Modeling of the secondary electron emission in rf photocathode guns

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Accelerator Physics Seminar

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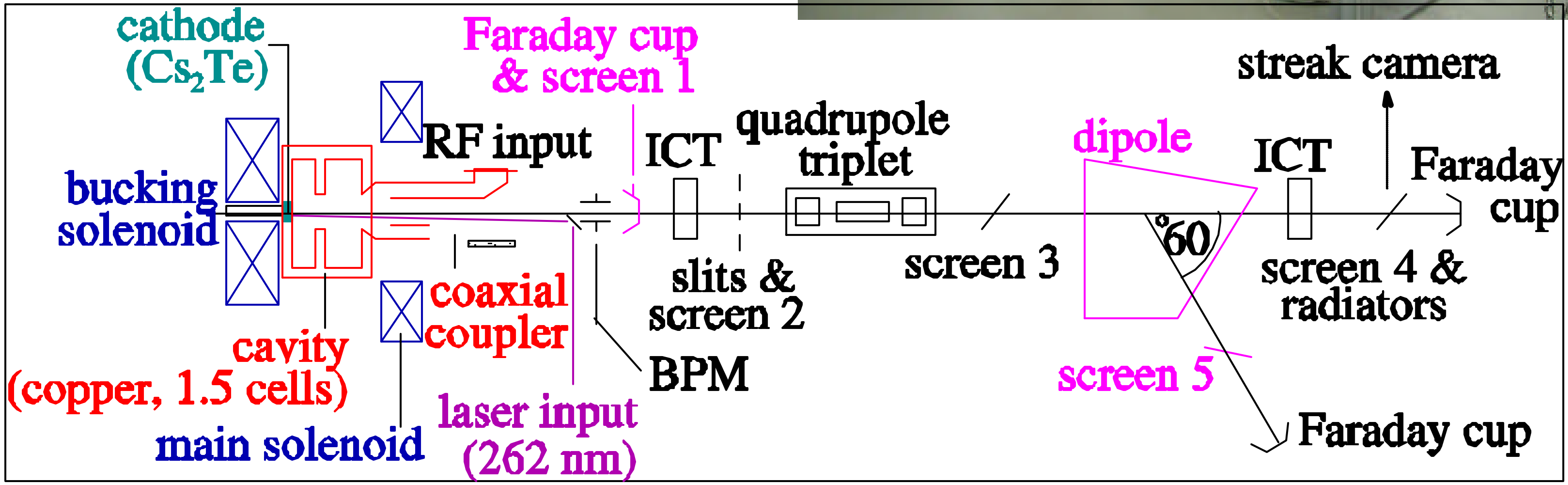
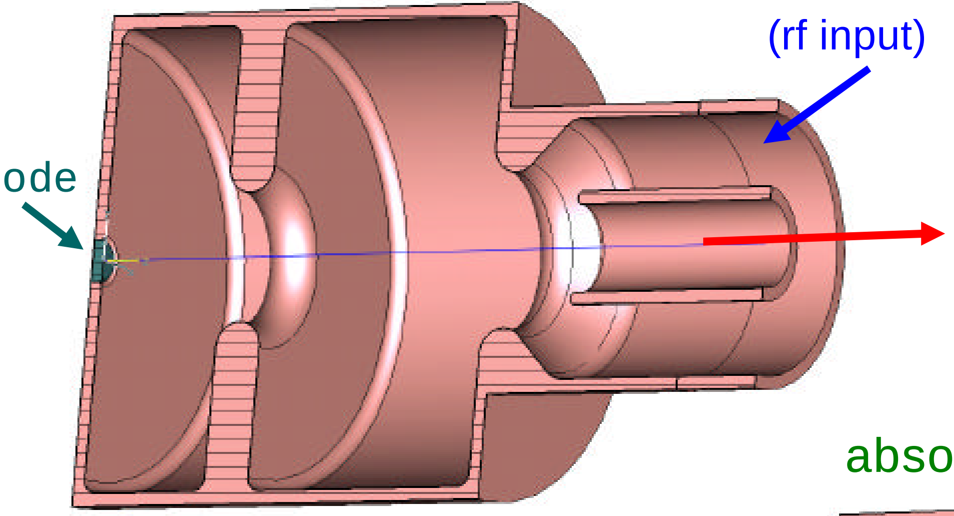
Photoinjector Test facility at DESY Zeuthen (PITZ)

- Test facility for FELs
  ⇒ 1 π mm mrad @ 1 nC
  with stable operation
- Extensive R&D on photoinjectors in parallel with TTF operation



Gun cavity



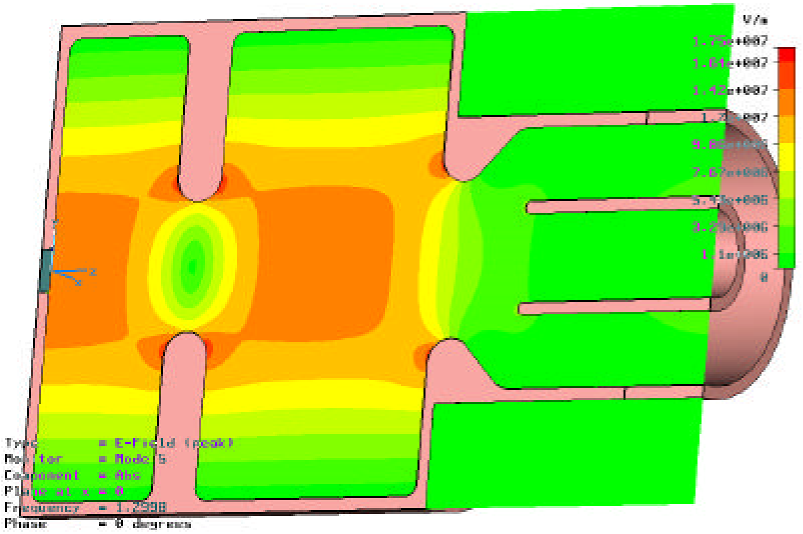
coaxial coupler
(rf input)

photocathode

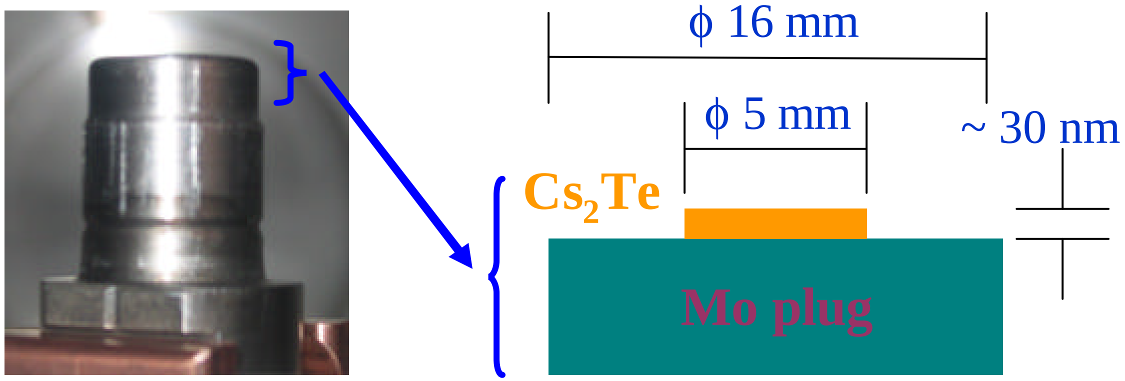
beam injection
to the downstream

cavity geometry

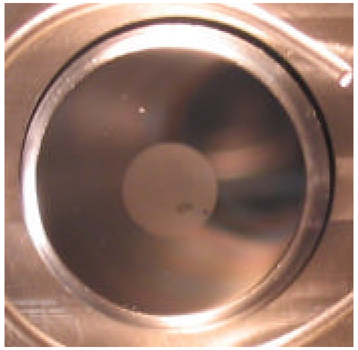
absolute electric field in the cavity



Cs_2Te photocathode



side view of the cathode plug

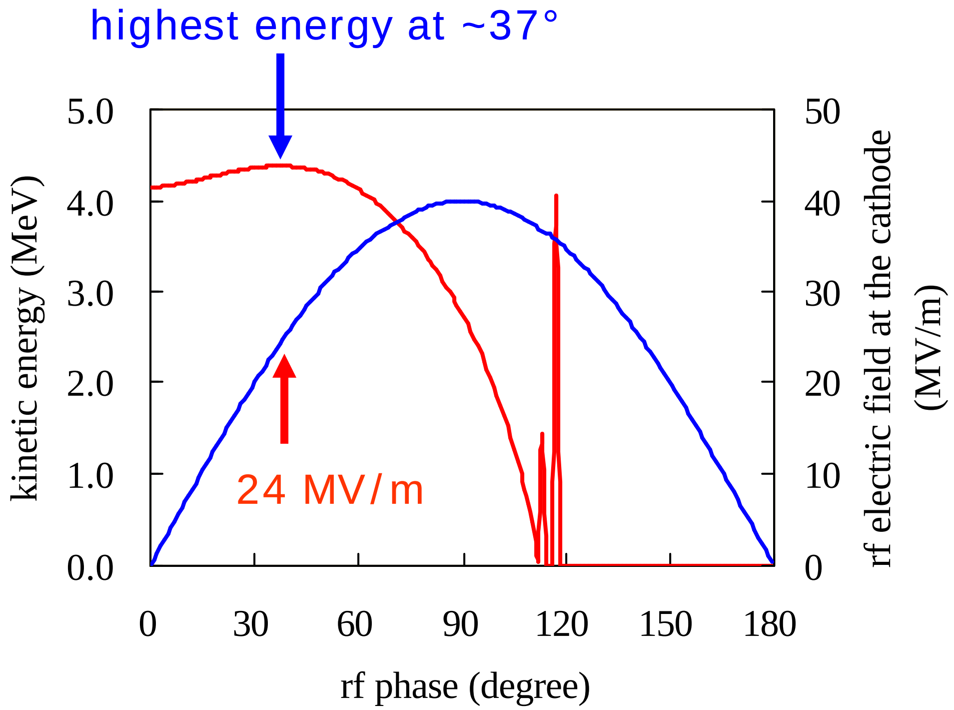


top view of the cathode

Why Cs_2Te?

- Relatively high electronic band gap (3.3 eV)
  → Low thermalization of the photoexcited electrons
- Low electronic affinity (0.2 eV)
  → Easy for electron escape to the vacuum
- High quantum efficiency
  ~ 10 % for fresh one,
  ~ 0.5 % for used one in normal operation

Laser driven electron emission in rf gun



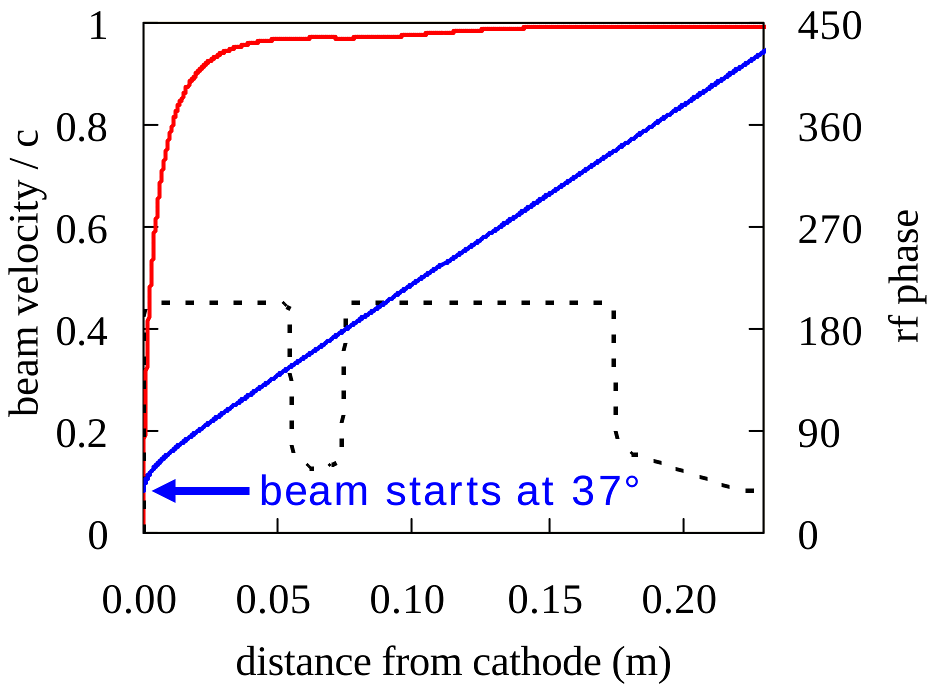
rf electric field at the cathode and kinetic energy of the beam after gun Vs. rf phase

Operating rf phase at 40 MV/m: 37°

highest energy
smallest transverse emittance

rf longitudinal electric field at the cathode during electron beam emission
= 40 (MV/m) * sin (37°)
= 24 (MV/m)

Synchronization between electron beam and E_z in full cell



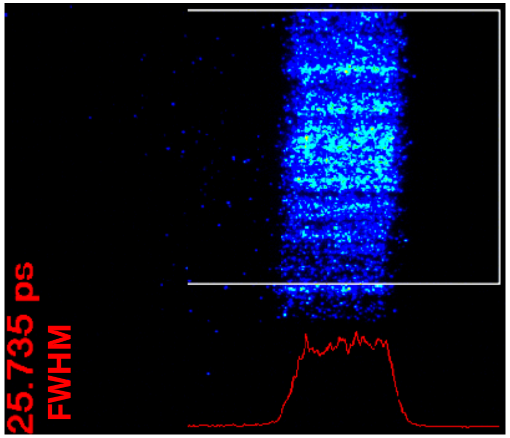
beam velocity and rf phase advance Vs. distance from cathode

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

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

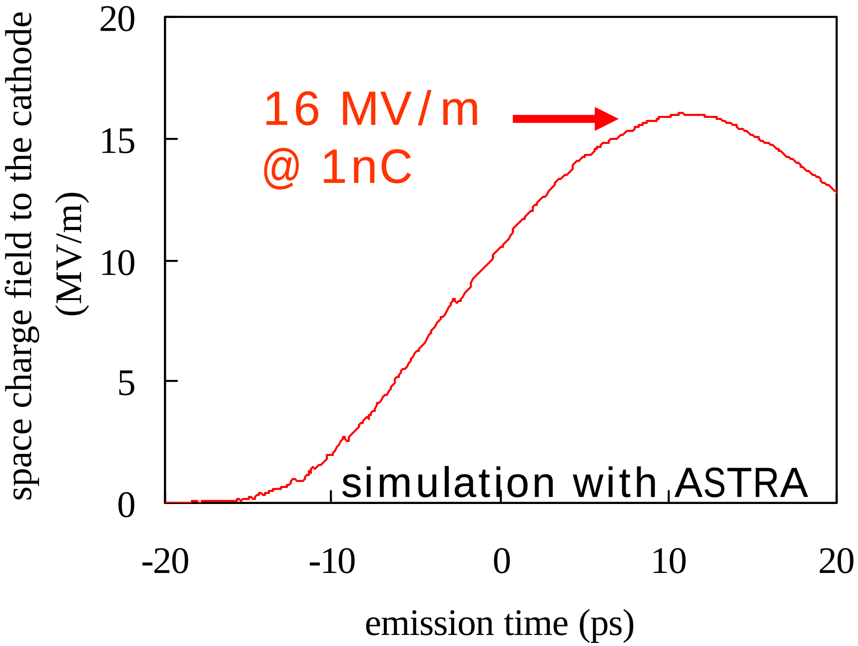
Longitudinal space charge field

longitudinal laser profile taken with the streak camera



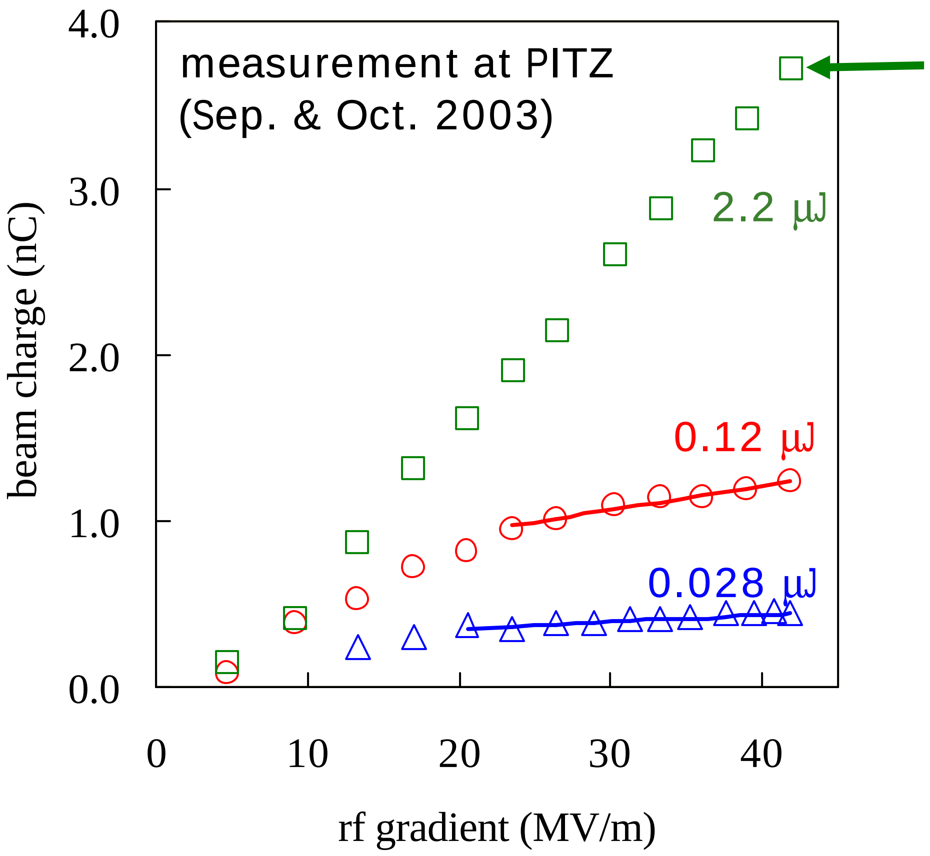
Transverse laser size:

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



longitudinal space charge force to the cathode

Beam extraction from the gun



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

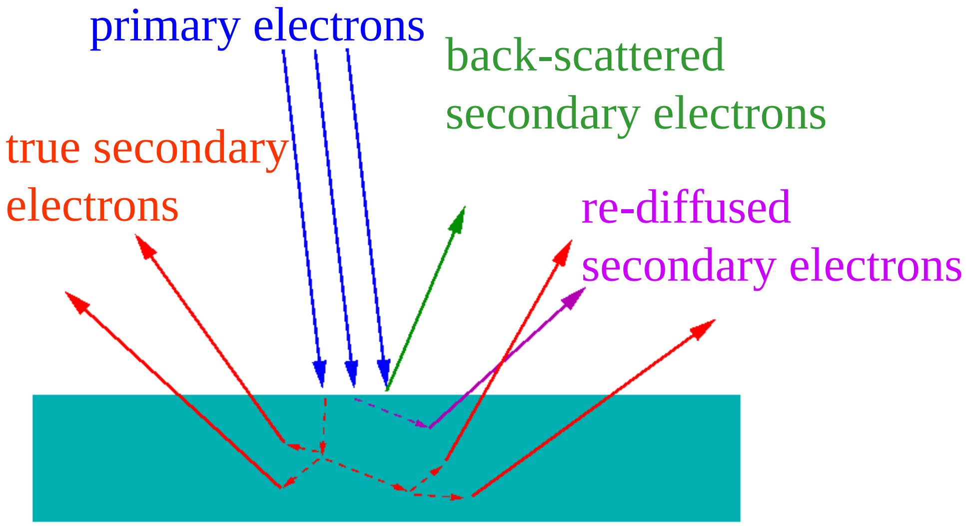
Space charge force is still higher than the rf electric field.

→ Some electrons emitted by 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.

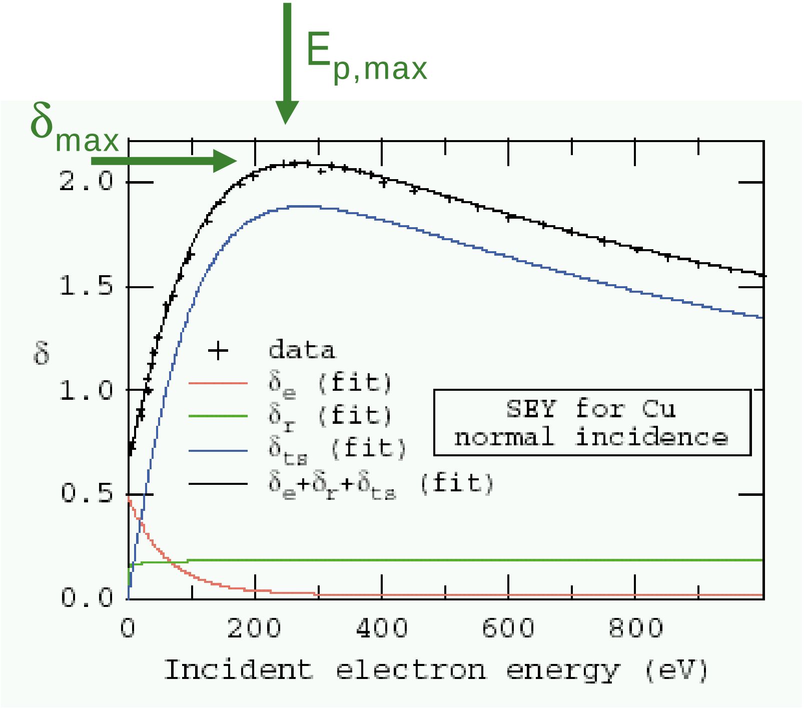
Secondary electron emission



secondary emission mechanism

secondary emission yield (δ):

$$d = \frac{\textbf{number of secondary electrons}}{\textbf{number of primary electrons}}$$



secondary emission yield of Cu[1)]

[1)] M. A. Furman, *et. al*., Phys. Rev. ST Accel. Beams **5**, 124404 (2002).

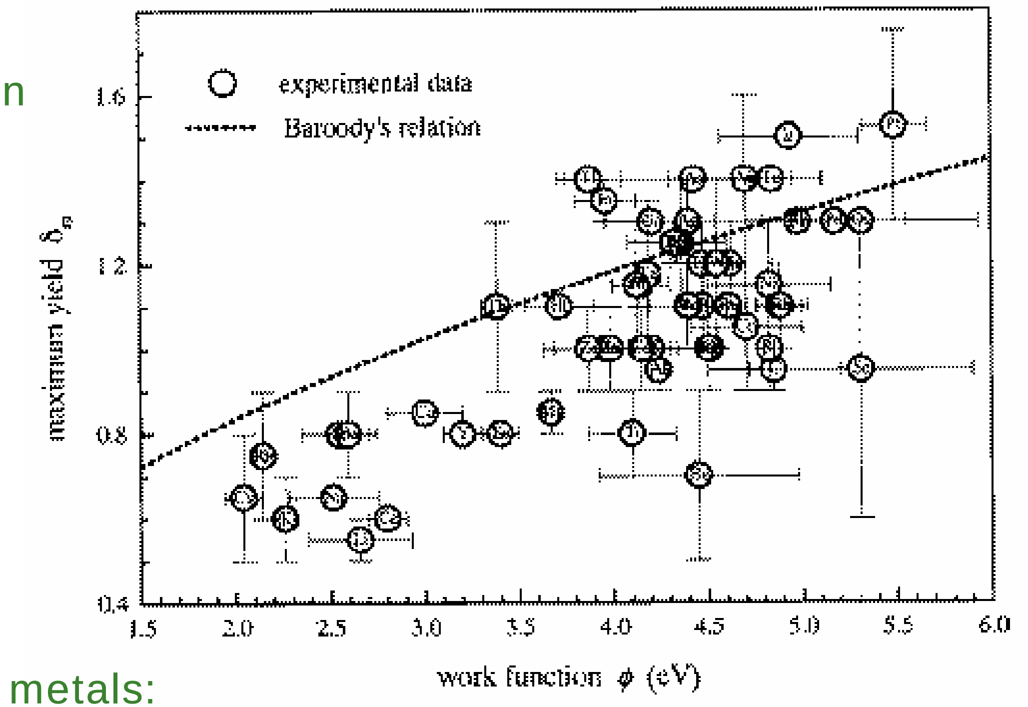
Emission of true secondary electrons:

(1) Production by kinetic impact of the primary electrons
(2) Transport toward the surface
(3) Escape through the solid-vacuum interface

Secondary electron emission feature of metal

maximum secondary emission yield of metals1)

1)Z. J. Ding, *et. al*., J. Appl. Phys. **89**, 718 (2001)



Secondary electron emission yield of metals:

δ_{max}: 0.5 ~ 2

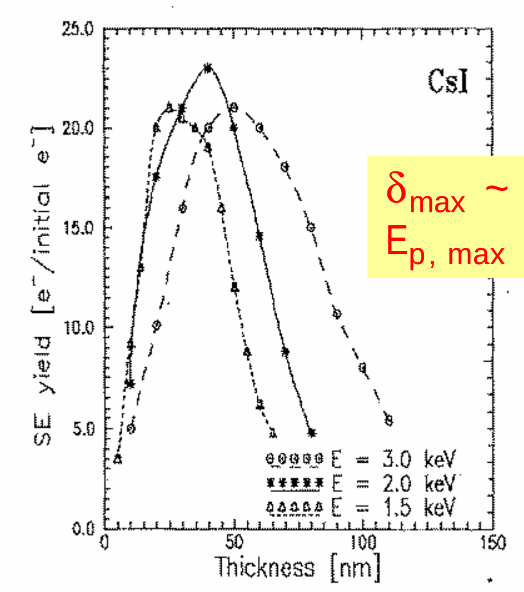
$E_{p,\ max}$ = 1 keV

Low yield caused by

(1) short penetration depth of primary electrons

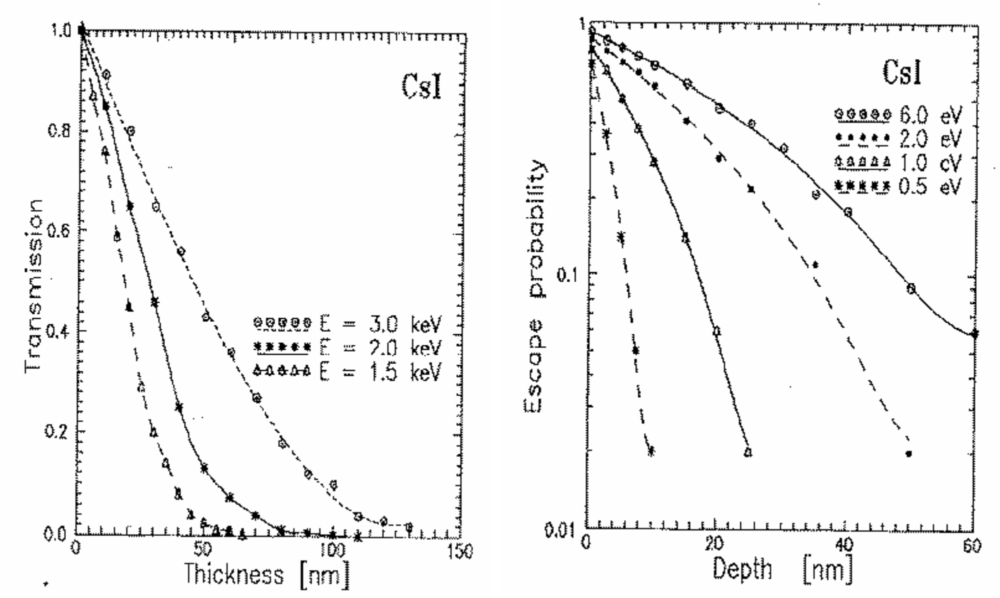
(2) thermalization of secondary electrons by electrons in conduction band

Secondary electron emission feature of CsI



δ_{max} ~ 20
$E_{p,\ max}$ ~ 2 keV

secondary emission yield of CsI$^{1)}$



transmission depth & escape probability of electrons in CsI$^{1)}$

$^{1)}$A. Akkerman, *et. al*., J. Appl. Phys. **72**, 5429 (1992)

High yield caused by
(1) long penetration depth of primary electrons due to wide band gap
(2) no thermalization of secondary electrons by electrons in conduction band
(3) low electron affinity

Estimation of the secondary emission properties of Cs_2Te

- Secondary emission properties are very different for different dielectric materials
- No measured data on the secondary emission properties of Cs_2Te
- Rough estimation of the values from similar materials such as CsI and CsBr.
- Most important parameters: electronic band gap (E_g),
  electron affinity (c).

material	E_g (eV)	c (eV)	$E_{p,max}$(keV)	d_{max}
CsI[a)]	6.3	0.1	2.15	17.23
CsBr[a)]	7.0	0.2	2.34	18.61
Cs_2Te	3.3[b)]	0.2[b)]	2 (?)	15 (?)

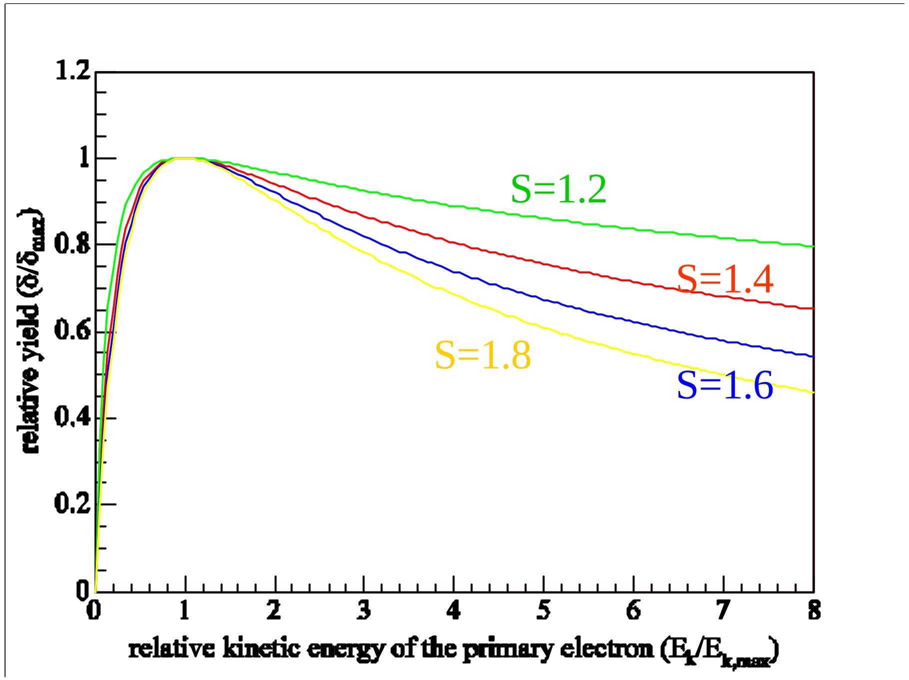
[a)] K. I. Grais, *et. al*., J. Appl. Phys. **53**, 5239 (1982).

[b)] R. A. Powel , *et. al*., Phys. Rev. B **8**, 3987 (1973).

Modeling of secondary electron emission for simulation

$$d(E_p)=d_{max}\frac{E_p}{E_{p,max}}\cdot\left[\frac{s}{s-1+\left(E_p/E_{p,max}\right)}\right]^s$$

Three fit parameters:
Maximum yield (δ_{max}),
Primary electron energy ($E_{p,max}$) for δ_{max}
Yield curve shape (s).

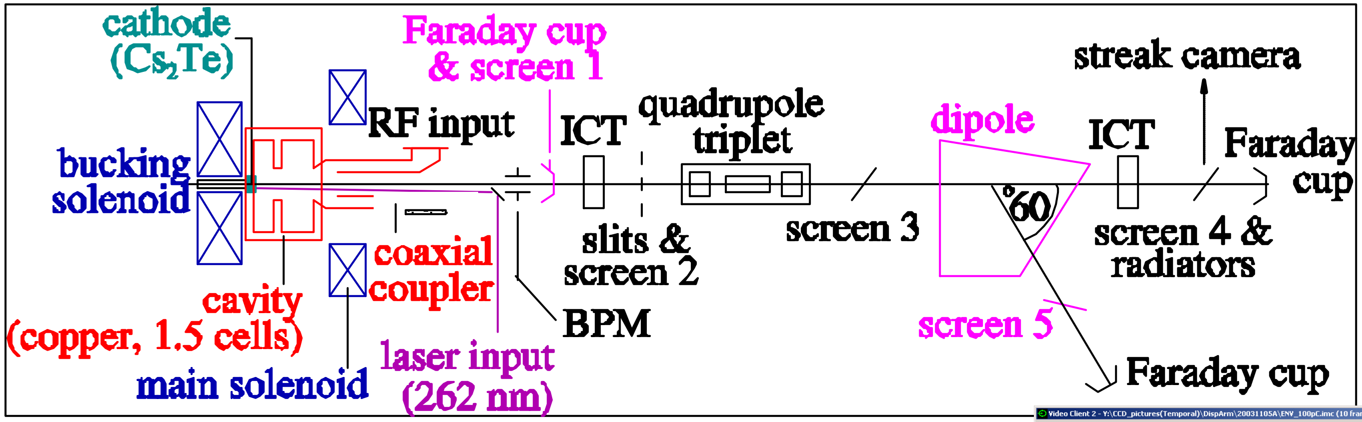


Missing parameters:

(1) Delay time between impact of primary electron and secondary electron emission is assumed to be 1 ps.

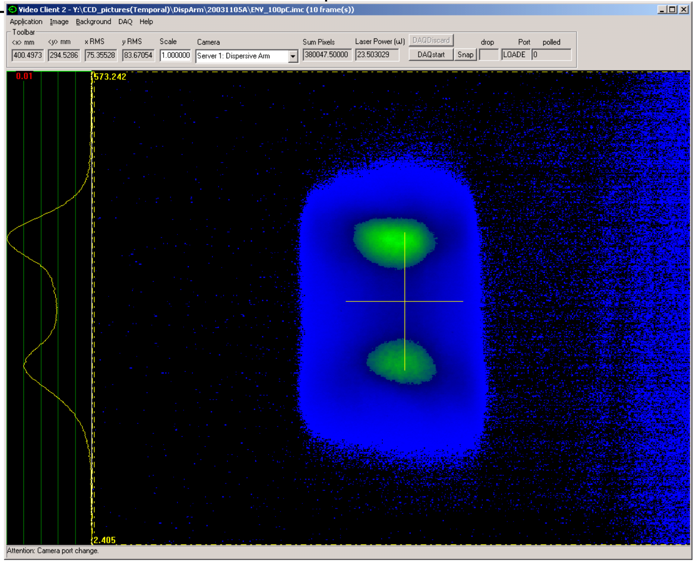
(2) Electric field dependence of secondary emission characteristic is neglected.
→ These parameters will be included soon.

Charge and momentum measurement



Beam charge measurement:
Faraday cup at 0.78 m downstream
from cathode

Beam momentum measurement:
dipole at 3.45 m downstream
screen at 4.13 m downstream



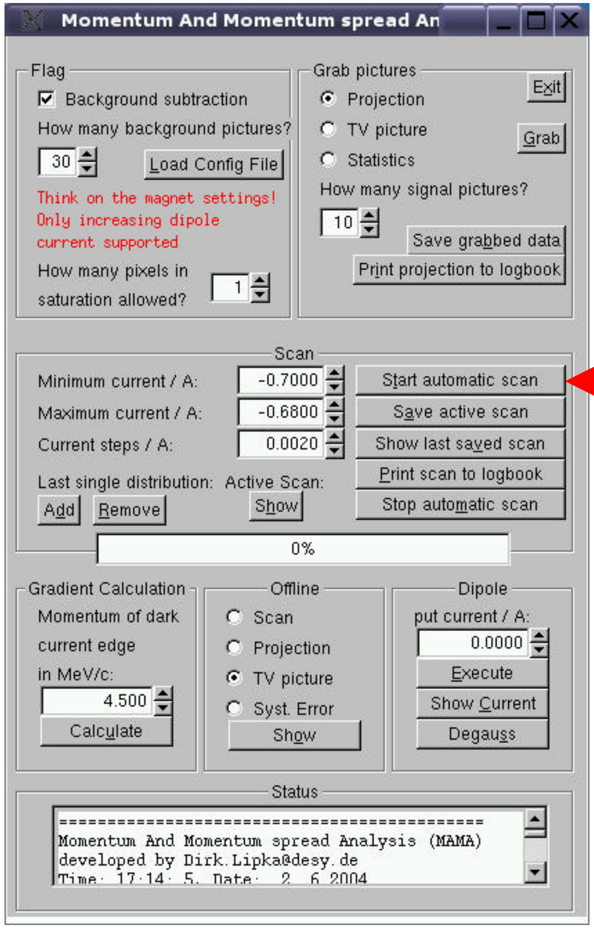
<x> mm: 400.4973
<y> mm: 294.5286
x RMS: 75.35528
y RMS: 83.67054
Scale: 1.000000
Camera: Server 1: Dispersive Arm
Sum Pixels: 380047.50000
Laser Power (uJ): 23.503029
drop:
Port: LOADE
polled: 0

Attention: Camera port change.

Projected beam image on the screen
for momentum measurement

Momentum measurement tool (MAMA)

developed by Dirk Lipka



Flag

☑ Background subtraction

How many background pictures? 30

Think on the magnet settings! Only increasing dipole current supported

How many pixels in saturation allowed? 1

Grab pictures

● Projection
○ TV picture
○ Statistics

How many signal pictures? 10

Scan

Minimum current / A: -0.7000
Maximum current / A: -0.6800
Current steps / A: 0.0020

Last single distribution: Active Scan:

0%

Gradient Calculation

Momentum of dark current edge in MeV/c: 4.500

Offline

○ Scan
○ Projection
● TV picture
○ Syst. Error

Dipole

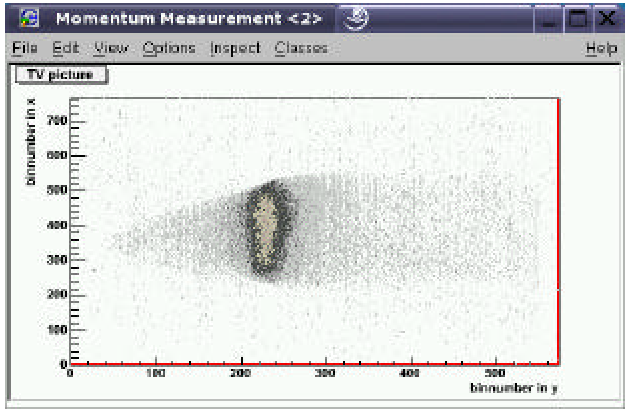
put current / A: 0.0000

Status

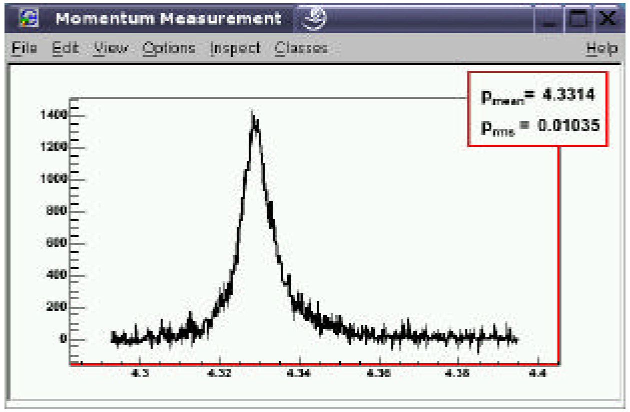
```
=============================================
Momentum And Momentum spread Analysis (MAMA)
developed by Dirk.Lipka@desy.de
Time: 17:14: 5, Date: 2. 6.2004
```

main panel of MAMA
(Momentum And Momentum spread Analysis)

Automatic scan
of the dipole current



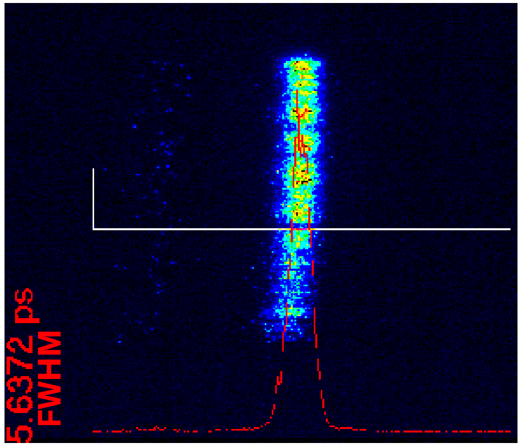
picture taken by MAMA

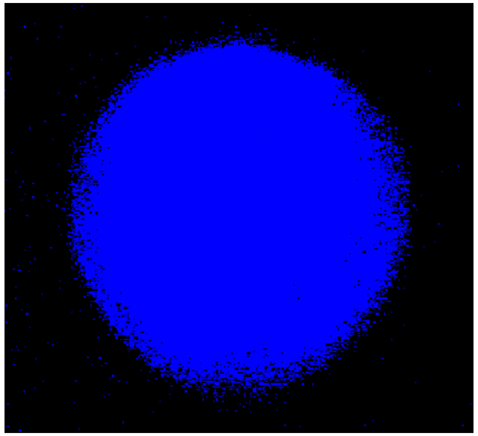


analysis by MAMA

Application of secondary emission model

- Short Gaussian laser (5.6 ps FWHM)
  → phase dependence of electron beam is clear.
- Low charge (~ 5 pC) → space charge effect negligible.
- Low gradient (21 MV/m) → low impact energy of primary electrons to generate many secondary electrons
- Cs2Te cathode with 60 nm thickness → more secondary generation



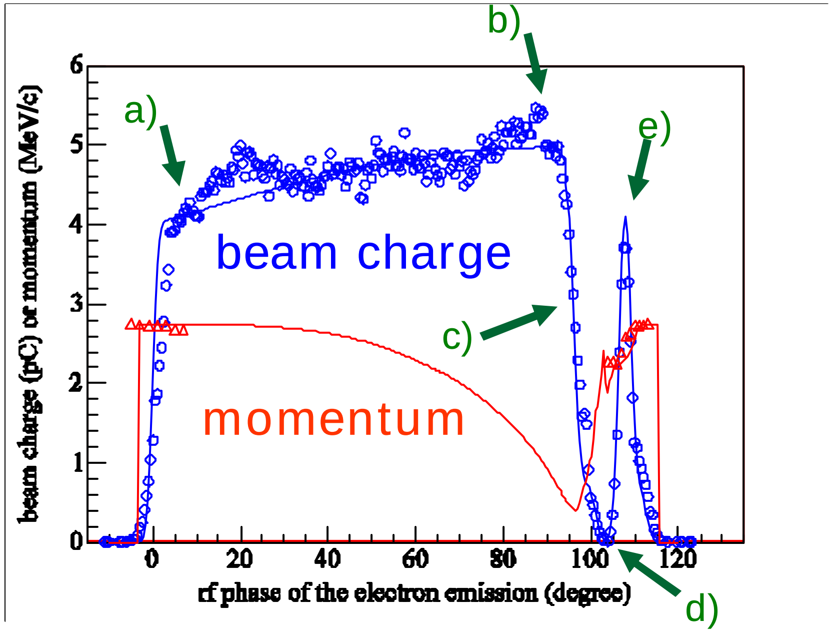


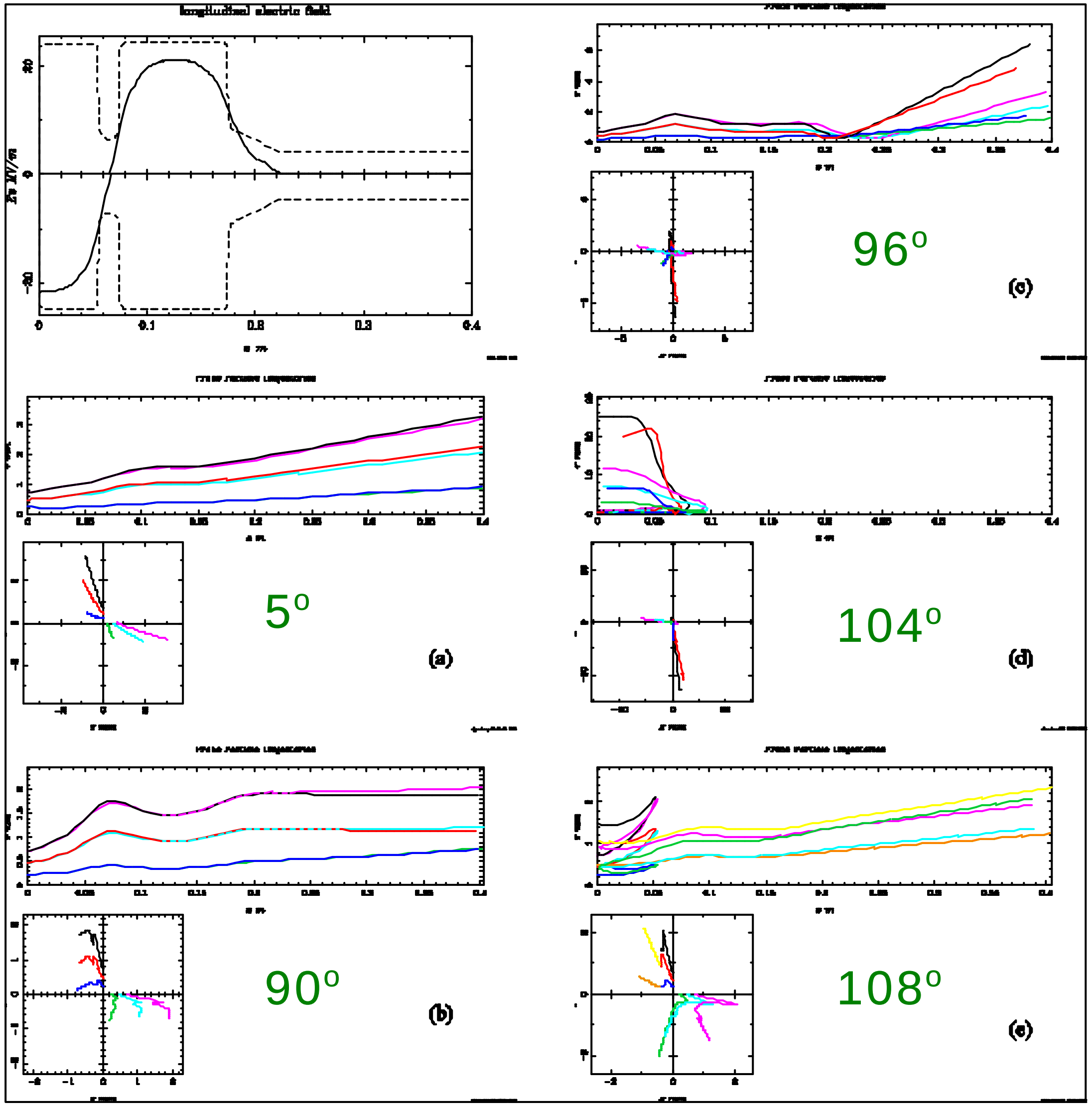
x_{rms} = 0.44 mm
y_{rms} = 0.51 mm

Beam dynamics at low gradient and low charge

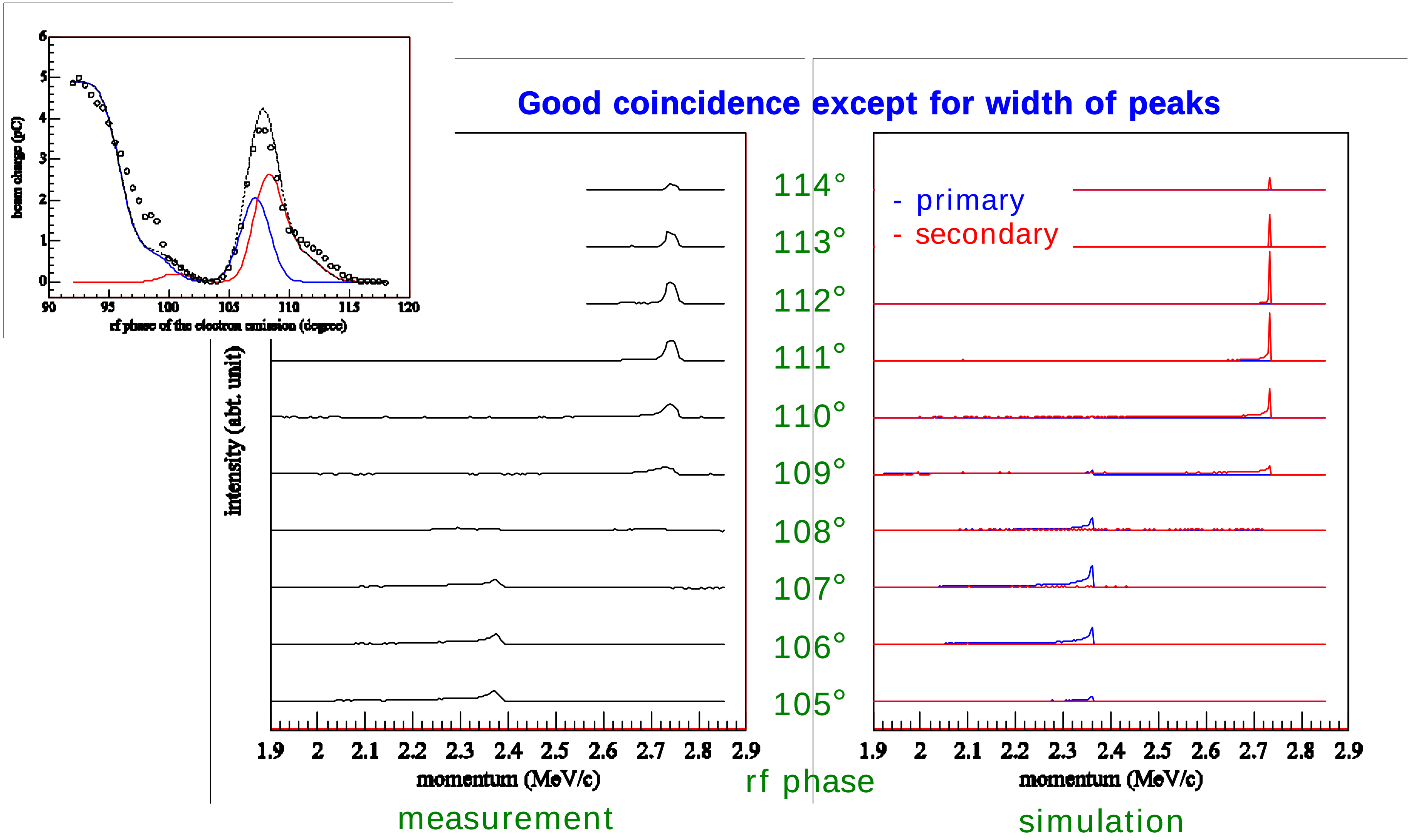
Beam charge ~ 5 pC

Gradient: 21 MV/m





Closer view of the bump

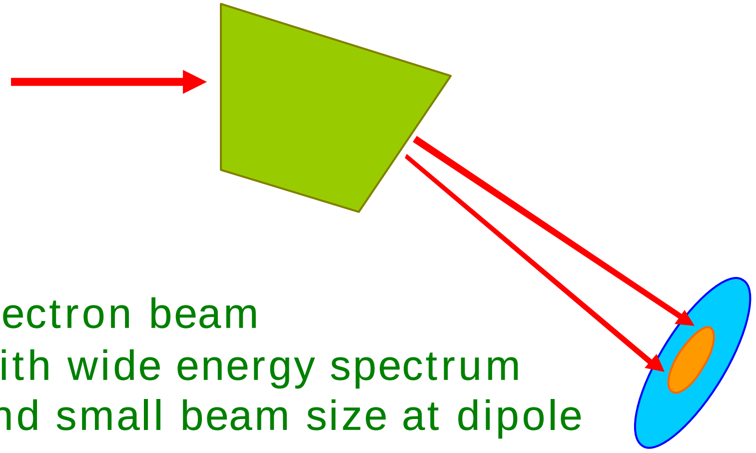


Good coincidence except for width of peaks

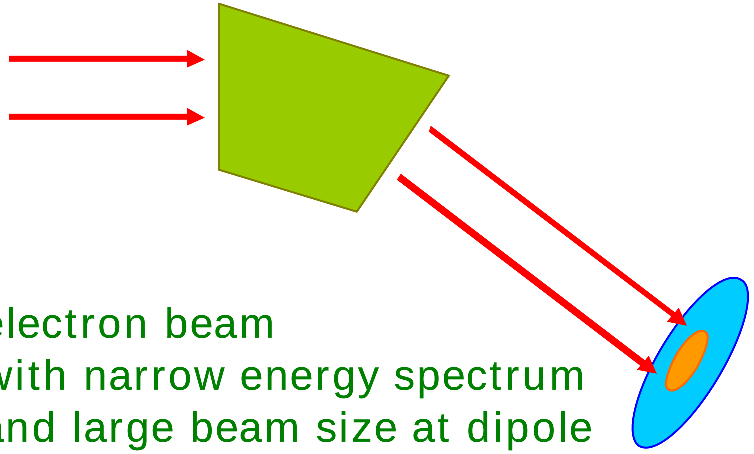
measurement

simulation

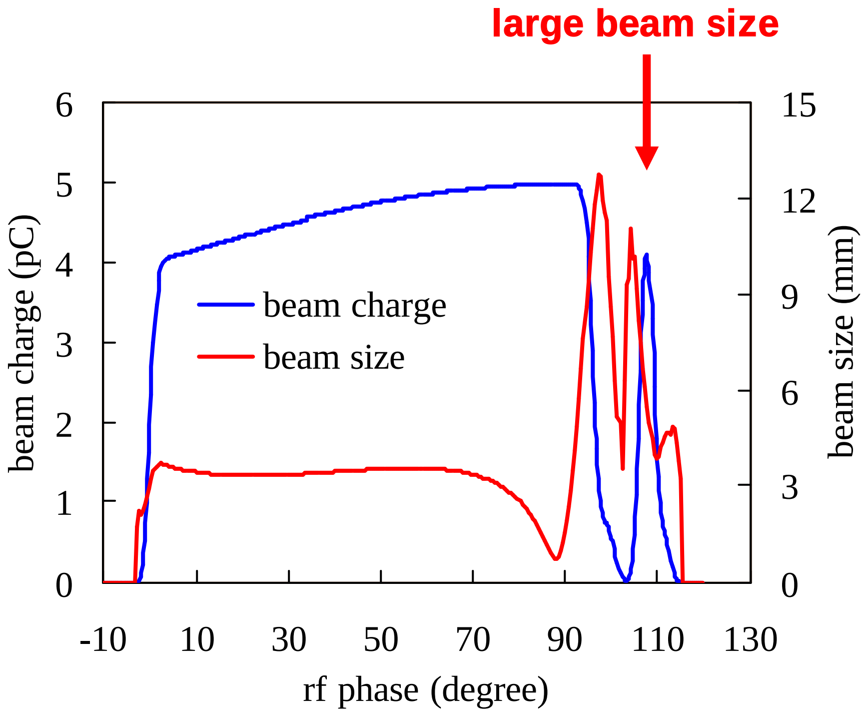
Uncertainty of momentum measurement



electron beam
with wide energy spectrum
and small beam size at dipole



electron beam
with narrow energy spectrum
and large beam size at dipole



simulation of beam charge and
beam size Vs. rf phase;
large beam size at the bump makes
measured momentum distribution wider

Summary

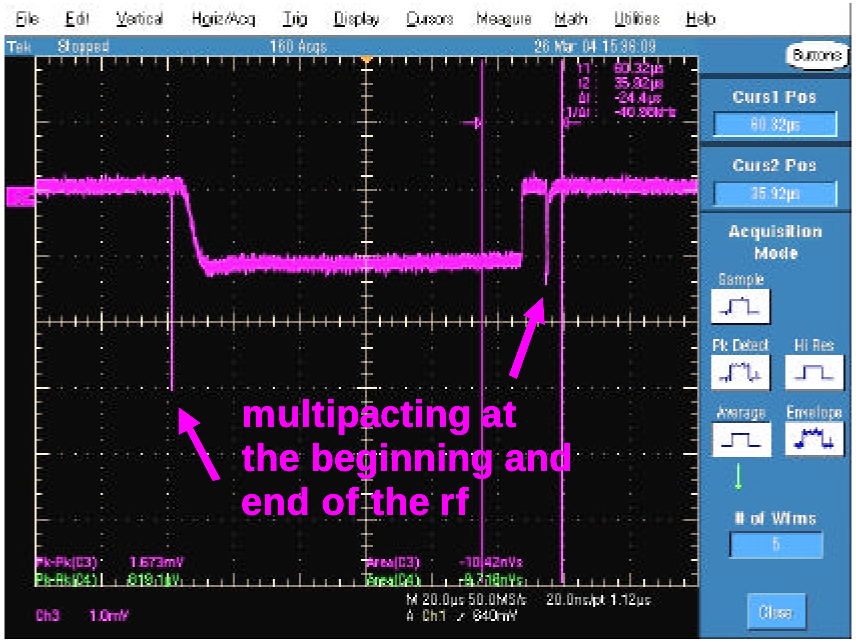
- Secondary electron emission should be included into simulation of electron dynamics in rf guns.
- Simple secondary model is implemented to ASTRA.
- Parameters of Cs_2Te was estimated from CsI and CsBr
- To test this model, the bump which happens at low charge and low gradient was investigated.

  (Almost all other parameters except for secondary electron emission are clear.)
- The first application of the model is successful to explain the measurement of beam charge and momentum distribution as a function of phase.

Outlook

- Better model is under investigation.
- Fitting of the secondary electron emission is ongoing.
- Direct measurement of the secondary parameters of Cs_2Te photocathodes is foreseen with INFN Milan colleagues.
- With this model, secondary electron emission related phenomena in rf guns could be explained;
  - emission of the very high density beam
  - multipacting on the cathode
  - more detailed dark current simulation
  - …

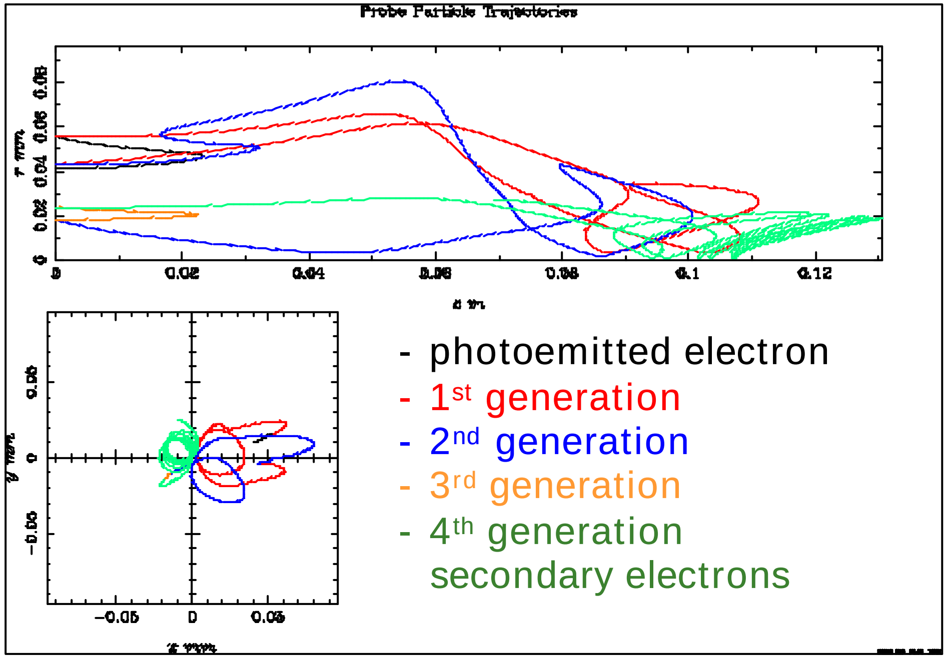
Phenomena related to secondary electron emission (example 1): multipacting



```
Tek   Stopped          160 Acqs          26 Mar 04 15:38:09
t1:    60.32µs
t2:    35.92µs
Δt:    -24.4µs
1/Δt:  -40.98kHz
Curs1 Pos 60.32µs
Curs2 Pos 35.92µs
Pk-Pk(C3)   1.673mV      Area(C3)  -10.42nVs
Pk-Pk(C4)   819.1µV      Area(C4)  -9.718nVs
Ch3   1.0mV              M 20.0µs 50.0MS/s    20.0ns/pt 1.12µs
                         A Ch1 ⁄ 840mV
```

multipacting at the beginning and end of the rf

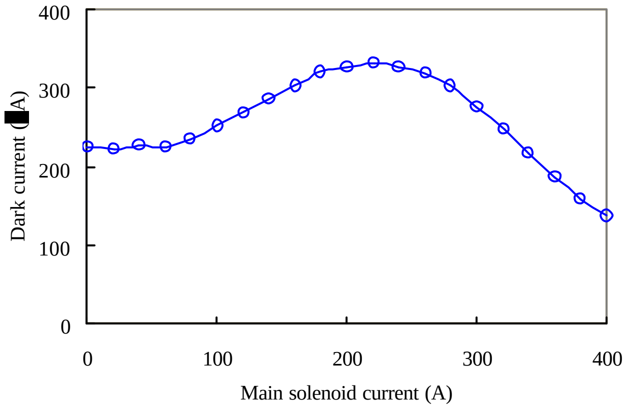
measured multipacting



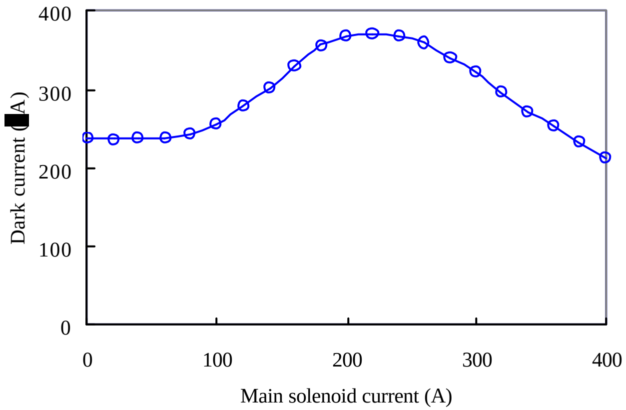
- photoemitted electron
- 1^{st} generation
- 2^{nd} generation
- 3^{rd} generation
- 4^{th} generation secondary electrons

simulated multipacting on cathode

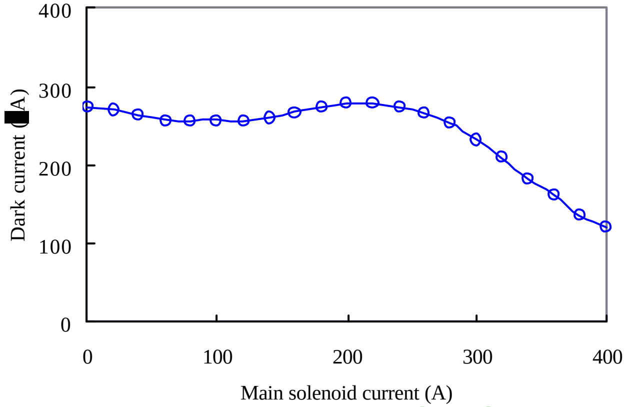
Phenomena(?) related to secondary electron emission (example 2): dark current



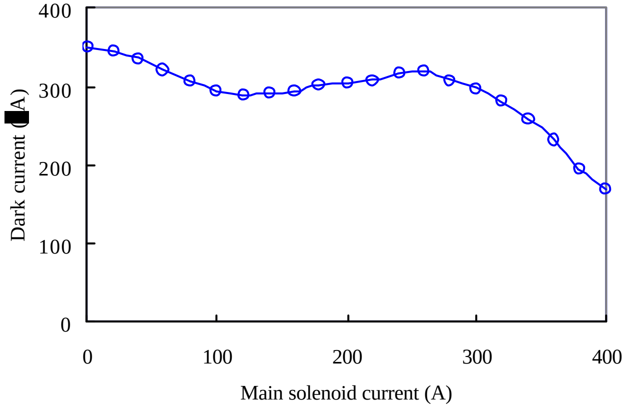
Mo cathode



Cs_2Te cathode
with 30 nm thickness

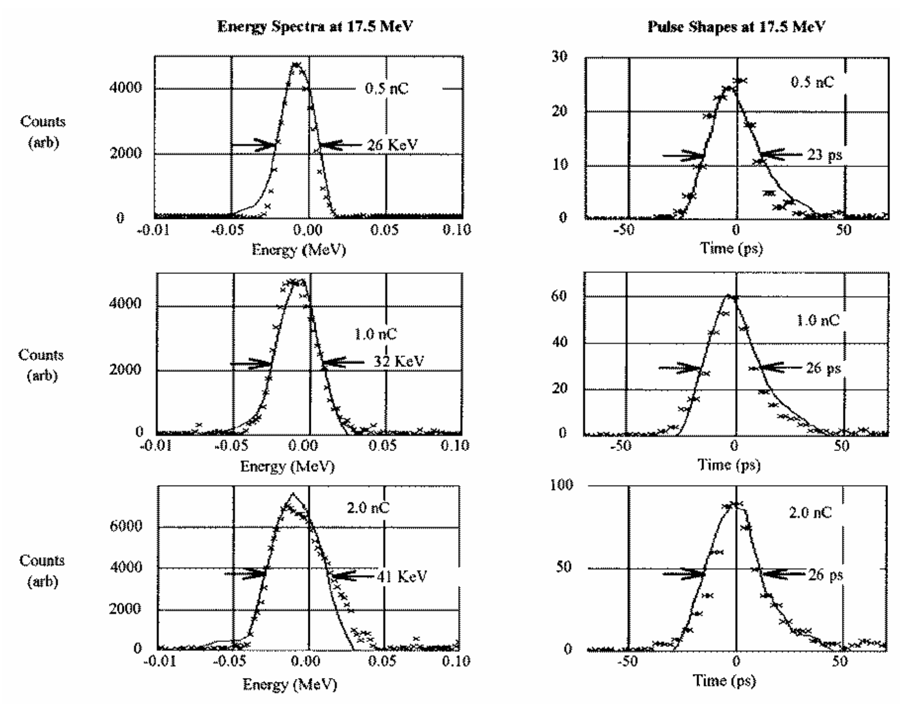


Cs_2Te cathode
with 45 nm thickness

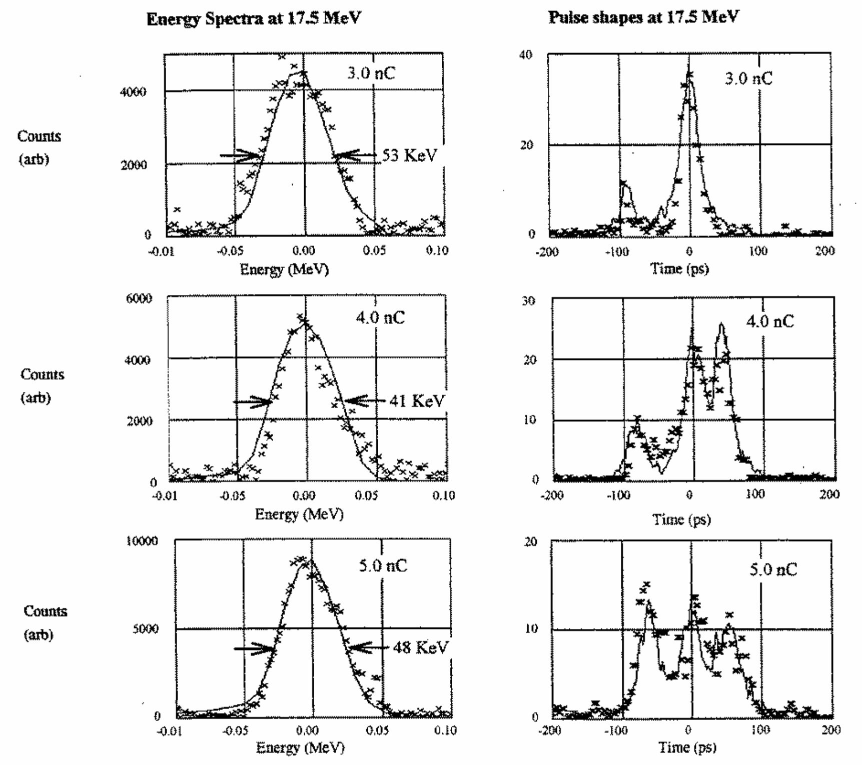


Cs_2Te cathode
with 60 nm thickness

Phenomena(?) related to secondary electron emission (example 3): emission of very high density beam



low charge case



high charge case

D. H. Dowel, *et. al*., Phys. Plasmas **4**, 3369 (1997).