Investigations on spiky charge distributions emitted from cathode at FLASH

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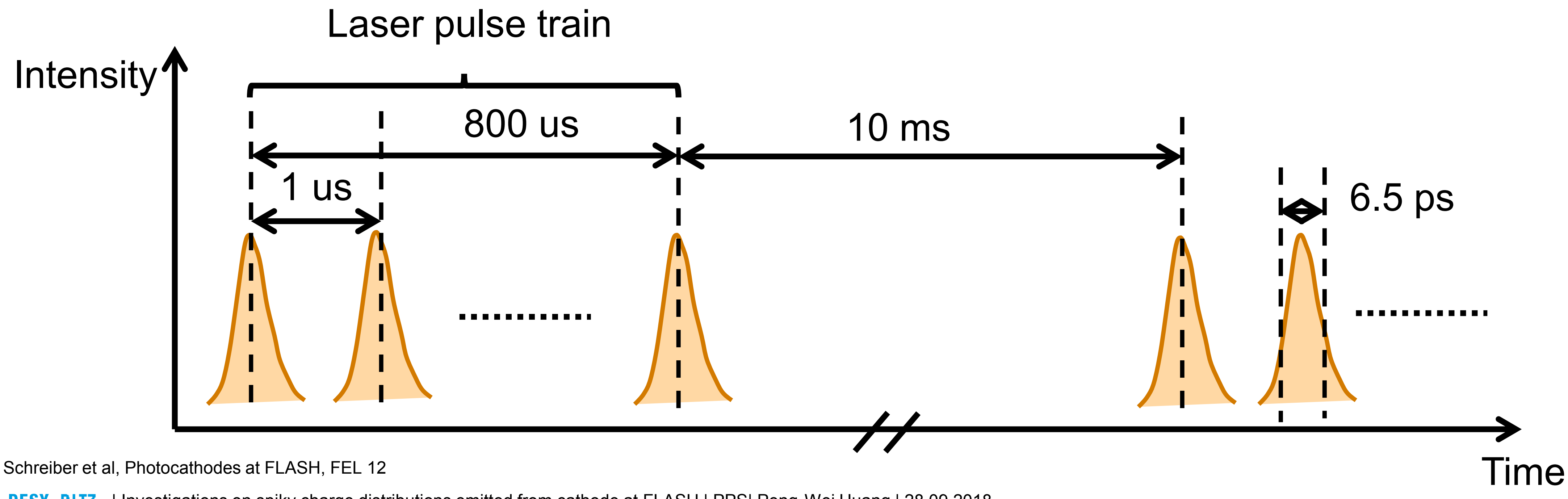
Gun setting

Background [1]

- Cathode : Cs_2Te
- Laser Wavelength : 262 nm
- RF gun : 1.3 GHz, copper cavity, 1.5 cell
- Working mode : Long pulse train, ten macro pulses per second, each macro pulse has 800 micro pulses, separated by 1 microsecond.



[1] S. Schreiber et al, Photocathodes at FLASH, FEL 12

Spiky charge distribution

Summary from the experiment

- With single laser pulse train, the spiky charge distribution is prominent.
- With two laser pulse trains, if the time interval is short, the spiky distribution will be alleviated. But the spike will turn out gradually with the increase of time interval.
- The power of the former pulse train will influence the spiky distribution. High power will suppress the spike.
- Even with two laser pulse trains, if the RF field is set up after the first pulse train, the distribution seems no interference by the first pulse train.

The spiky distribution strongly suppress the lasing of electron bunch, especially the front part. Therefore it needs to be avoided. Surely changing the laser pulse train shape is one way to manage it.

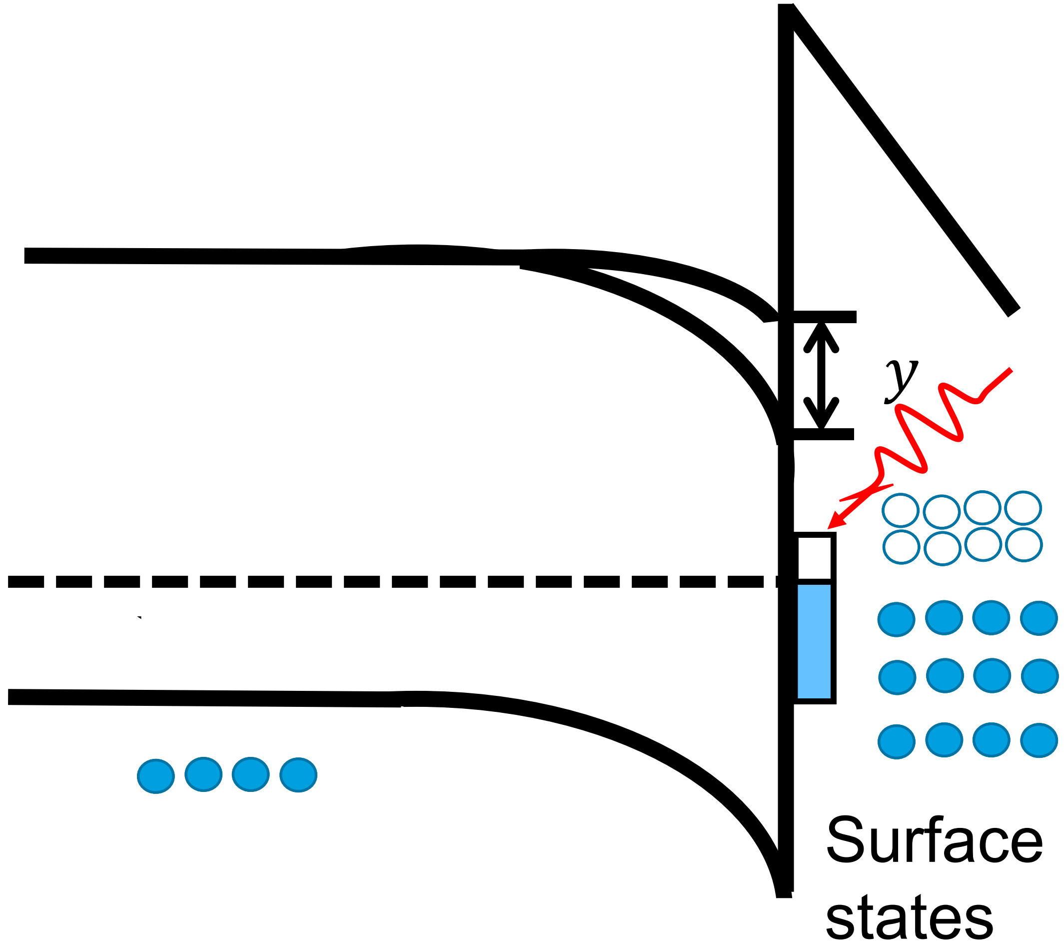
Laser to photocathode

We used to focus on

- Wavelength
- Pulse energy
- Transvers/Temporal profile
- Laser heating effect, for very short pulse
- Laser cleaning? Some evidence in experiments, but no systematic analysis.

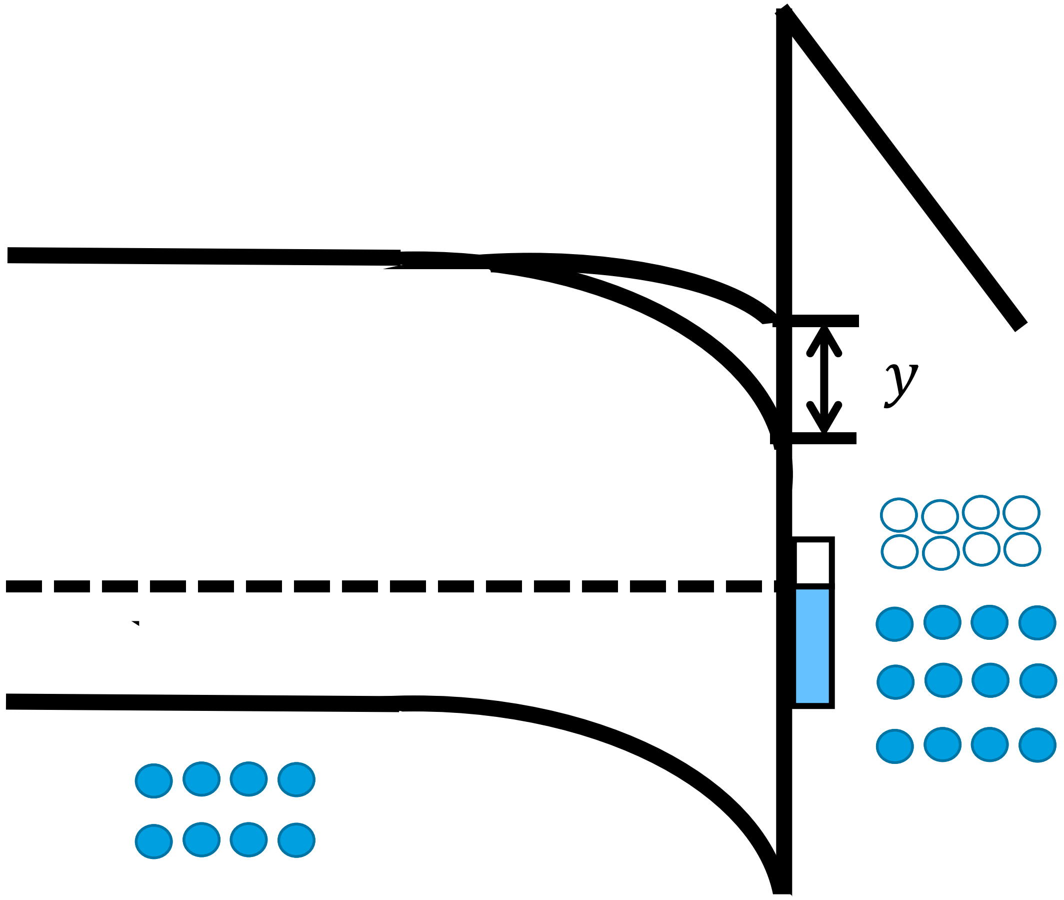
But the incident laser may still have other effects on the photocathode. Surface photovoltage is one of them.

Surface photovoltage (SPV) effect



When the cathode is illuminated with laser, the generated photoelectron current will come to the surface and recombine with the holes at the surface state, leading to the decrease of band bending by ***y***.

Model description



The process is separated into two parts.

- When the laser is on, the generated photoelectron current flow towards the cathode surface, recombine with the holes at surface. In this process the SPV is enhanced, leading to the reduction of band bending.
- When the laser is off, the holes current (Why holes?) in bulk flow towards surface and mitigate the SPV. The band bending tends to return to the original value. Meanwhile there is also a hole current from the surface to the bulk. When the SPV is 0, two current should cancel each other.

Basic Information

Band bending at surface

Charged states : $n_s = N_{sD}^{+} - N_{sA}^{-} \sim 10^{12}\ \mathrm{cm}^{-2}$ Contribution to the band bending

Unoccupied states : $N_s^{*} = N_{sA} + n_s \sim 10^{14}\ \mathrm{cm}^{-2}$ Recombine with bulk electrons; source of hole current from surface to bulk

Occupied states : $n_s^{*} = N_{sD} - n_s \sim 10^{14}\ \mathrm{cm}^{-2}$ Recombine with hole current from the bulk

Simple model for band bending $\Phi = \dfrac{N_A q^2 w^2}{2\epsilon\epsilon_0}$ The width of band bending is approximated as $w = \dfrac{n_s}{N_A} = \sqrt{\dfrac{2\Phi\epsilon\epsilon_0}{q^2 N_A}}$

The corresponding density of charged states due to SPV :

$$n_s(y) = \sqrt{\frac{2(\Phi_0 - y)\epsilon\epsilon_0 N_A}{q^2}} = n_s(0)\sqrt{1 - \frac{y}{\Phi_0}}$$

[1] M. A. Reshchikov et al, JOURNAL OF APPLIED PHYSICS 107, 113535 2010

Equation

The change of density of charge states $$\frac{\mathrm{d}n_s}{\mathrm{d}t} = R_{bs} - R_{sb} - R^*$$

The hole current from bulk to surface

$$R_{bs} = \sigma_{n1} v_{th1} n_s^* n_h \exp\left(-\frac{\Phi_0 - y}{\eta k_B T}\right) = \sigma_{n1} v_{th1} n_s^* N_v \exp\left(-\frac{\Phi_0 - y + E_F - E_v}{\eta k_B T}\right)$$

The hole current from surface to bulk

$$R_{sb} = \sigma_{n2} v_{th2} N_s^* N_v \exp\left(-\frac{E_s - E_v}{\eta k_B T}\right)$$

When $y = 0$, there should be $R_{bs} = R_{sb} = R_0$

$$E_s - E_v = E_F - E_v + \Phi_0$$

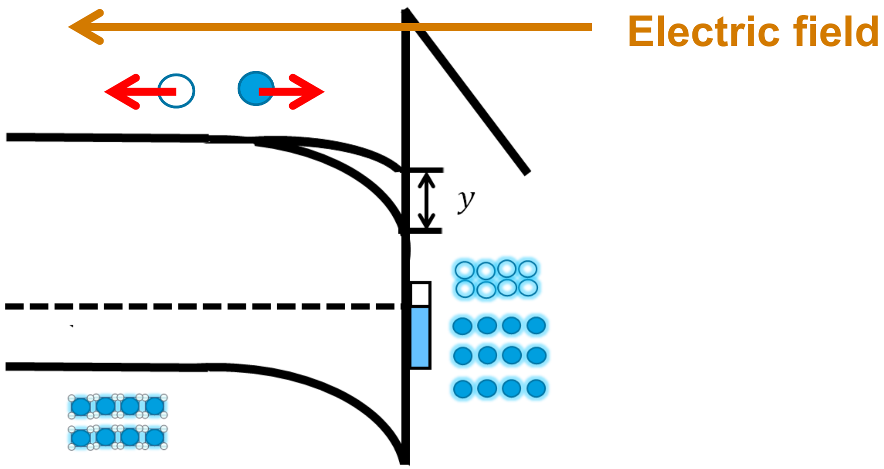
[1] M. A. Reshchikov et al, JOURNAL OF APPLIED PHYSICS 107, 113535 2010

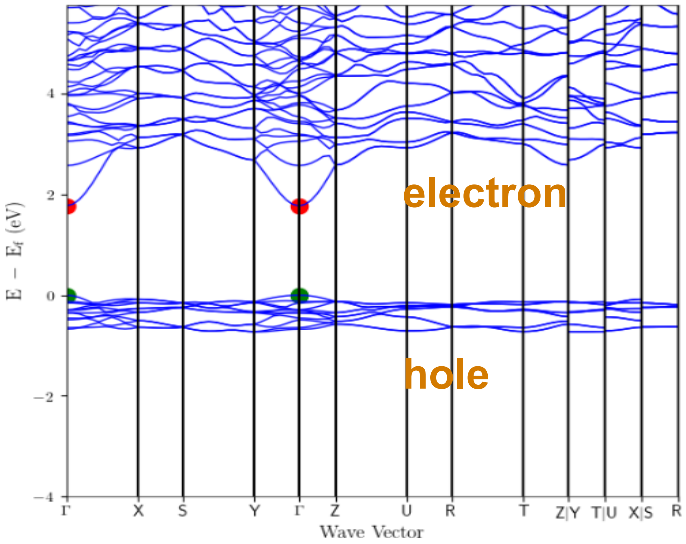
Equation

When laser is on $$R^* = c\sigma_{eh} N_s^* P_0 \exp\left(\frac{-y}{\eta k_B T}\right)$$ P_0 is the laser intensity, with unit $\mathrm{cm}^{-2} \cdot \mathrm{s}^{-1}$

Here we only consider the electron current for two reasons :

1. The applied electric field will penetrate into the photocathode film. The field is in the direction that help the electrons move towards the surface and force the holes move to the opposite side. Therefore at our interested surface the laser excited carriers current is mostly composed of electrons. This argument will be used to explain the RF field effect on the spiky distribution.
2. The holes at valance band usually have large effective mass and hard to move. They will tend to recombine with thermal electrons at bulk.





$$v = \frac{1}{\hbar}\frac{dE_k}{dk}$$

[1] Persson Kristin, Materials Data on Cs2Te (SG:62) by Materials Project, 10.17188/1276525, 2014

Equation

Due to $R^* \gg R_{sb}, R_{bs}$, the laser on equation is (short time effect ~ 10 ps)

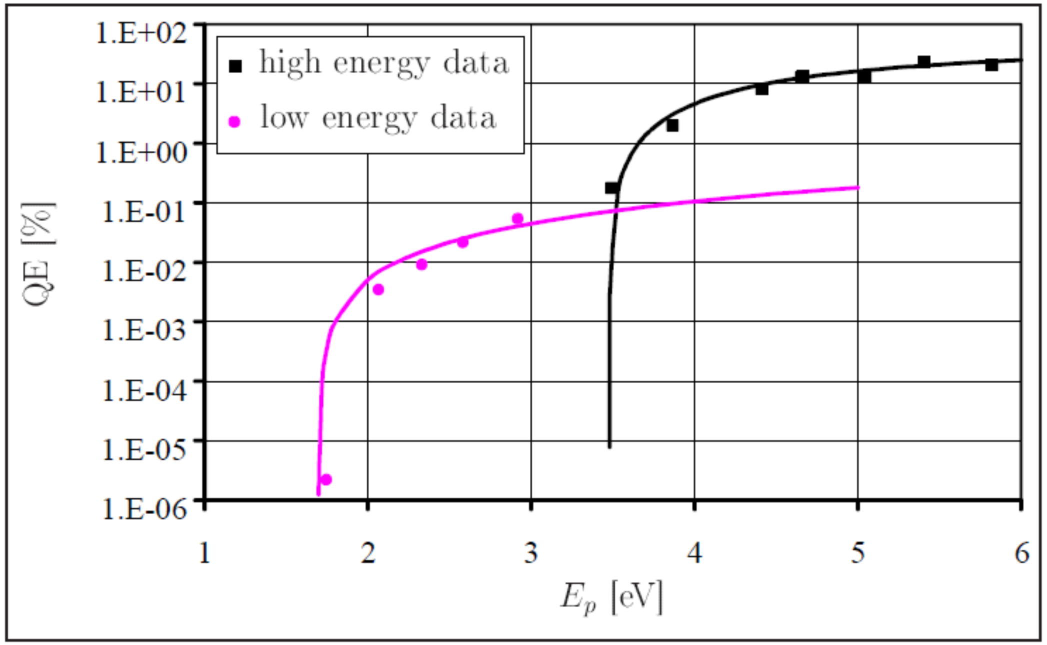
$$\frac{d(\frac{y}{\Phi_0})}{dt} = \frac{2c\sigma_{eh}N_s^*P_0}{n_s(0)} \exp\left(-\frac{y}{\Phi_0} \times \frac{\Phi_0}{\eta k_B T}\right) \times \sqrt{1 - \frac{y}{\Phi_0}}$$

the laser off equation is (long time effect ~ 1 us)

$$\frac{d(\frac{y}{\Phi_0})}{dt} = -\frac{2R_0}{n_s(0)} (\exp\left(\frac{y}{\Phi_0} \times \frac{\Phi_0}{\eta k_B T}\right) - 1) \times \sqrt{1 - \frac{y}{\Phi_0}}$$

QE of Cs_2Te

cathode	90.3	94.3	104.4	127.3
$(E_G + E_A)_1$ (eV)	2.77	2.73	2.82	2.70
m_1	2.50	2.50	1.12	2.50
A_1	0.02	0.01	0.04	0.01
$(E_G + E_A)_2$ (eV)	3.26	3.27	3.28	3.23
m_2	1.83	1.75	1.63	2.02
A_2	4.09	4.26	4.58	3.42
QE(%)	10.4	10.1	10.2	10.1



Two step model $$\mathrm{QE} = A_1(\hbar\omega - (E_G + E_A)_1)^{m_1} + A_2(\hbar\omega - (E_G + E_A)_2)^{m_2}$$

We focus on the high energy region, so it is a good approximation to neglect the contribution from the low threshold term. So SPV related QE is expressed as

$$\mathrm{QE(y)} = A_2(\hbar\omega - (E_G + E_A)_2 - \mathrm{y})^{m_2}$$

[1] S. Schreiber et al, Photocathodes at FLASH, FEL 12

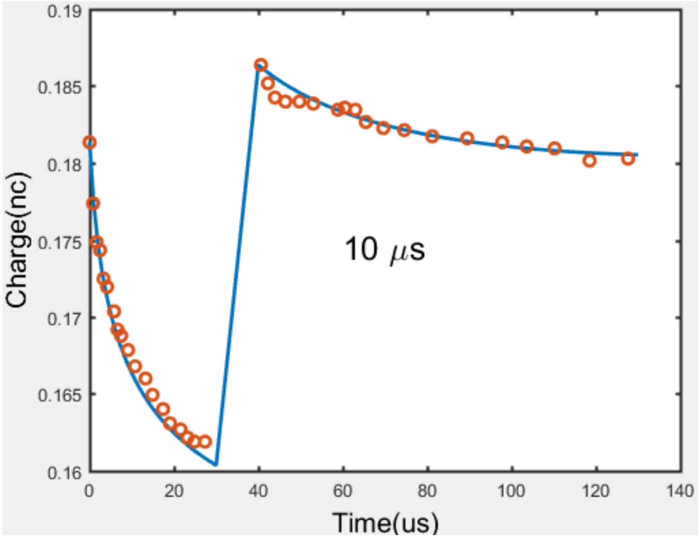
Parameters

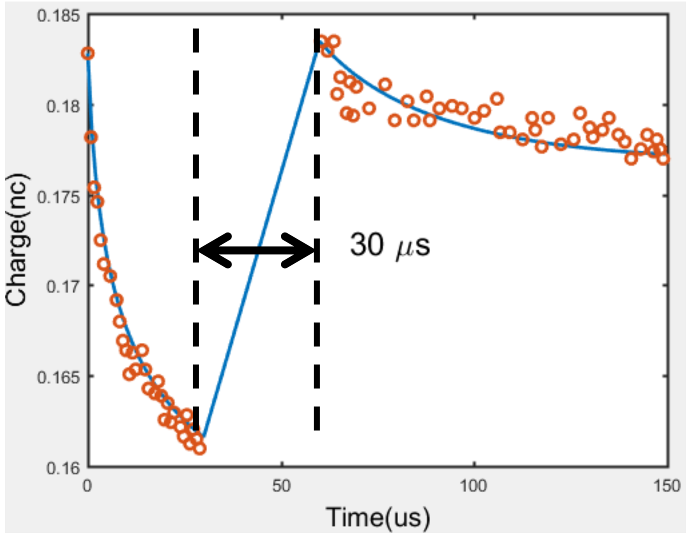
Parameter	Value
Photon energy	4.742 eV
QE	8.4019 %
Band bending Φ_0	0.12 eV (fit)
$c\sigma_{eh}N_s^*$	0.075 (fit)
Laser intensity	Deduced from the charge quantity
Density of charged states $n_s(0), N_s^*, n_s^*$	$10^{12}\ \mathrm{cm}^{-2}, 10^{14}\ \mathrm{cm}^{-2}$ $10^{14}\ \mathrm{cm}^{-2}$
Recombination velocity $\sigma_{n1}v_{th1}n_s^*$	$3\times10^{5}\ \mathrm{cm/s}$ (fit) Lies in the normal region
η, k_BT	1.5 (fit, 1~2 is a normal range), 0.02585 eV
Fermi level $E_F - E_v$	1.2 eV
Valance band density Nc	$10^{22}\ \mathrm{cm}^{-3}$

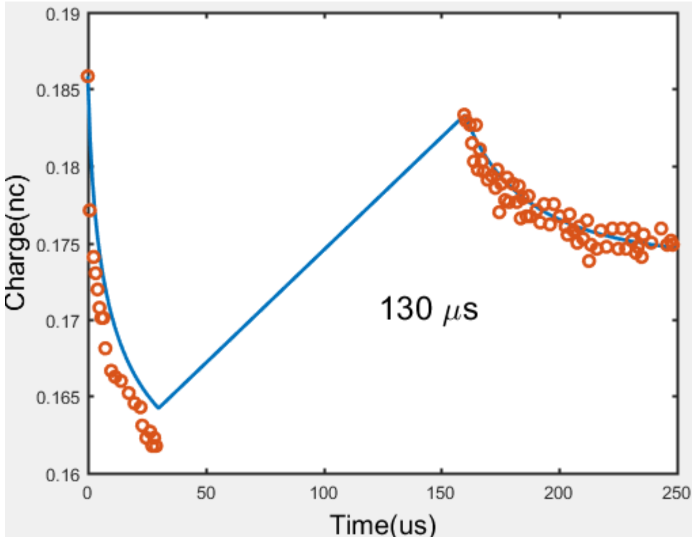
Note : I found that the laser pulse energy actually fluctuates. If the same laser intensity is applied, it will lead to a deviation from the experiment data by less than 10%. In order to alleviate this effect, I calibrate in every single picture with the real yield charge quantity and QE, but only for the first pulse in each pulse train.

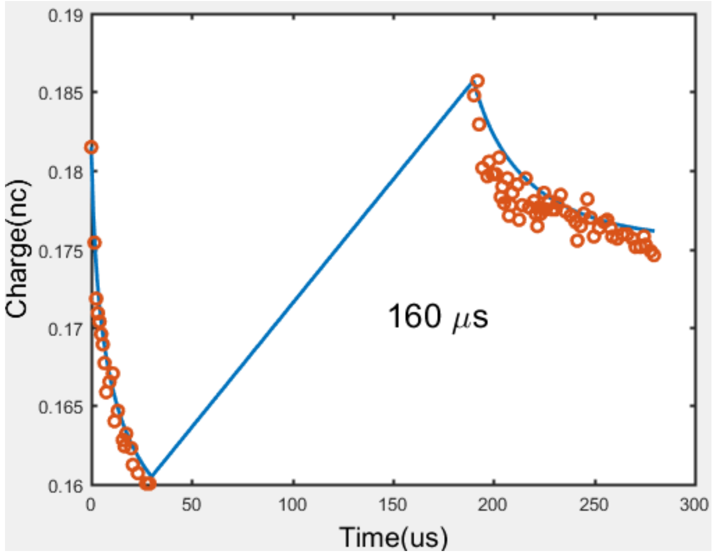
Results

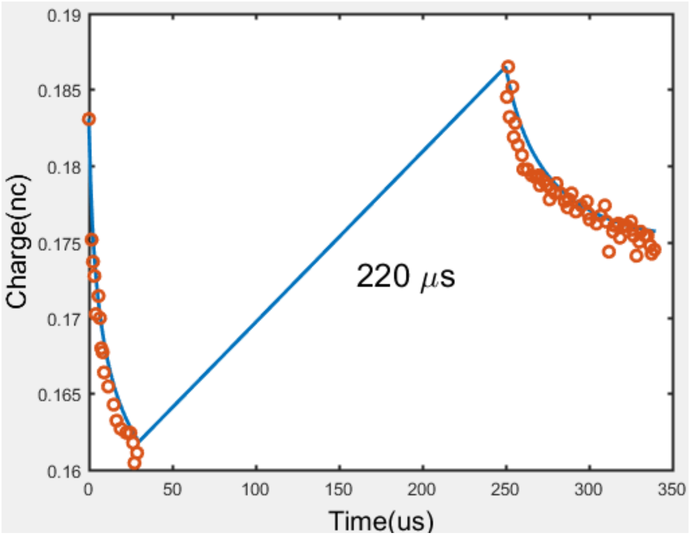
Blue line– Model ; Red circle– Experiment ; The time in the figure means the intervals between two laser pulse train.

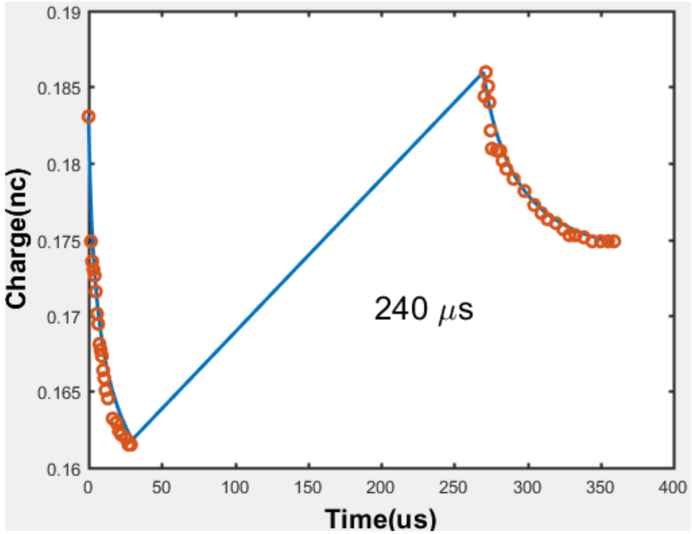






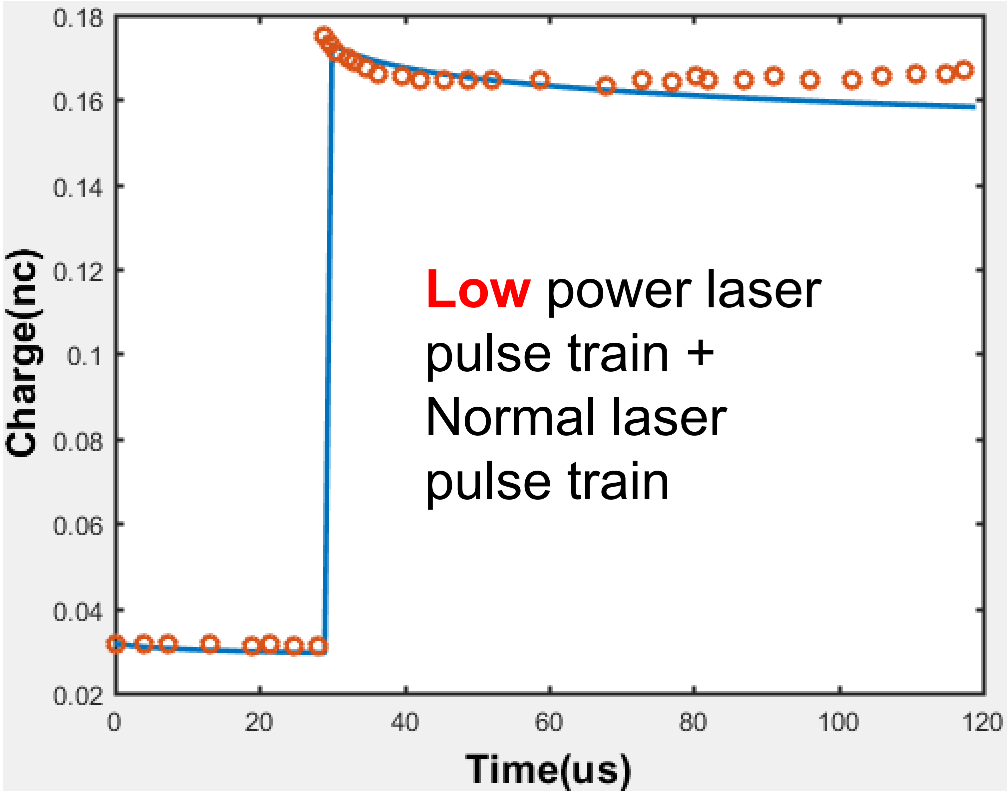


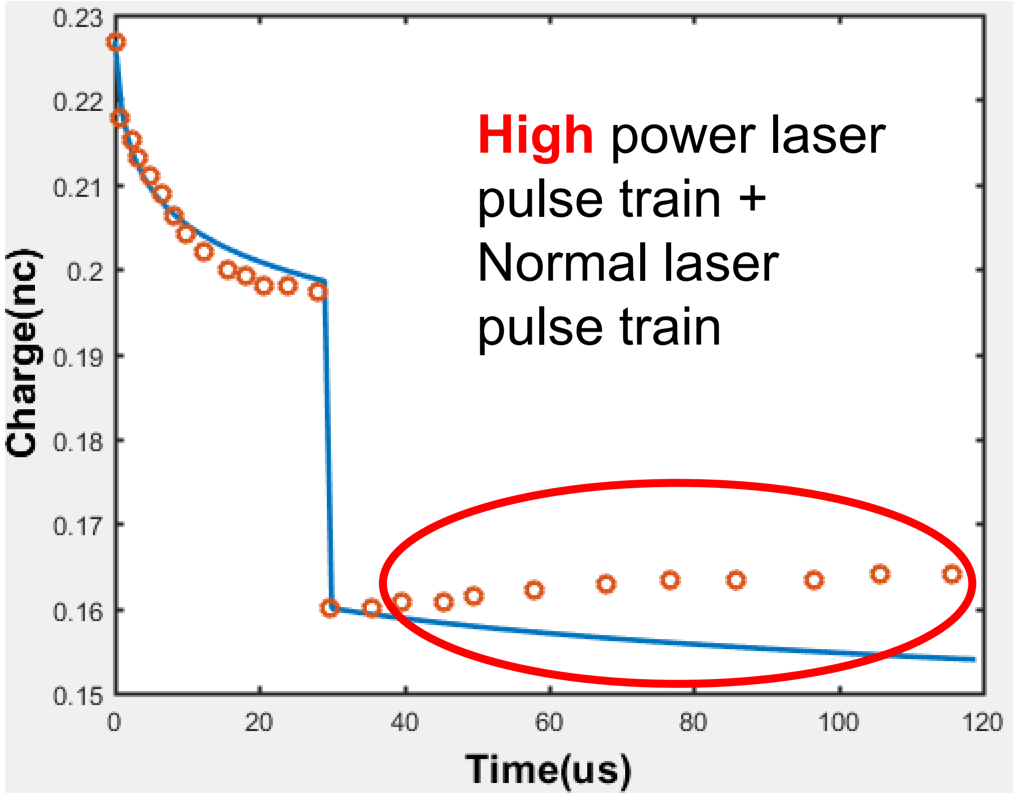




Results

Blue line– Model ; Red circle– Experiment .





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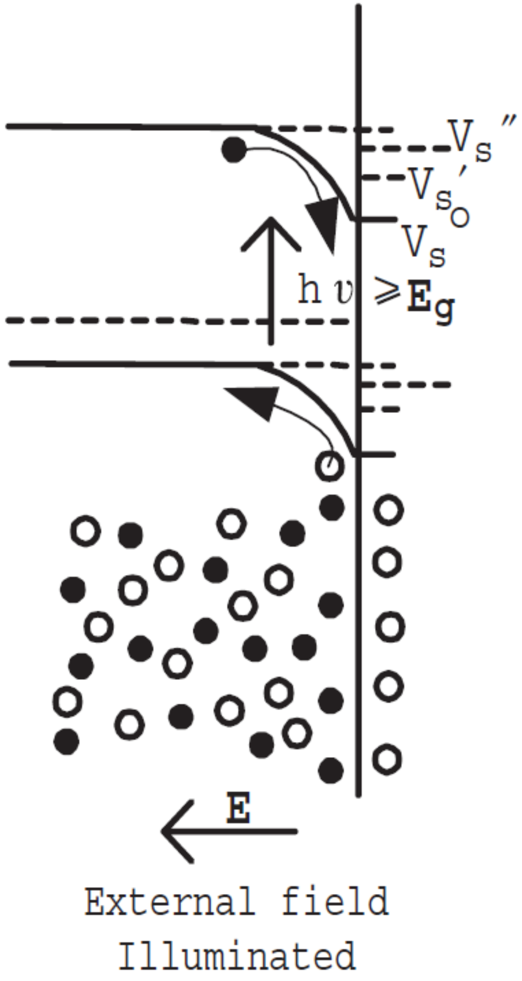
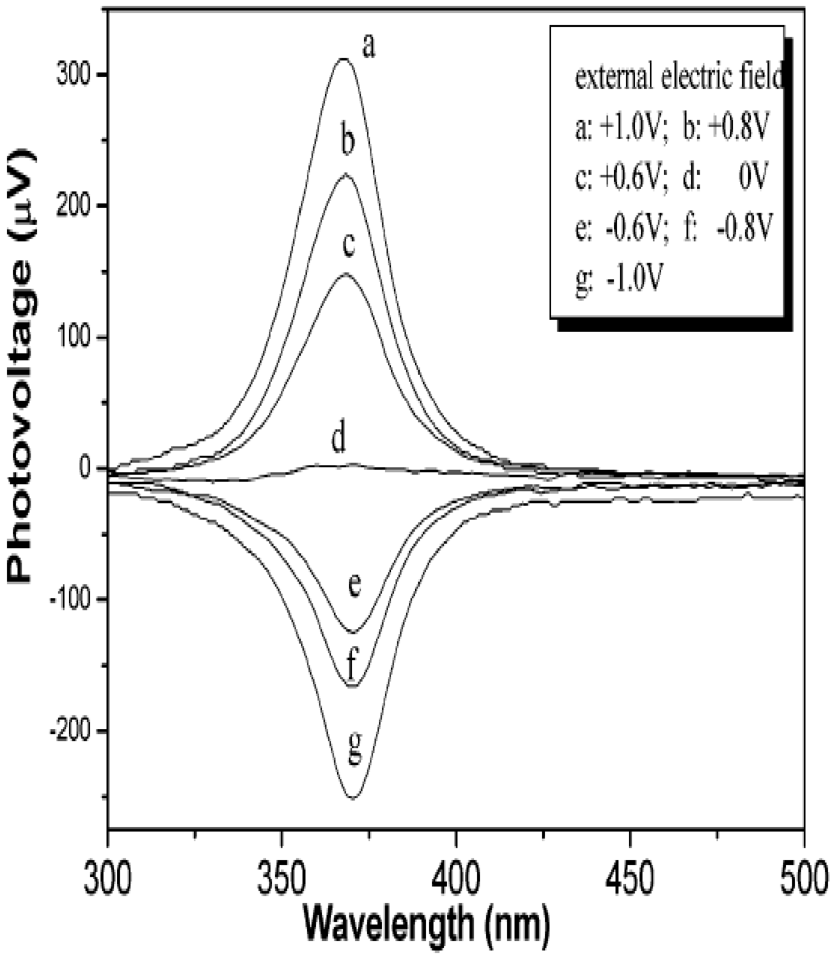


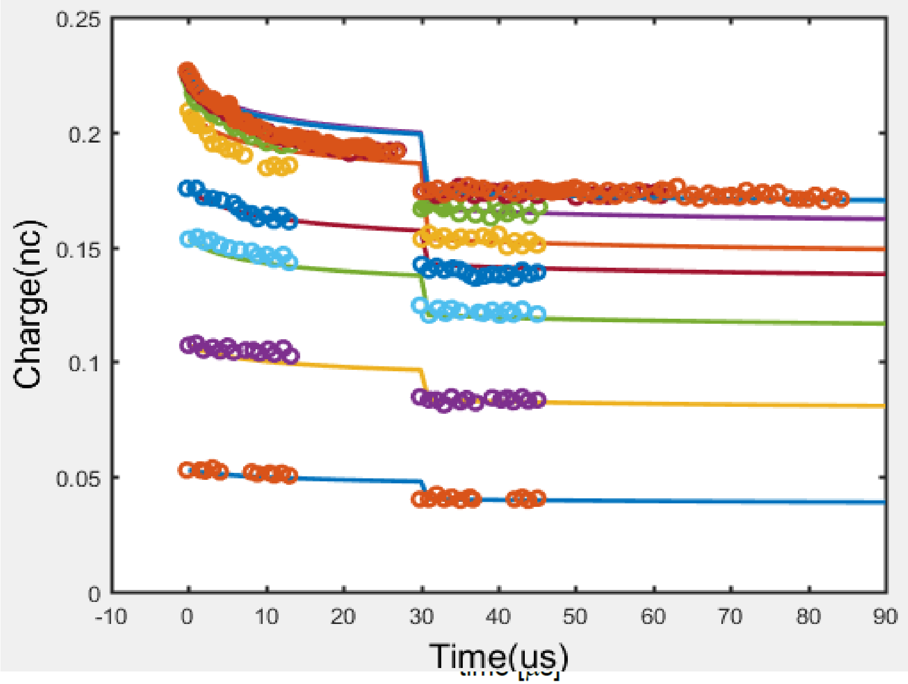


- In the experiment, the first pulse train can not be seen because the detector is away from the cathode surface. The photoelectrons will be ionized with air before be collected by the detector without the acceleration of RF field.
- Here we assume the absence of RF field will decrease the number of electrons moving towards the surface, reducing the SPV. From the fit I find that the recombination rate will decrease by 12 times. The complete picture need further explore.

[1] J. Liqiang et al. / Solar Energy Materials & Solar Cells 79 (2003) 133–151
[2] Yanhong et al, J. Phys. Chem. B, Vol. 108, No. 10, 2004

Results

line– Model ; circle – Experiment .



Ecath (MV/m)	Pgun (MW)
30.2	1.60
33.7	2.00
41.3	3.00
47.7	4.00
53.3	5.00
58.4	6.00
60.0	6.34
63.1	7.00

$$P_{gun}[MW] = 0.00176 \cdot (E_{cath}[MV/m])^2$$

The influence of RF power on the number of detected electrons is not limit to the electric field at cathode. The QE change brought by the Schottky effect can not account for such large variation.

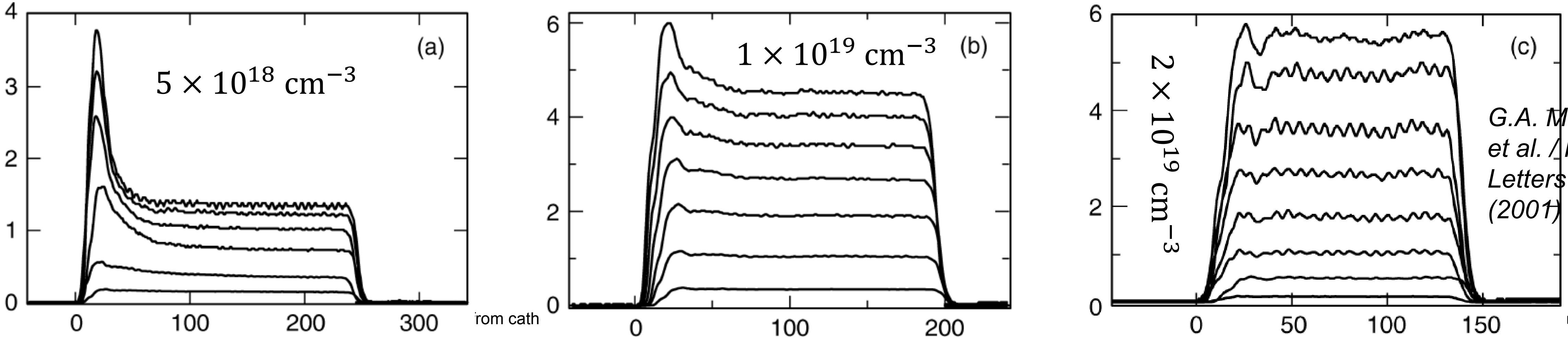
So in the calculation, the first point of every train is fixed by the experiment data. Here we assume the parameter ‘c’ in the irradiation process has a linear relation with the power.

Possible way to avoid spike distribution

Surface photovoltage induces the change of band bending, resulting in the variation of QE. If we can minimize the band bending, the effect of SPV can also be reduced.

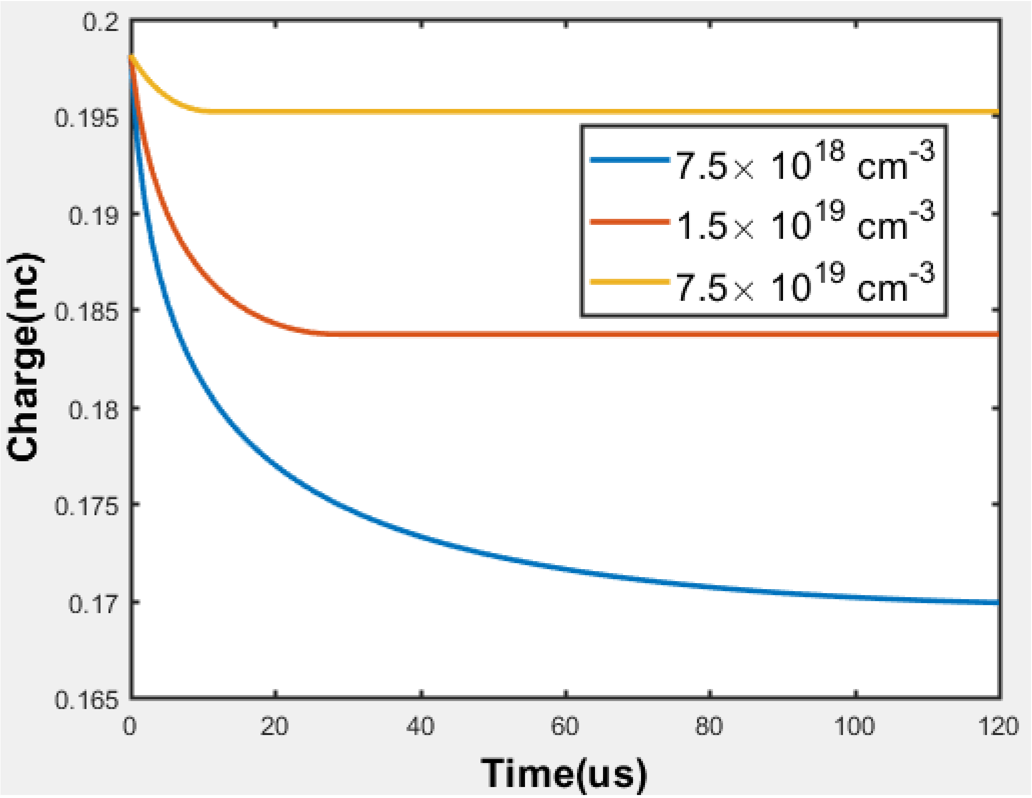
$$n_s(y) = \sqrt{\frac{2(\Phi_0 - y)\epsilon\epsilon_0 N_A}{q^2}} \Rightarrow \Phi \sim \frac{n_s^2}{N_A}$$

Either Reducing the density of surface state or increasing the density of acceptor level is an option to obtain smaller band bending (or surface potential). For the latter, there is another advantage that it provides a higher hole current in the recovery process of SPV, faster to cancel the contribution during the irradiation, which has been seen for GaAs in the experiment.



G.A. Mulhollan et al. / Physics Letters A 282 (2001)

Possible way to avoid spike distribution

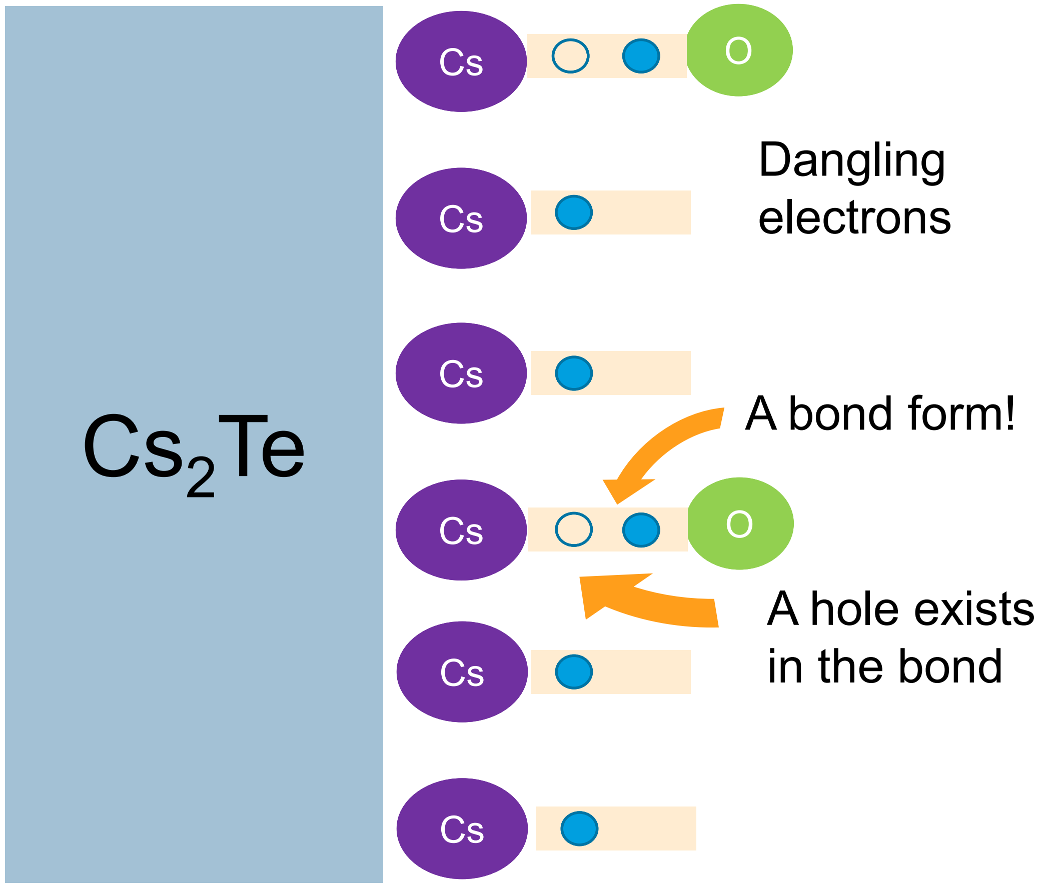


Deduced from the fitting number, the density of acceptor level is $7.5 \times 10^{18}\ \mathrm{cm}^{-3}$. Predicted results of different density are displayed.

- ➢ Less decay
- ➢ Shorter time to reach balance

Surface states

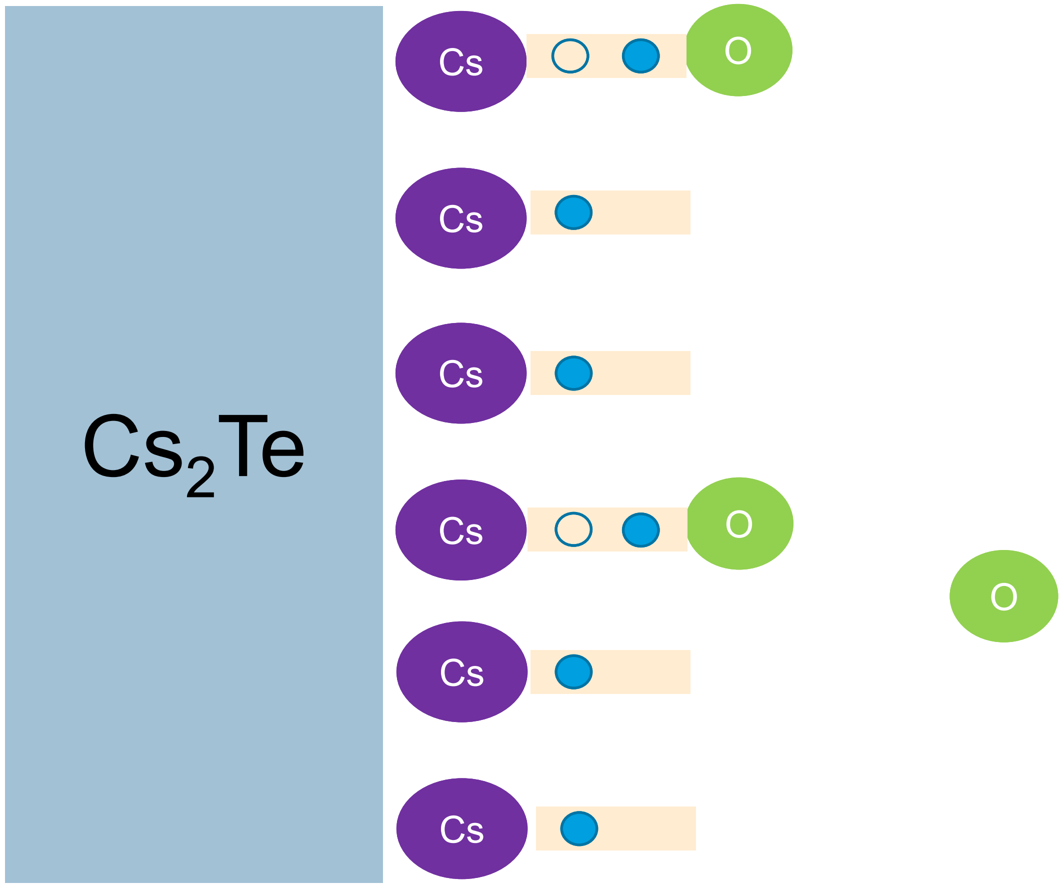
A proposed picture for the formation



- The cesium is last deposited onto the material.
- Free cesium atoms on the surface cause n-typed surface.
- Dangling electrons forms donor level at the surface.
- Oxygen atoms will have a chemical reaction with the cesium.
- Another two electrons are needed to form a stable state for oxygen.
- One cesium atom can provide one electron. So there will be a hole left in the bond, which will form the surface acceptor level.

A proposed picture for no spike after long time operation

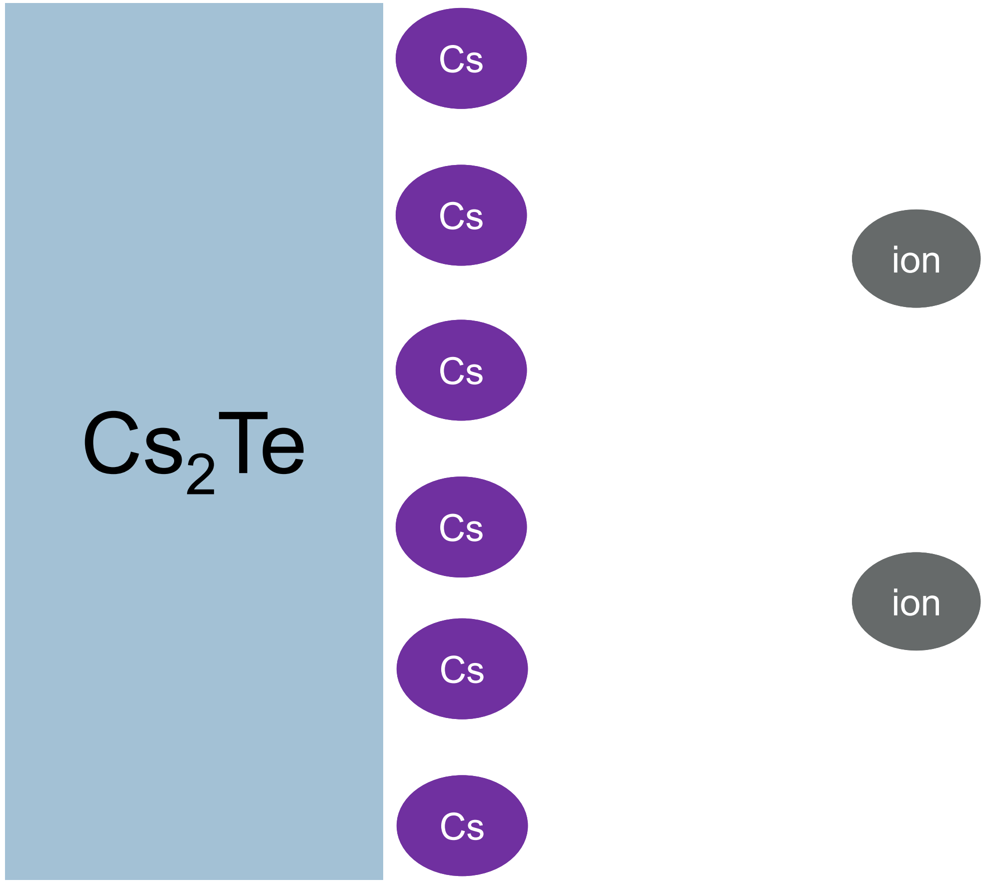
Picture I – Oxygen absorption



The oxygen will continuously be absorbed onto the surface. And the dangling electrons will move towards the hole position to form a stable state. So gradually the number of electrons on the donor level reduce, leading to the decrease of band bending. Consequently the surface photovoltage phenomenon will be less prominent after a long time operation.

A proposed picture for no spike after long time operation

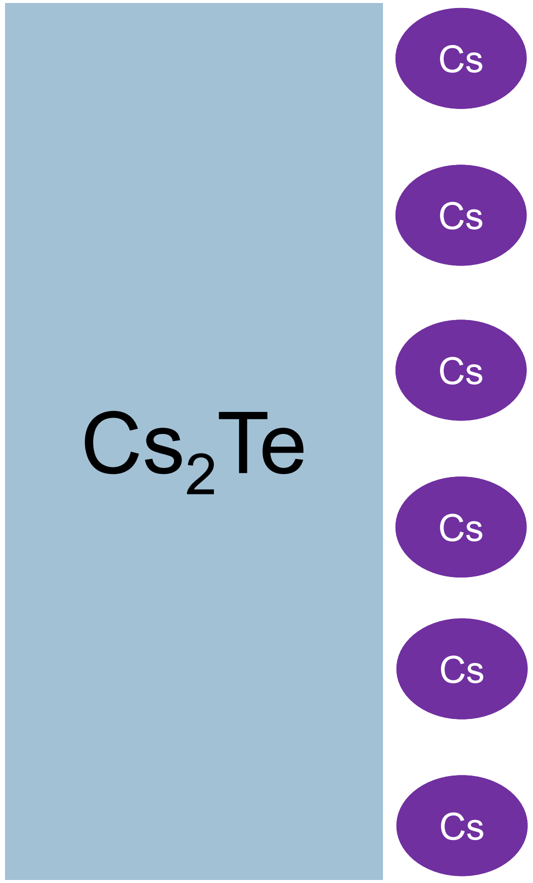
Picture II – Back scattering



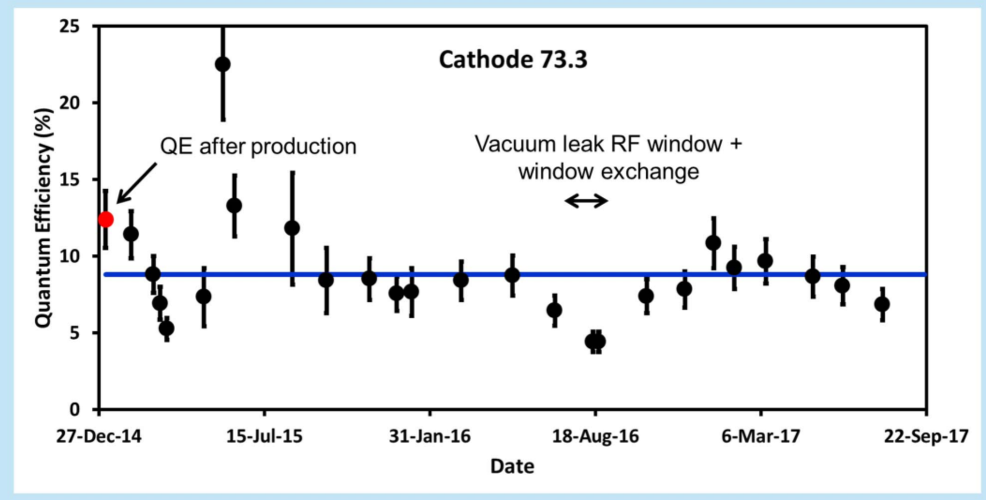
Back scattering induce the loss of cesium on the surface, leading to the reduction of the density of electrons on the surface donor level. This results in the decrease of band bending.

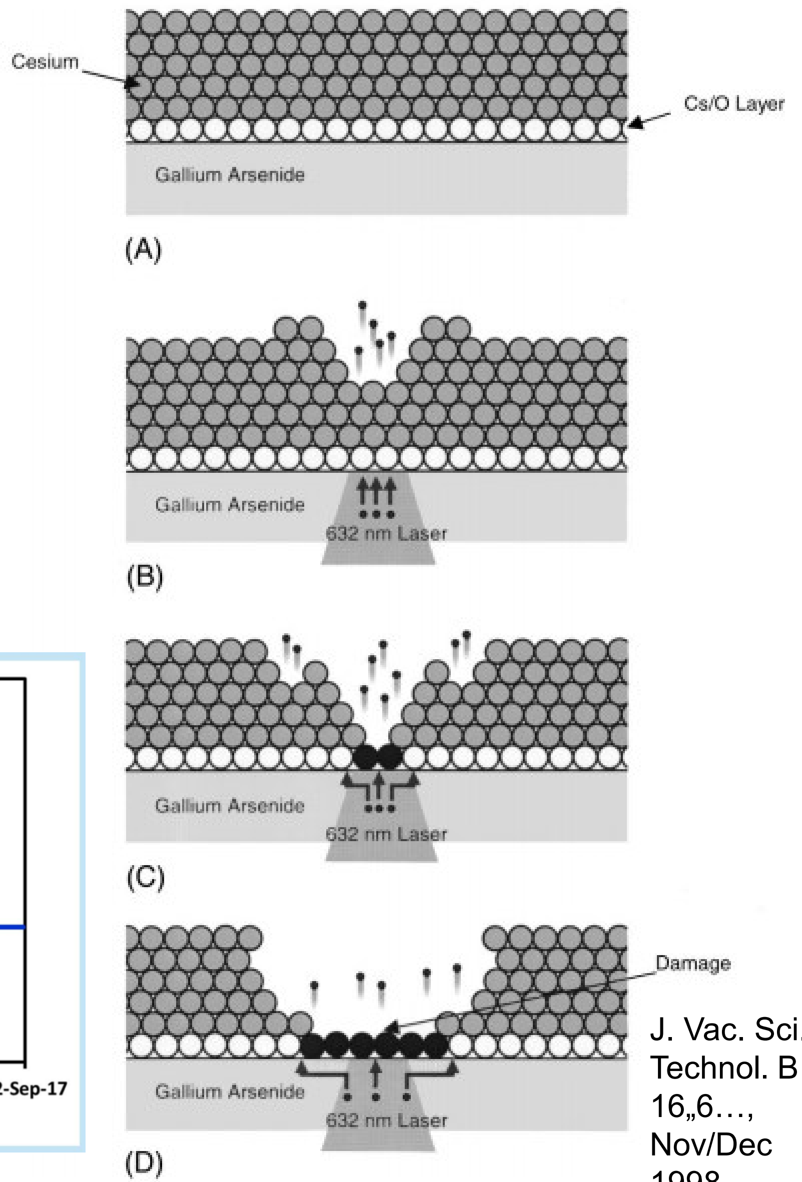
A proposed picture for no spike after long time operation

Picture III – Laser induced diffusion



The diffusion of cesium atoms may account for the oscillated QE performance discovered in the operation of FLASH





J. Vac. Sci. Technol. B 16,,6…, Nov/Dec 1998

Summary

- Introduce SPV to the analysis of photocathode in accelerator.
- A model is established to explain the spike distribution related experiment results in FLASH.
- Increasing the density of acceptor level can mediate the spike.
- Oxygen absorption, back scattering and laser induced diffusion may account for the vanish spike after long time operation.