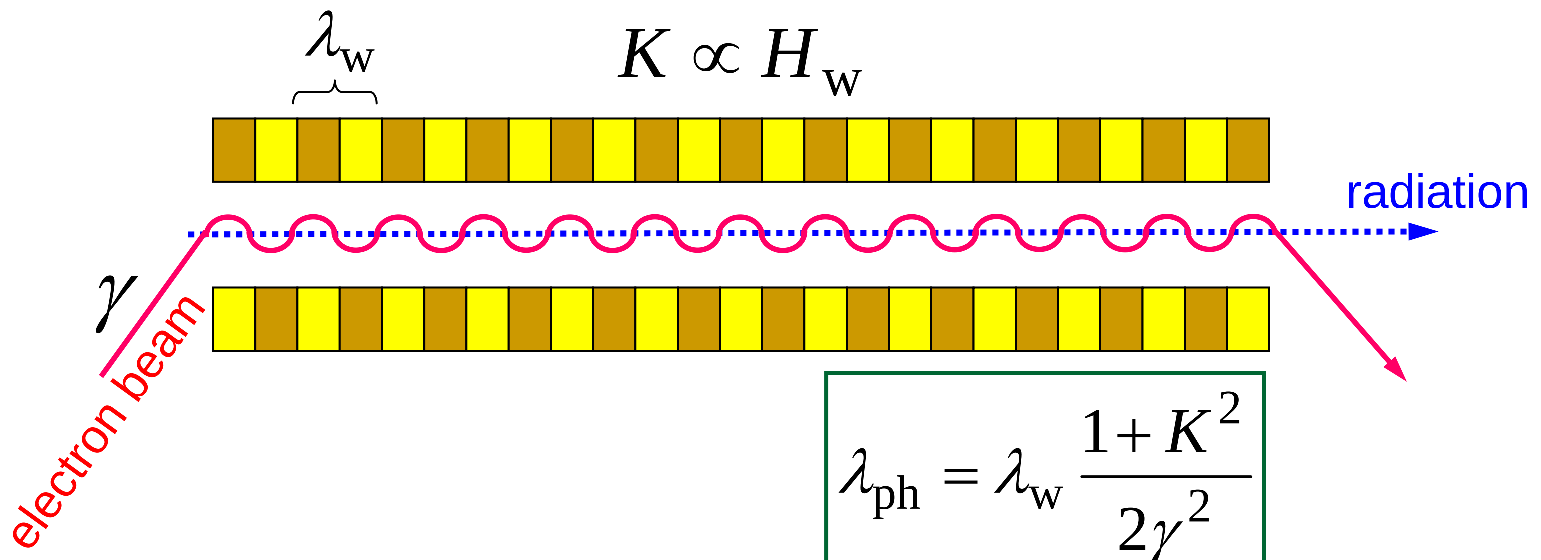
Contents

- FEL, SASE, TTF-FEL, PITZ
- Cs_2Te photocathodes
- Photoemission
- Secondary emission
- Field emission

Free-electron laser (FEL)

FELs are powerful sources of coherent EM radiation with high peak power and brightness.

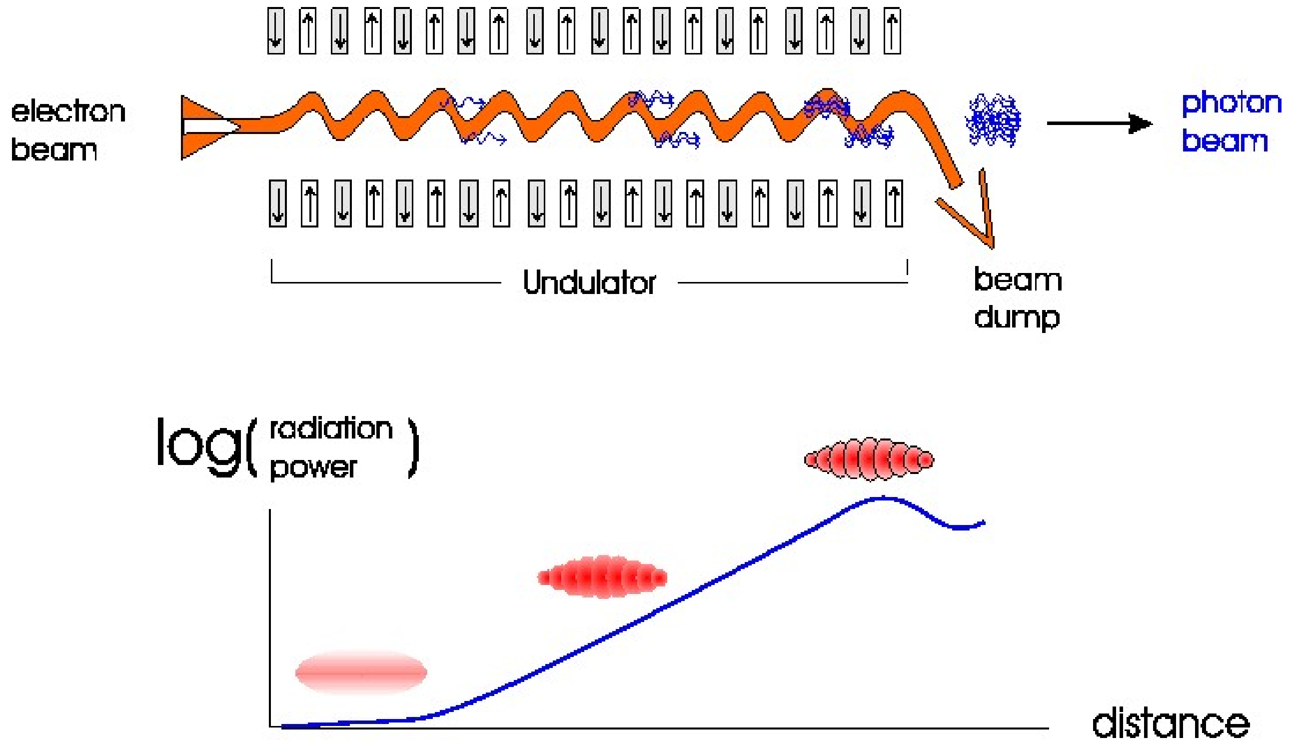
In a FEL, the magnetic field of the undulator magnet causes the electrons to oscillate transversely and generates the photons at resonant wavelength λ_{ph}.



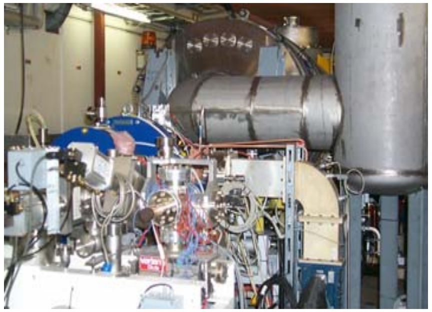
$$\lambda_{ph} = \lambda_w \frac{1+K^2}{2\gamma^2}$$

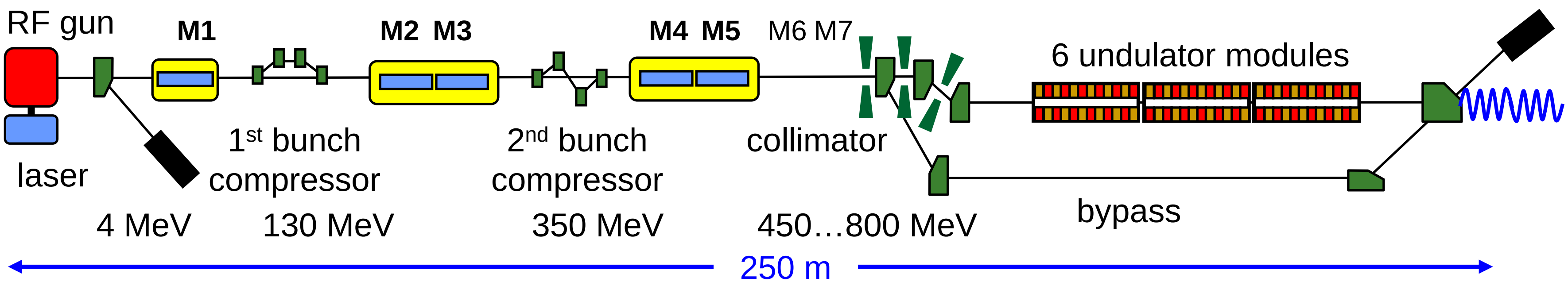
Self-amplified spontaneous emission (SASE)

At high phase space density of an electron bunch the FEL instability develops in a single pass through the undulator.

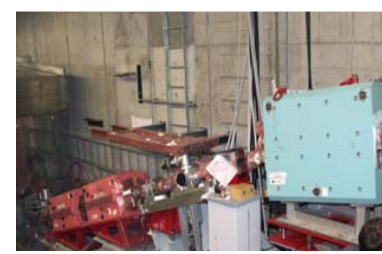


TESLA Test Facility (TTF) - FEL

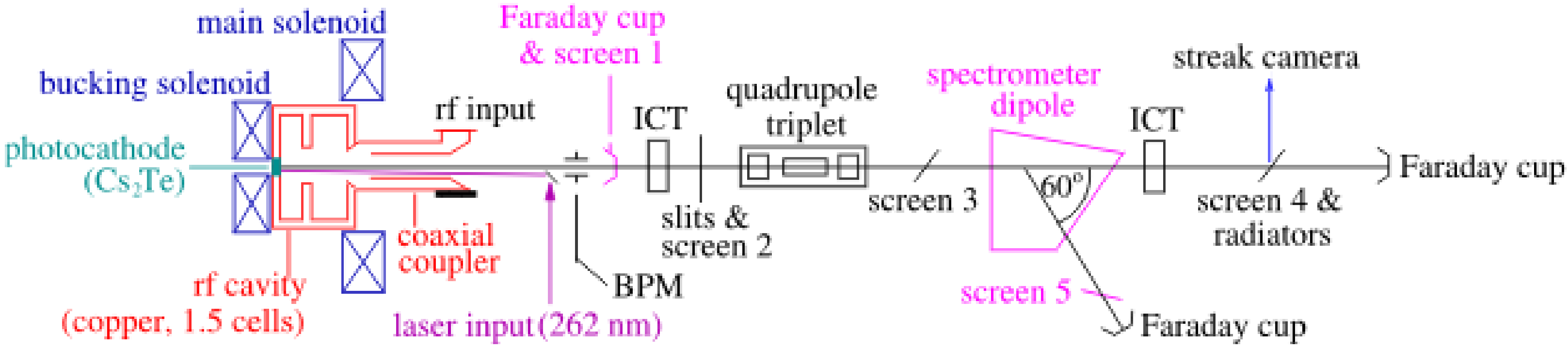


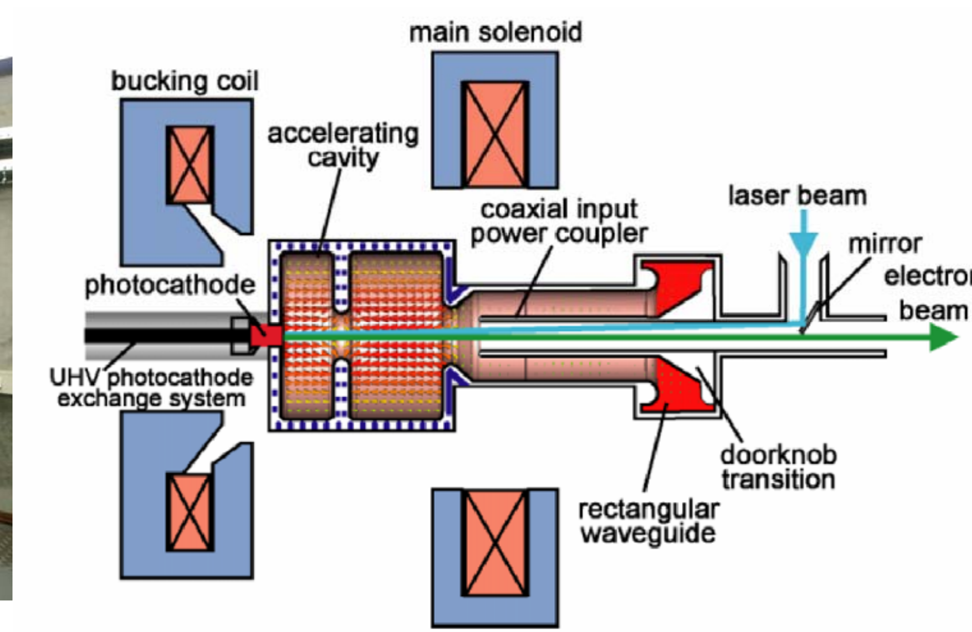





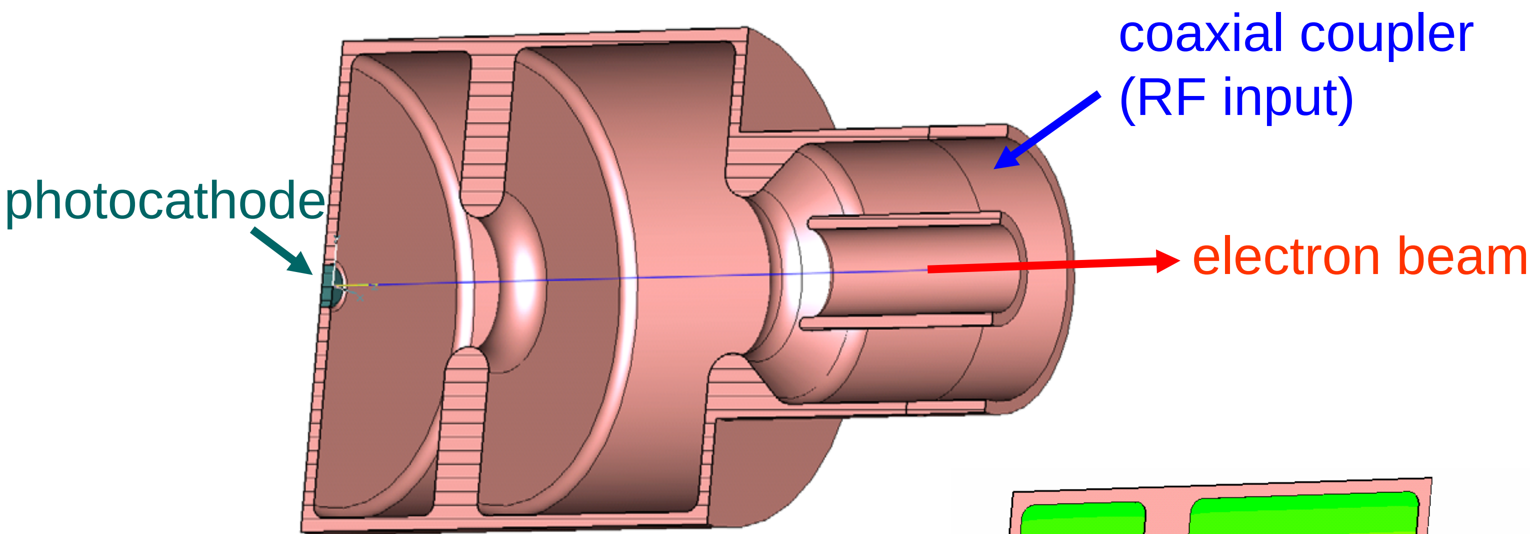



Photoinjector Test Facility (PITZ)

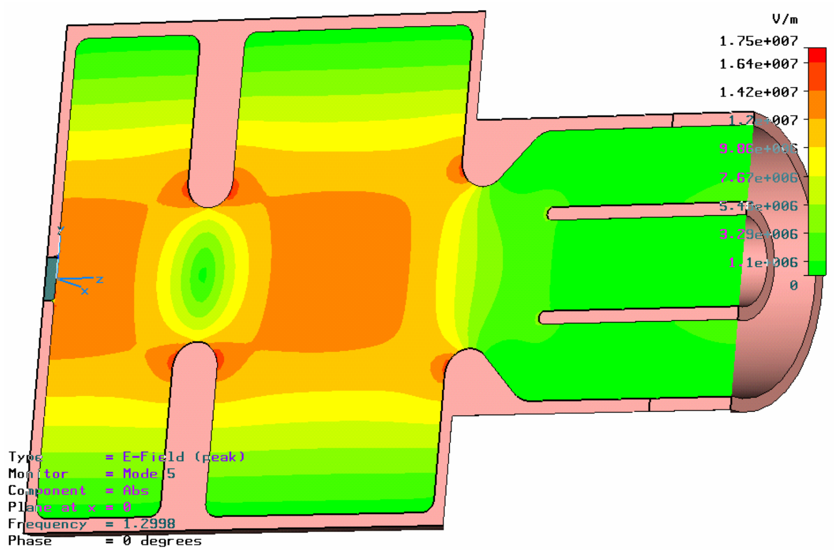




Gun cavity

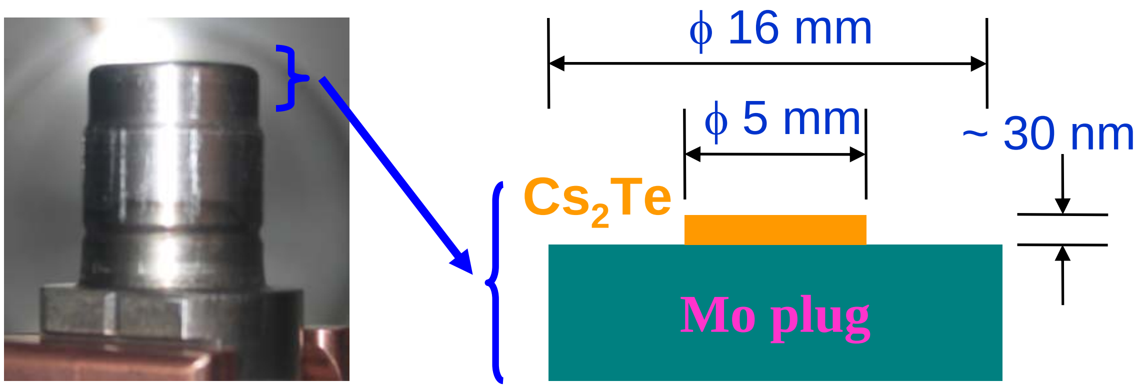


cavity geometry

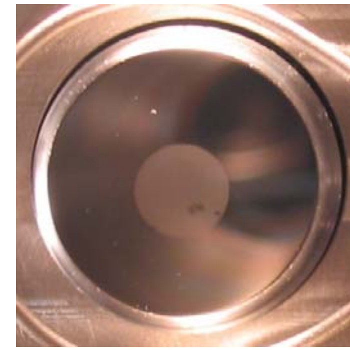


absolute RF field in the cavity

Cs_2Te photocathode



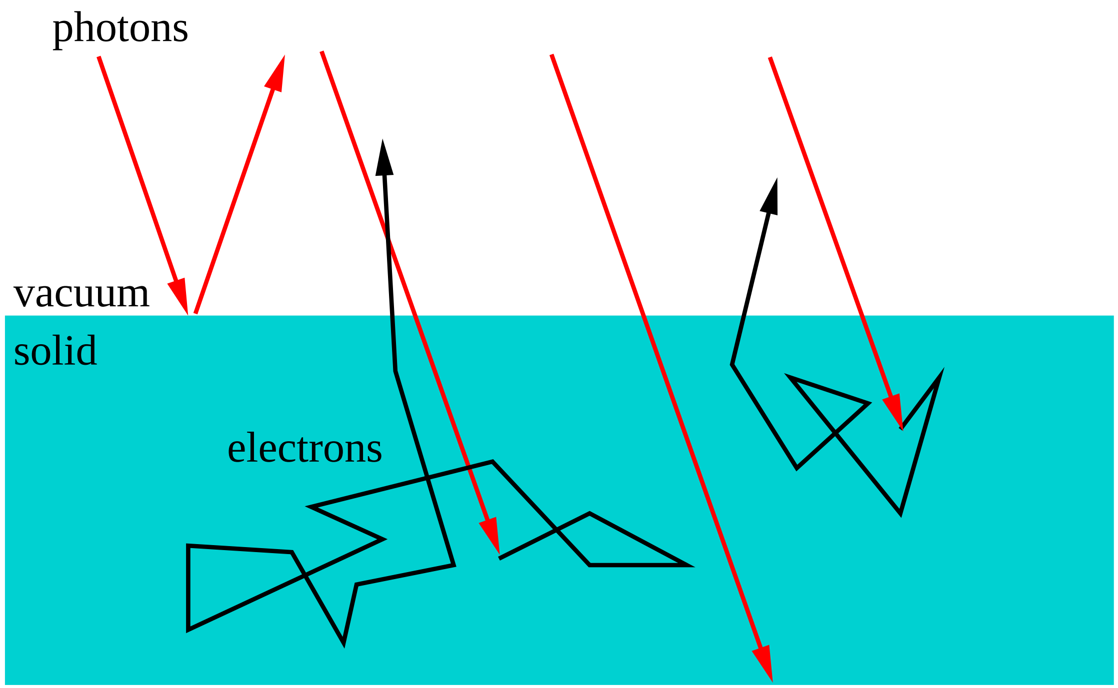
side view of the cathode plug


top view of the cathode

Why Cs_2Te?

- High quantum efficiency
  ~ 10% for fresh one
  ~ 0.5% for used one in normal operation (still enough)
- Long lifetime ~ several months

Photoemission process



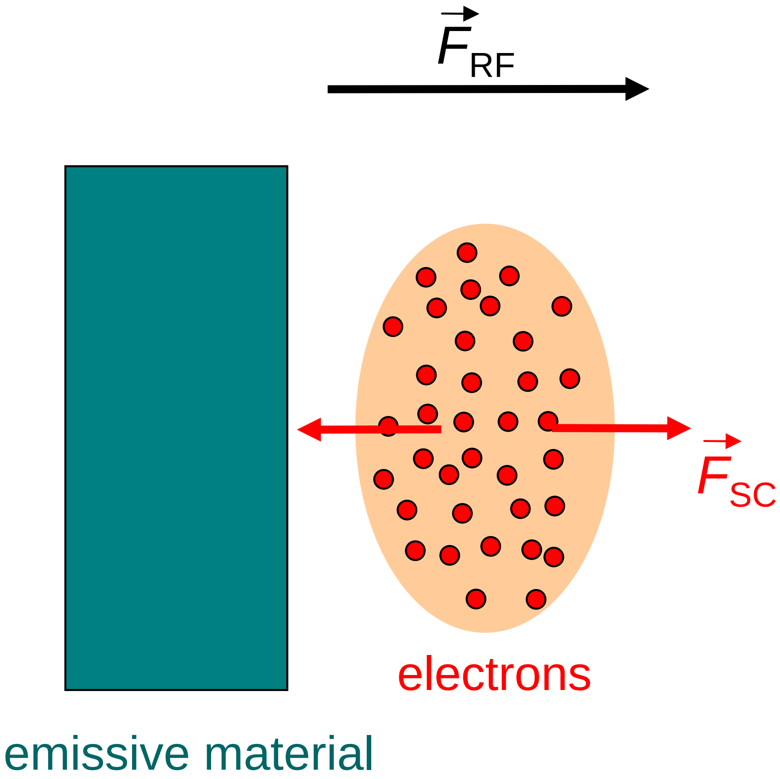
Process of photoemission:

(1) absorbed photons deliver their energy to electrons in the material

(2) the motion of the energized electrons through the material, losing some of their energy

(3) the escape of the electrons over the surface barrier into vacuum

Space charge force during the emission



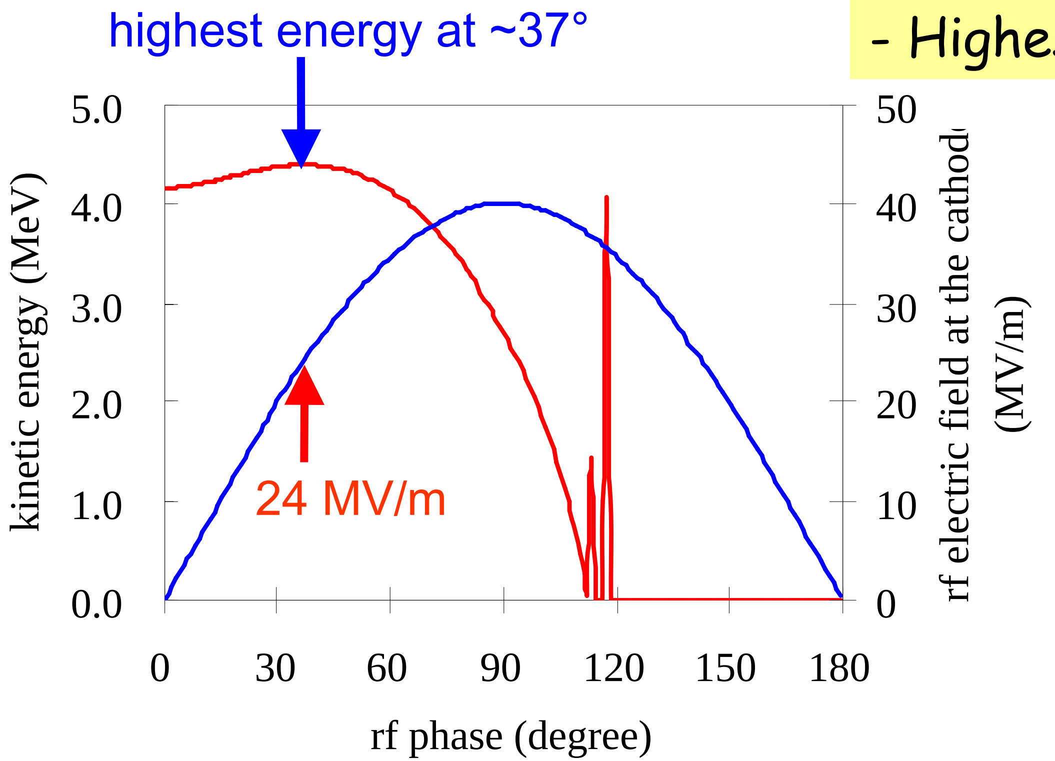
When F_{SC} is greater than F_{RF}, the electrons travel backward and cannot escape from the material.

At the PITZ operation condition, the RF field is typically on the order of 10 MV/m.
With the bunch charge of 1 nC, the space charge field induced the emitted electrons is comparable to the RF field.

Laser driven electron emission in RF guns

Operating RF phase at 40 MV/m: 37°

- Smallest transverse emittance
- Highest energy



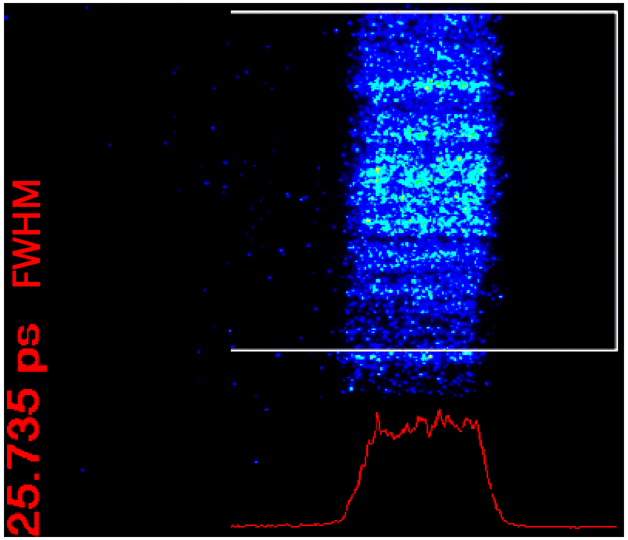
RF electric field at the cathode and kinetic energy of the beam after gun Vs. RF phase

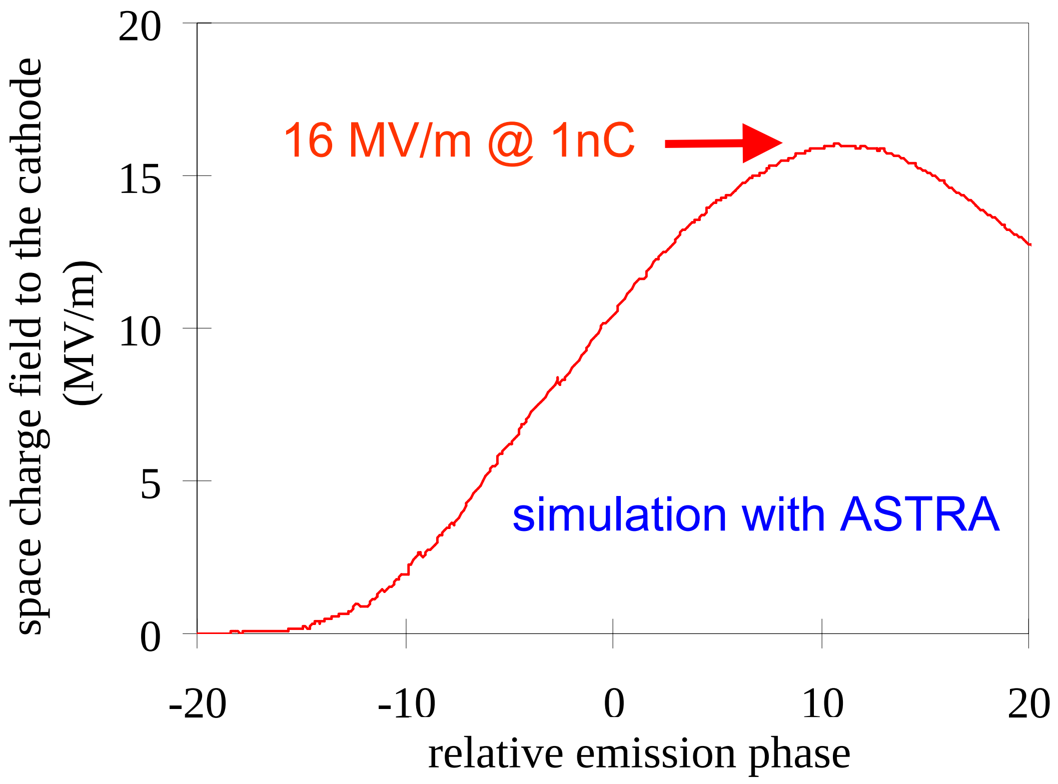
RF longitudinal electric field at the cathode during electron beam emission

= 40 (MV/m) * sin (37°)
= 24 (MV/m)

Longitudinal space charge field

longitudinal laser profile taken with a streak camera



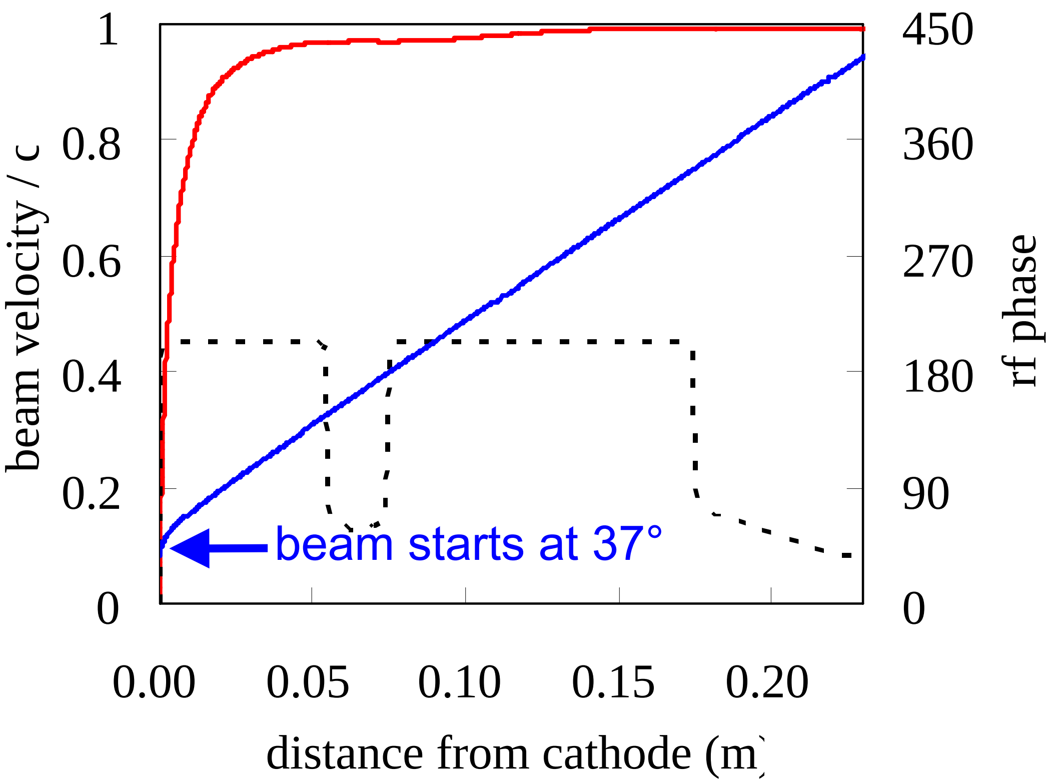


Transverse laser size:

$x_{rms} = y_{rms} = 0.5$ mm

longitudinal space charge force to the cathode

Synchronization between electron beam and E_z in full cell

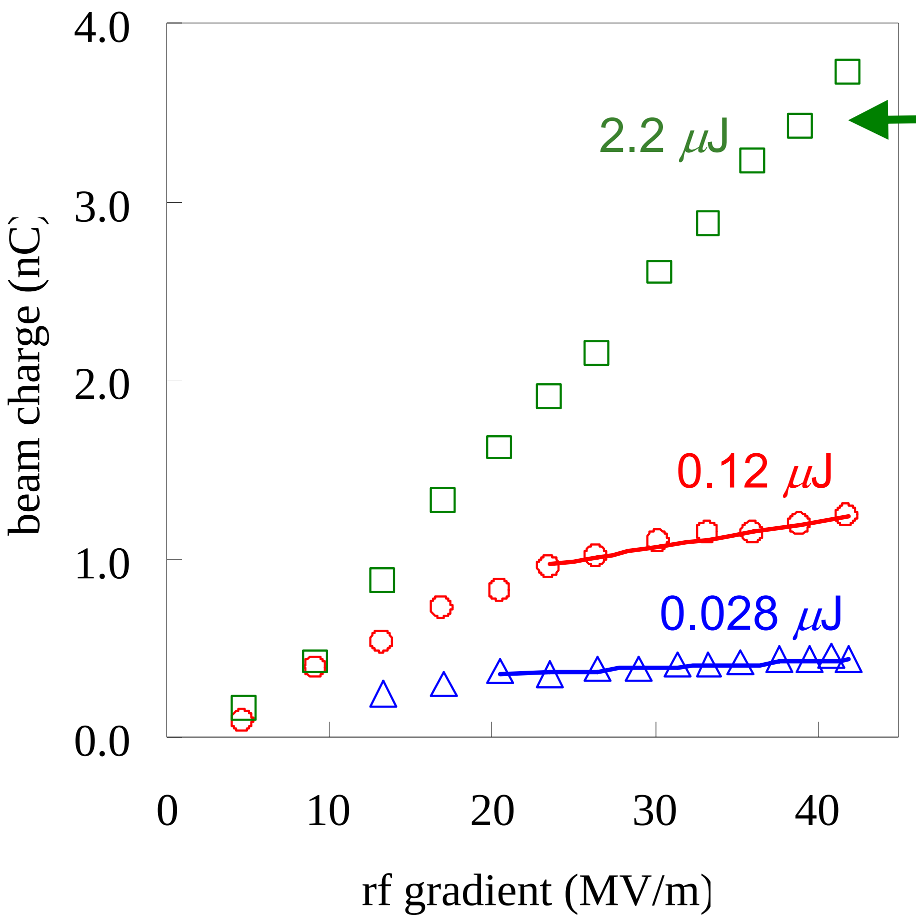


beam velocity and RF phase advance
Vs. distance from cathode

Beam velocity in the half cell is much smaller than the speed of light.

→ to synchronize electron beam and the longitudinal electric field in the full cell, the electron beam has to start earlier than 90°

Bunch extraction from the gun



beam extraction from gun cavity;
two lines are the Schottky effect fits.

Space charge force is still higher than the RF electric field.

→ Some electrons emitted by the laser hit back the cathode.

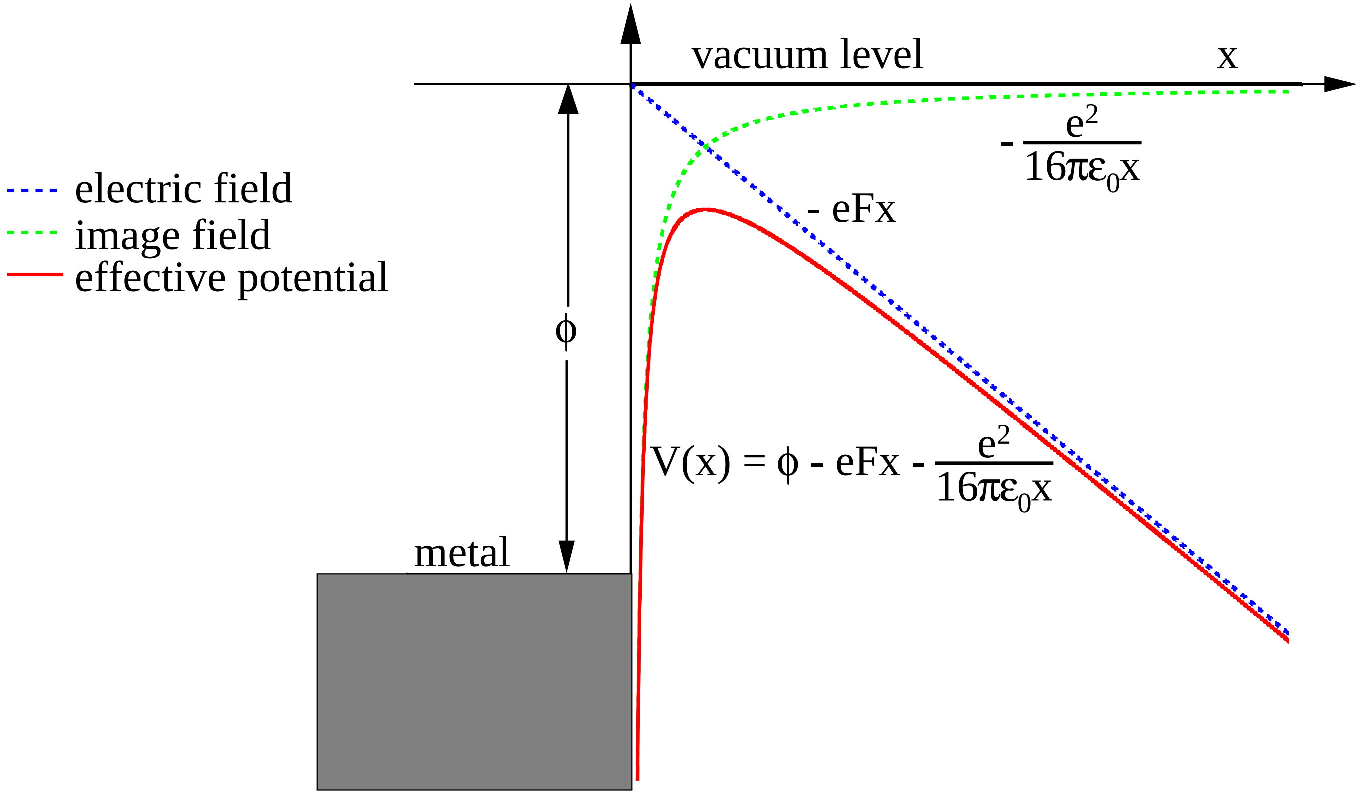
→ Secondary electron can be generated!

At low gradient region the Schottky effect fits do not work because the longitudinal space charge field effect is dominate.

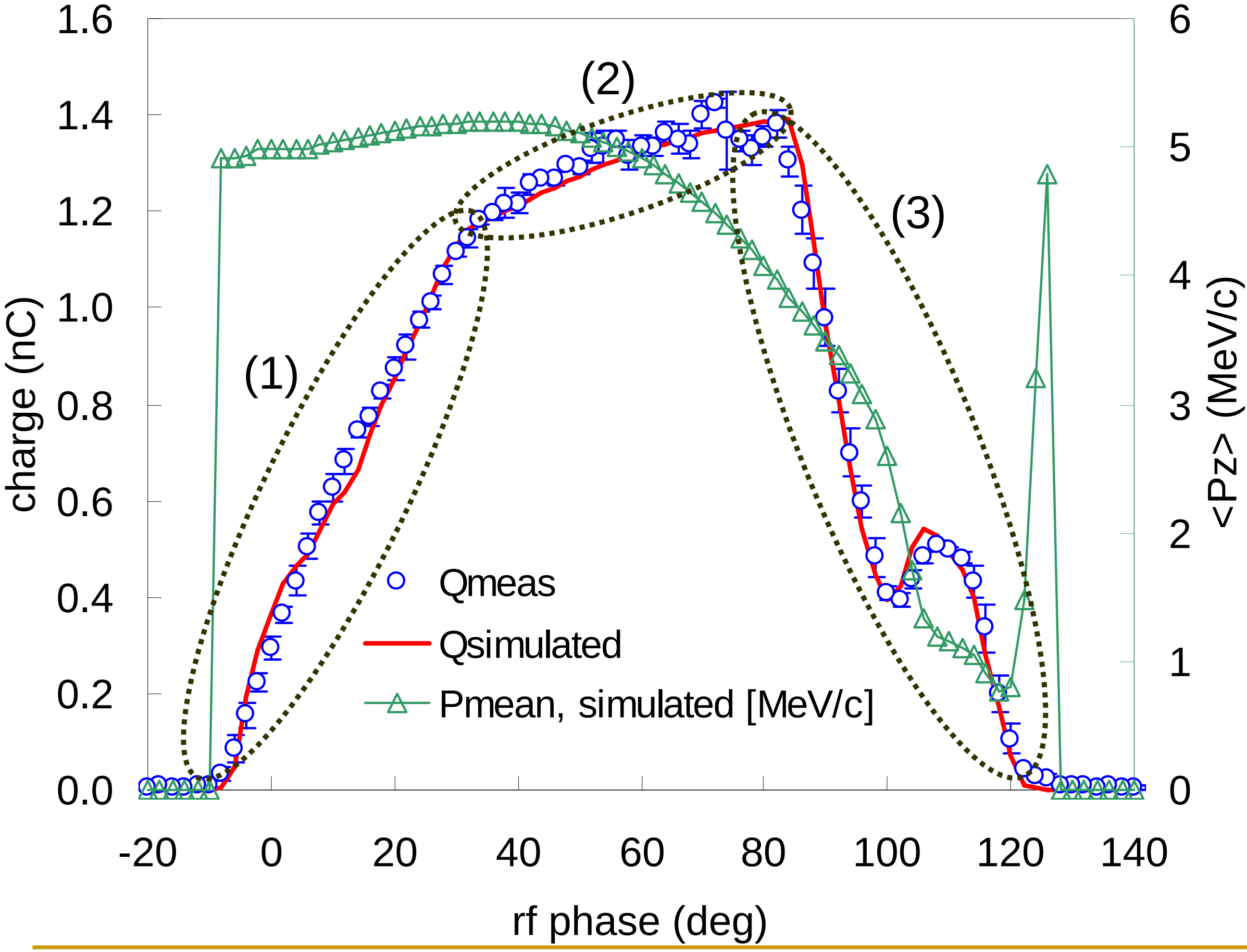
Schottky effect

Under the RF field, the surface barrier of the emissive material is deformed to be lower.

The generated electrons can be liberated to the vacuum more easily.



Measurement of the charge and momentum vs. the emission phase



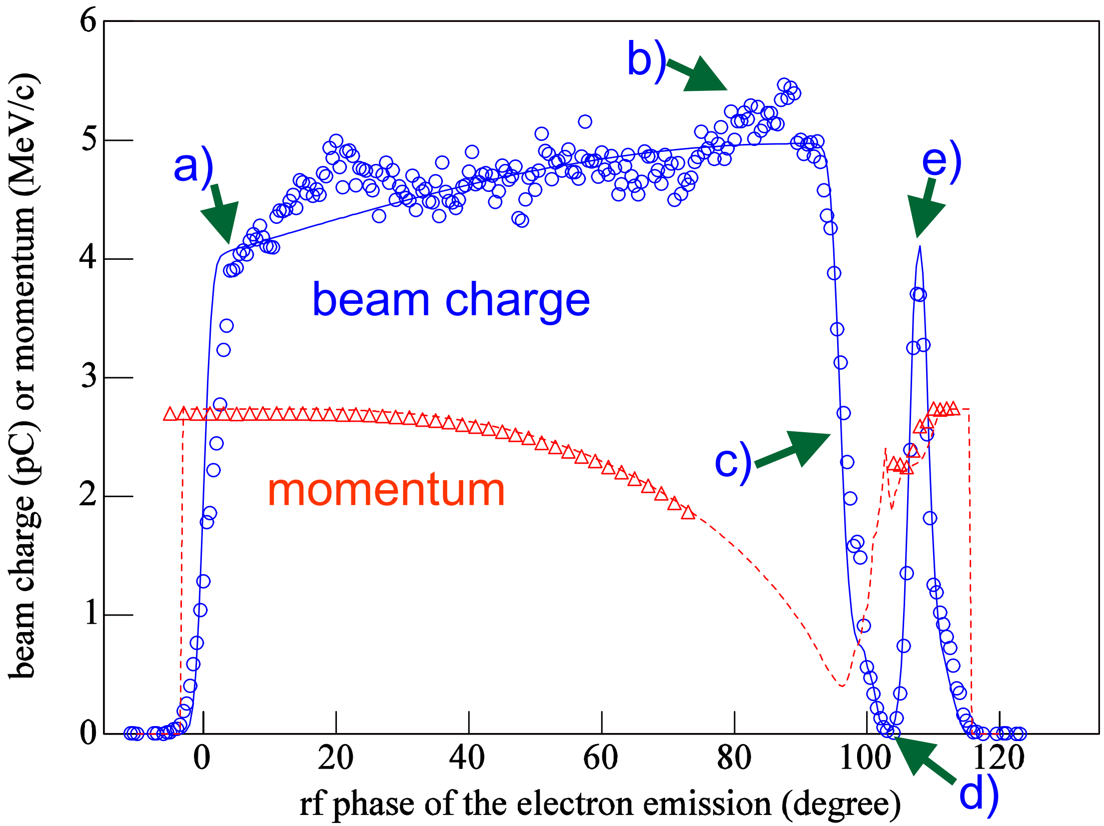
(1) Space charge dominated

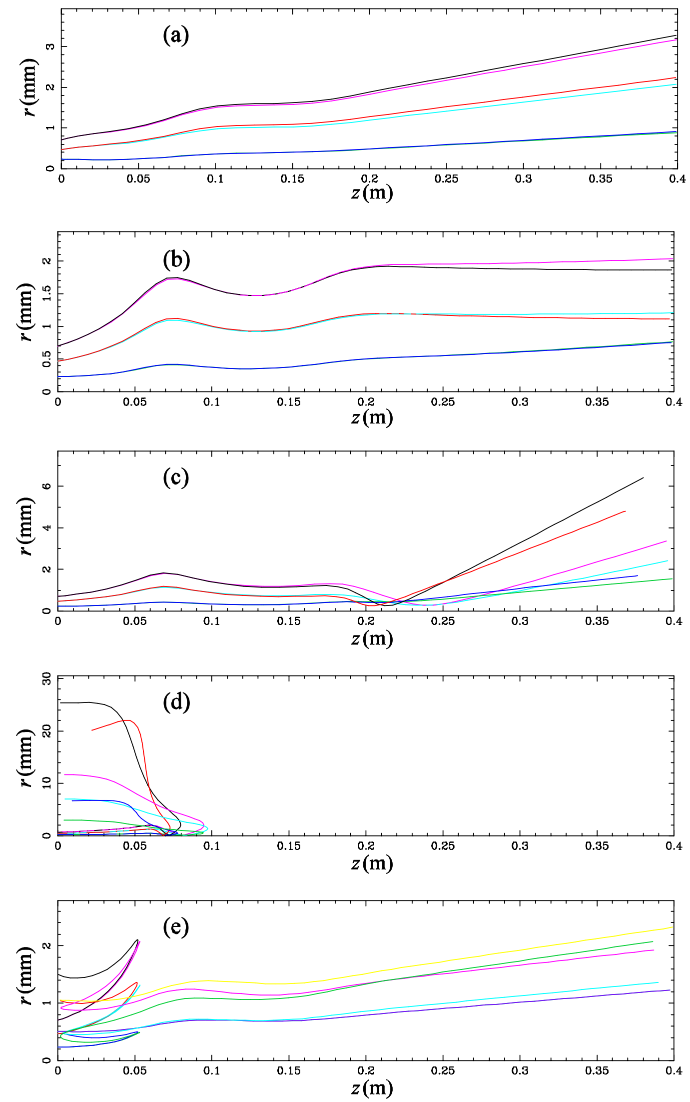
(2) Schottky effect dominated

(3) Aperture effect

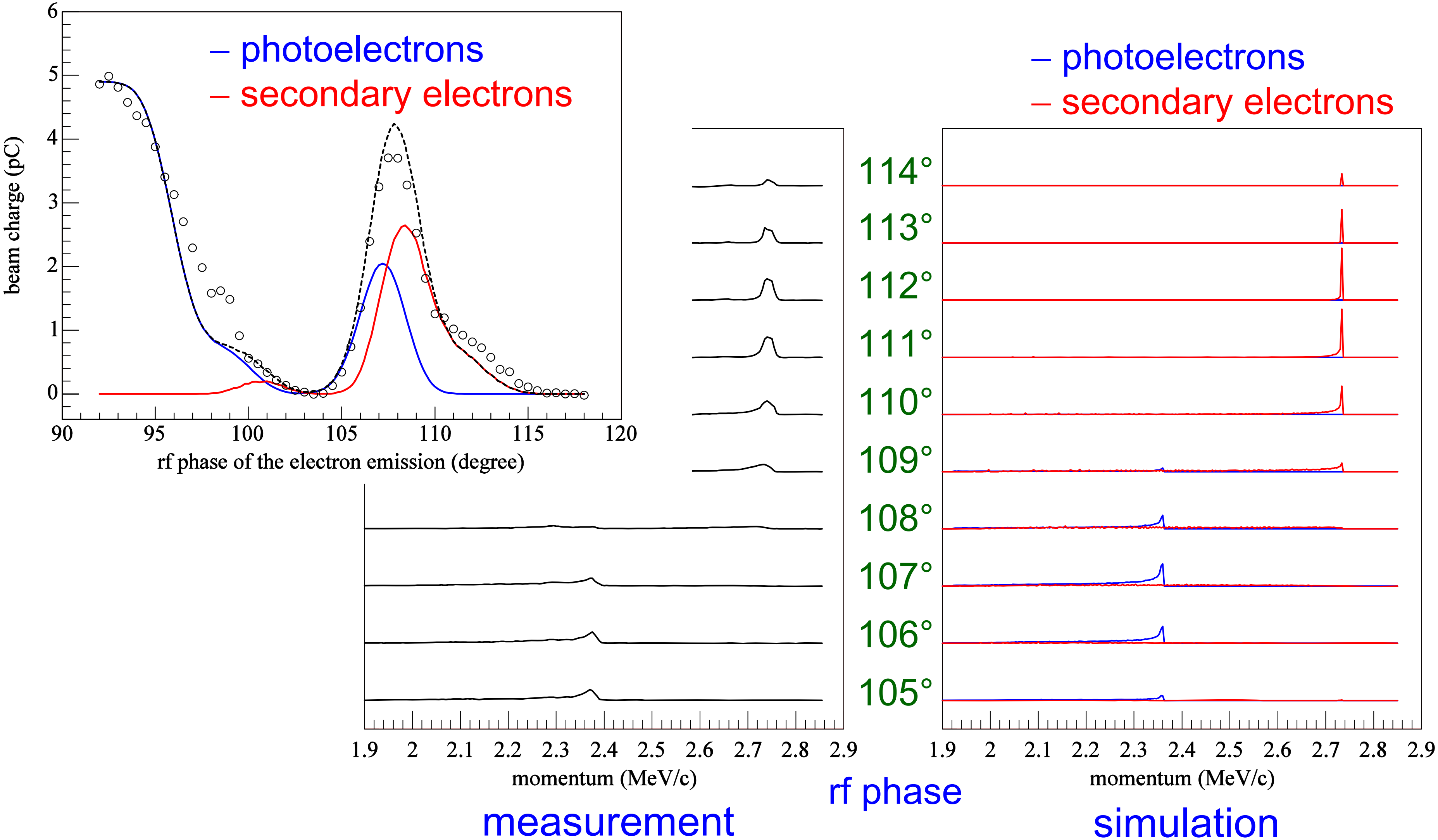
Beam dynamics at low charge

Beam charge: max. 5 pC, Gradient: 21 MV/m

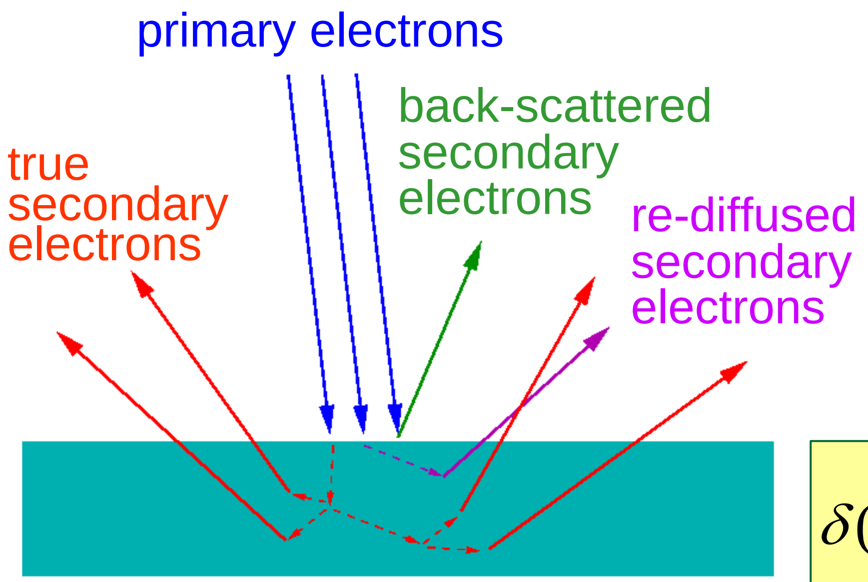




Secondary electrons in the RF gun



Secondary electron emission



secondary emission mechanism

secondary emission yield (δ):

$$\delta = \frac{\text{\# of secondary electrons}}{\text{\# of impact (primary) electrons}}$$

δ dependence on the primary energy:

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

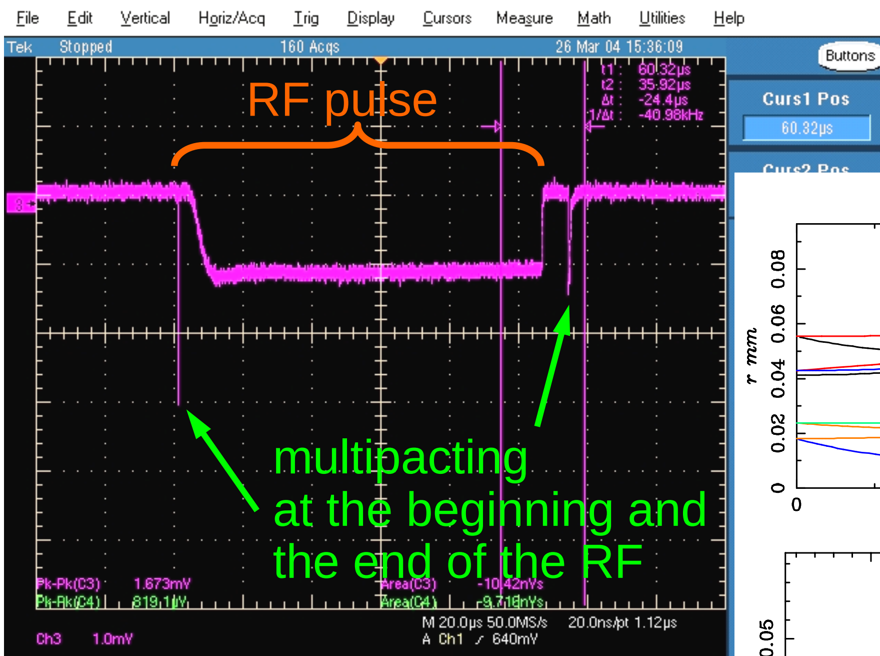
Emission of true secondary electrons:

(1) Production by kinetic impact of the primary electrons

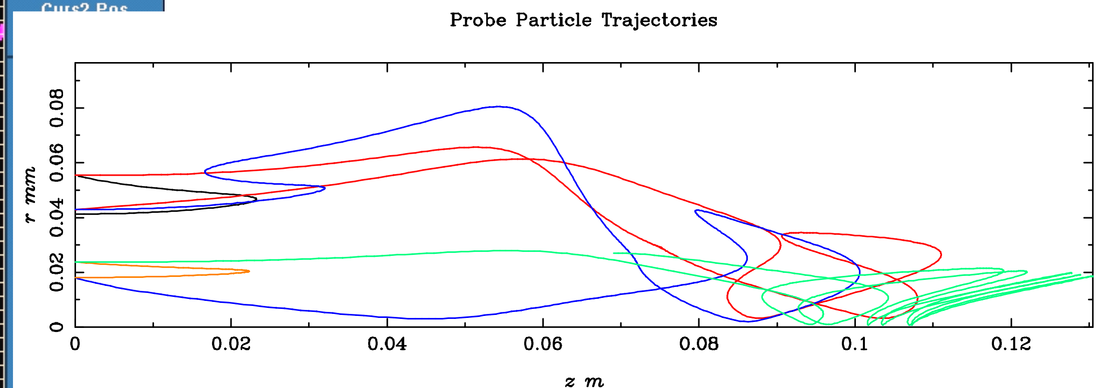
(2) Transport toward the surface

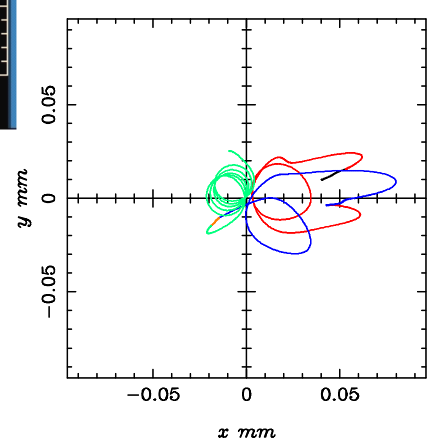
(3) Escape through the solid-vacuum interface

Multipacting at the cathode



measured multipacting





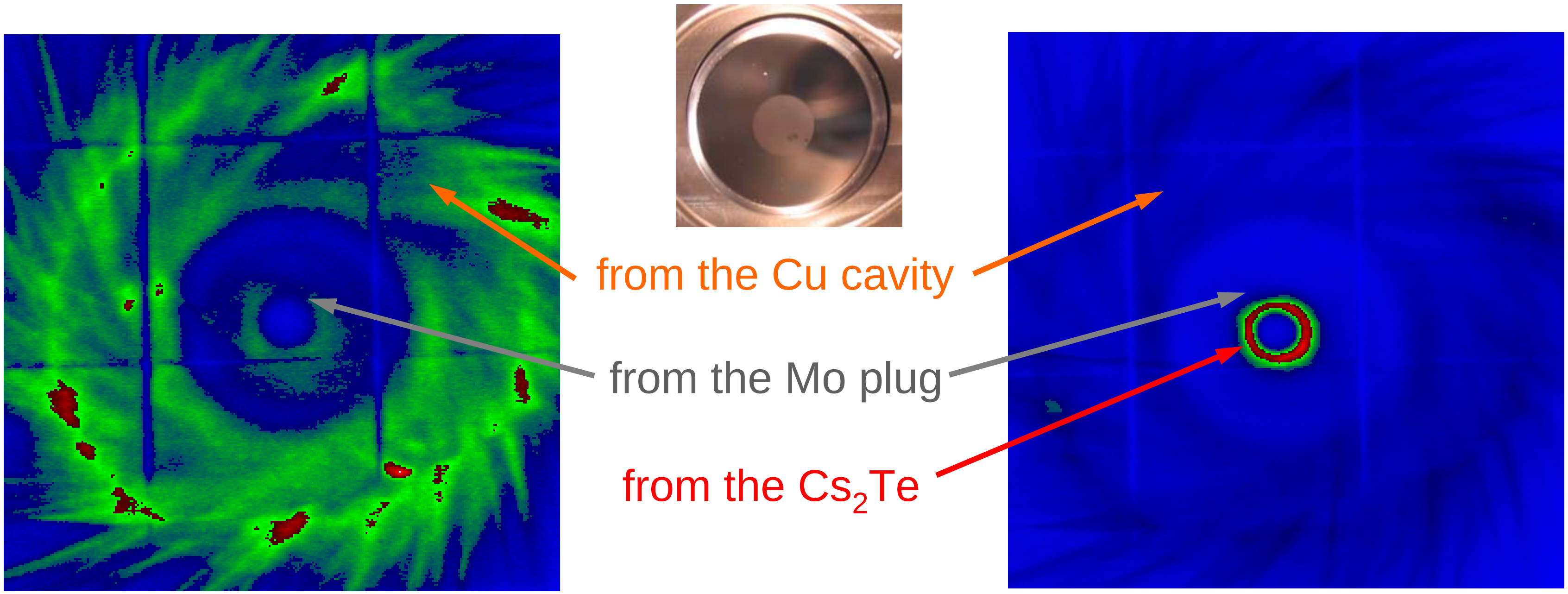
- photo-emitted electron
- 1st generation
- 2nd generation
- 3rd generation
- 4th generation

secondary electrons

simulated multipacting on cathode

Field emission

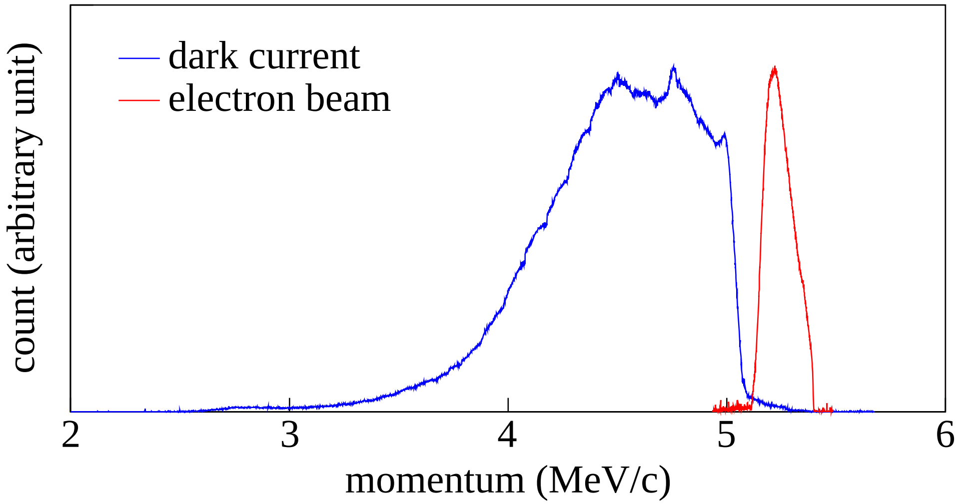
Even in the absence of the drive laser, electrons are generated with the high RF field.
This is un-wanted signal and called “dark current”.



Dark current from the Mo cathode plug and the Cu cavity

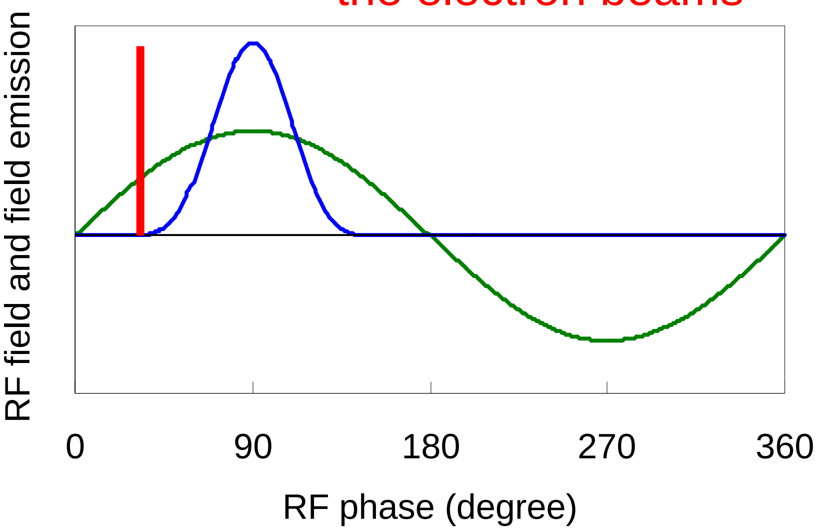
Dark current from the Cs_2Te cathode, the Mo cathode plug and the Cu cavity

Dark current and beam spectra



Spectra of the dark current and the electron beams

Emission phases of the dark current and the electron beams



Small part of the dark current overlaps with the electron beam. Nevertheless, the small part can survive till the end of the accelerator and make a damage at several vacuum components.

Summary

- Photo-emission process is determined with the space charge force as well as the Schottky effect.
- Secondary electrons are generated by electron beams or field emitted electrons. In the former case, the secondaries can arise with the beam. In the latter case, multipacting can take place.
- The geometry and the material of the cathode influence the dark current generation.
- The understanding of the emission processes is crucial for the next generation electron gun required for SASE-FEL or linear colliders.