Characterization of Multi-Alkali antimonide Cathodes at Cryogenic Temperature and their Performance in SRF Gun

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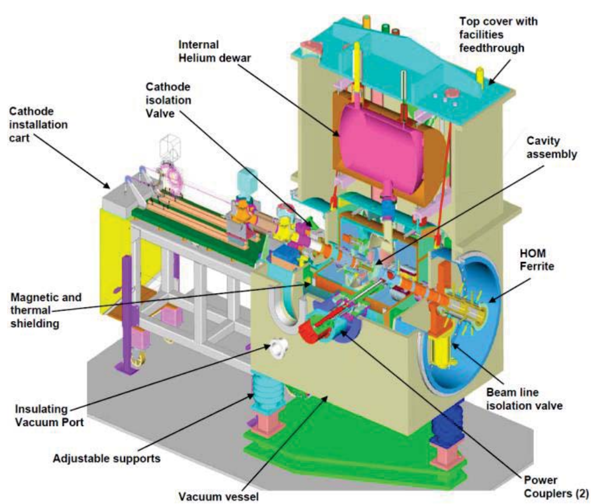
Outline

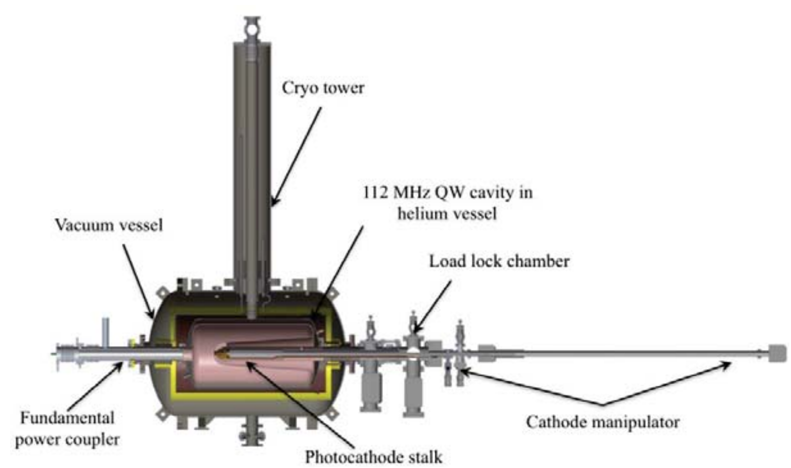
- Motivation
- Multi-alkali photocathode preparation for SRF guns in BNL
- Cathode performance in SRF gun
- Cathode QE evolution while it cools down and the model
- Monte-Carlo simulations of K_2CsSb photocathode photoemission
- Summary

Motivation

- BNL's high current ERL needs 300mA average current and CeC needs above 50mA average current beam.
- Alkali-antimonide photocathode such as $K_2Cs(Na)Sb$ QE is 10% @532nm, could survive in 10^{-10} torr scale vacuum.
- Alkali-antimonide photocathode has demonstrated delivery of 75mA average current with long lifetime in Cornell's DC gun.
- We are commissioning the SRF gun with K_2CsSb photocathode right now.

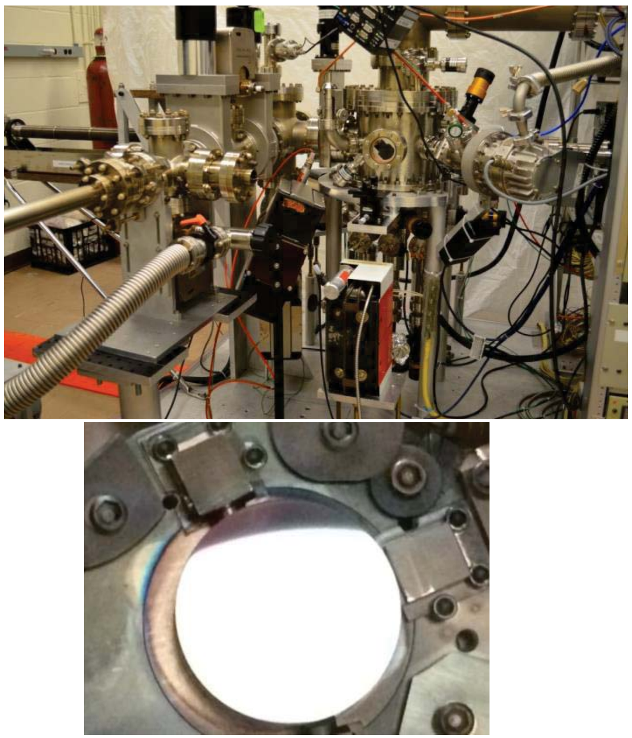
Dr. Dmitry Kayran **Status and Commissioning Results of the R&D ERL at BNL** ;
Dr. Wencan Xu **Commissioning Program for the 704 MHz SRF Gun at BNL**





Multi-alkali photocathode preparation

- From last year, we can provide ~10% QE photocathode to the 112MHz gun.
- Right now we can provide 4% QE cathode to the ERL gun.



Preparation system for 112MHz gun

Preparation system for 704MHz gun

Cathode preparation procedure

Substrate material: molybdenum or tantalum

Alkali source: Saes getter

- Conventional sequence deposition:
- Heat up the stalk to 350°C for 6 hours.
- Reduce the temperature to 90°C
- Evaporate Sb layer to 10 nm of thickness. The thickness is measured by a crystal monitor.
- Increase the substrate temperature to 130°C.
- Evaporate the K layer to reach 20nm, or by monitoring the photocurrent
- Gradually reduce the temperature while evaporating the Cs.
- Fine tune the Cs evaporation rate until we get the maximum photocurrent.
- Keep the Cs source at low evaporation rate until the cathode cools down to 50°C, then stop the evaporation.

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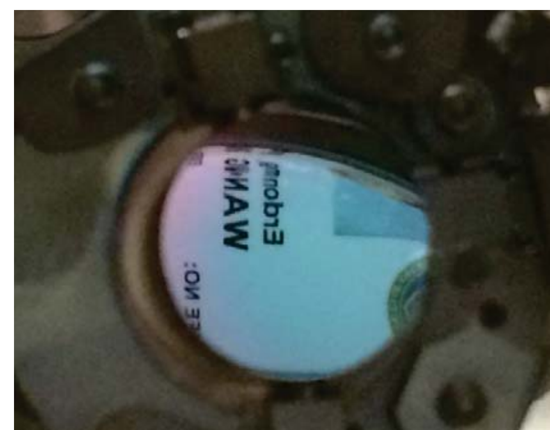

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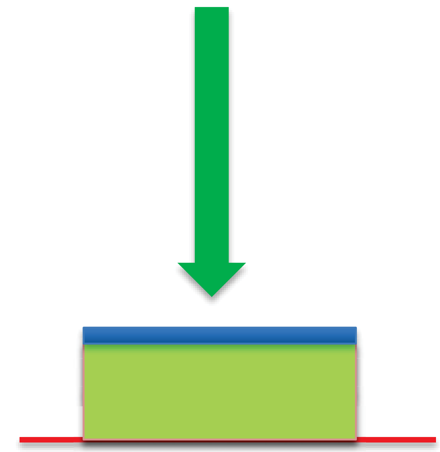

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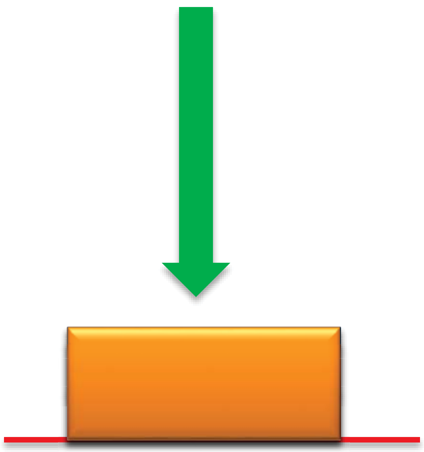

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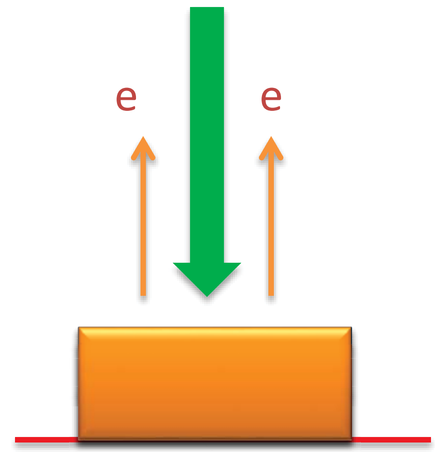
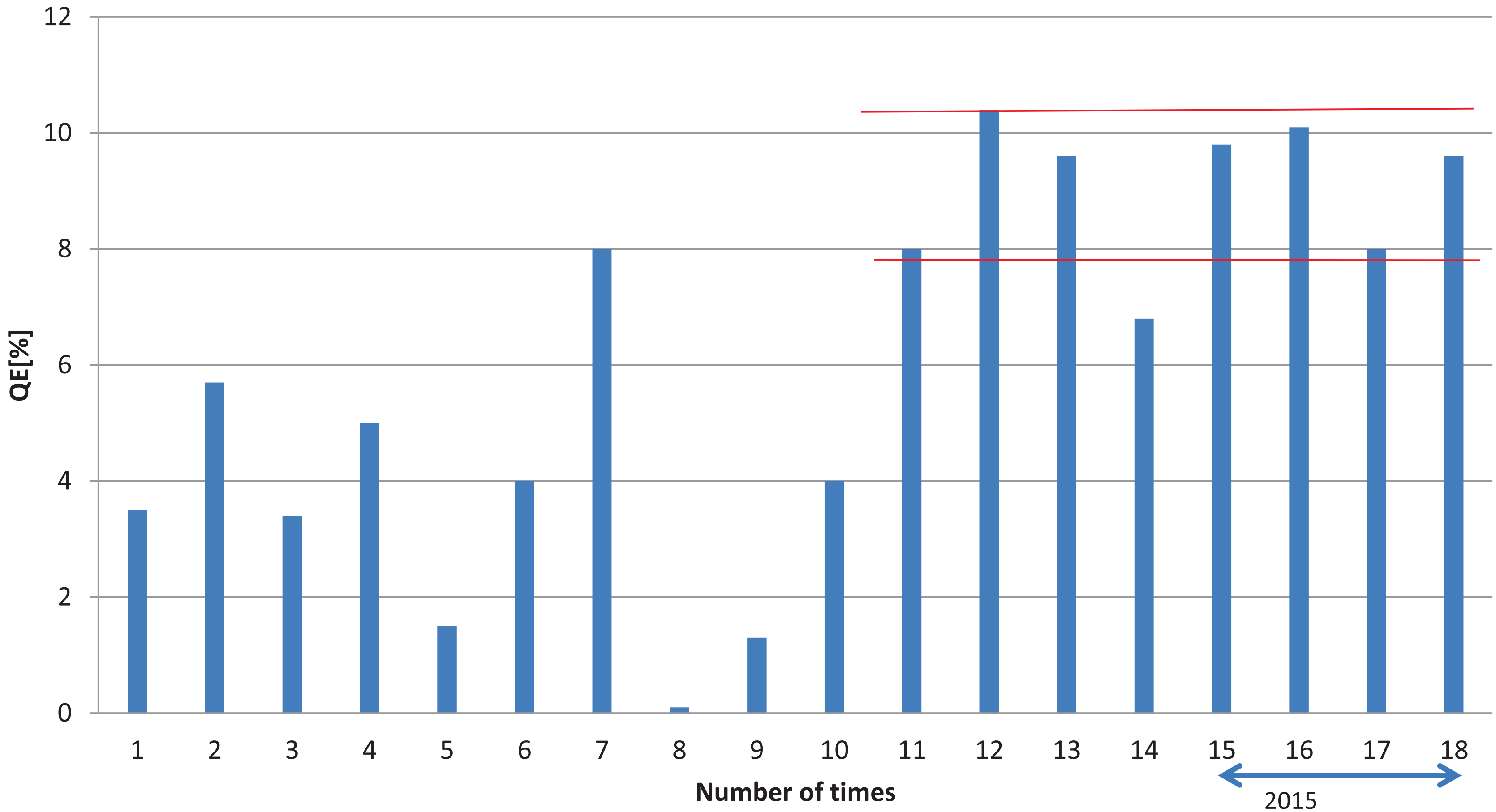


Photocathode preparation trend



For 112MHz gun photocathode preparation

Cathode transfer

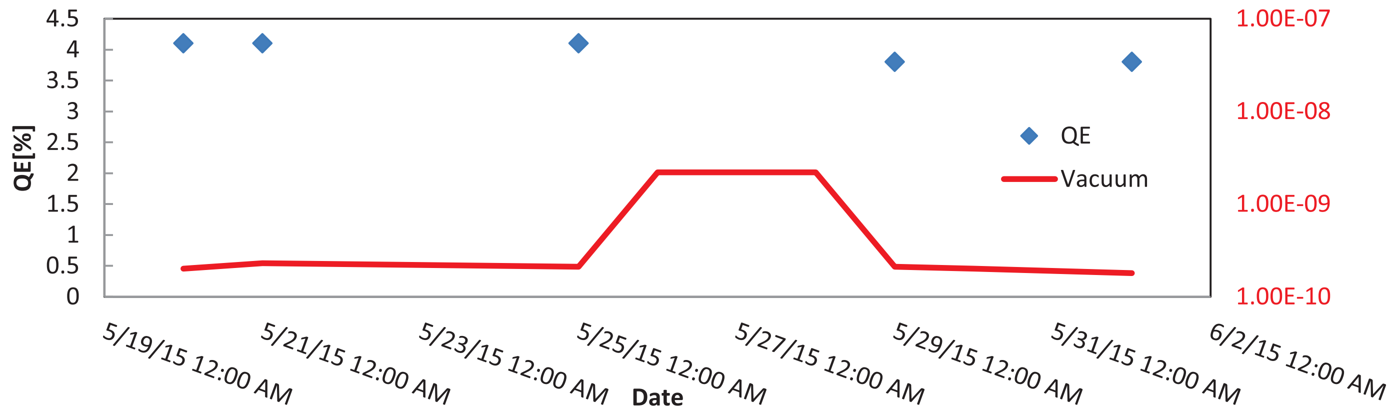
- The cathode is prepared in a dedicated cathode preparation system.
- The cathode is moved into transport cart which has low-10^{-10} torr scale vacuum.
- Disconnecting the transport cart from the preparation system and connecting the cart to the SRF gun require a class-100 clean enclosure.
- The loadlock section is baked about 2 days and reach 10^{-9} torr scale Vacuum.
- We keep monitoring the QE evolution inside the transport cart. We make sure that the cathode still has a good QE before moving it into the SRF gun.

112 MHz gun cathode transferring chamber

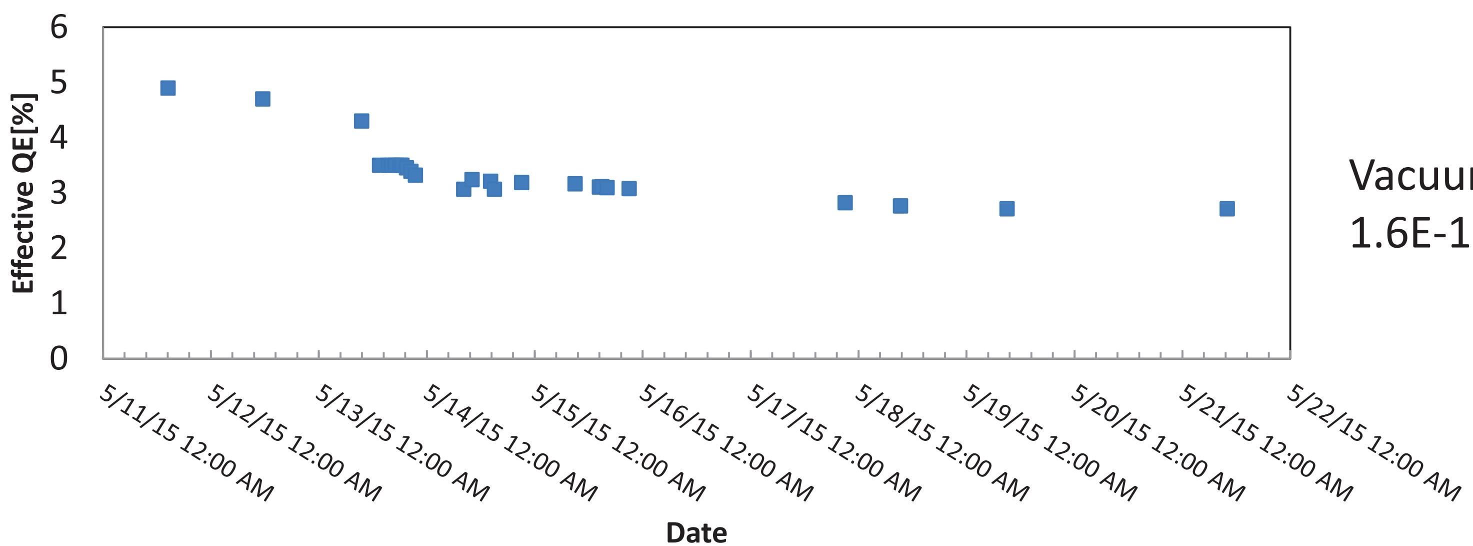
704 MHz gun cathode transferring cart

QE evolution in Cathode transfer

704MHz gun cathode:



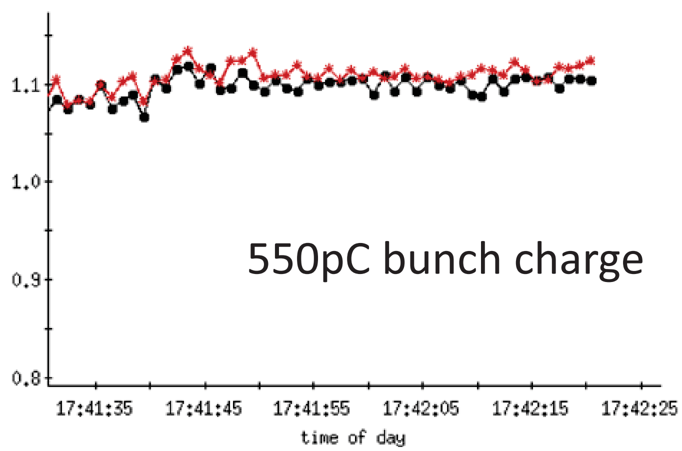
112MHz gun cathode in tunnel:

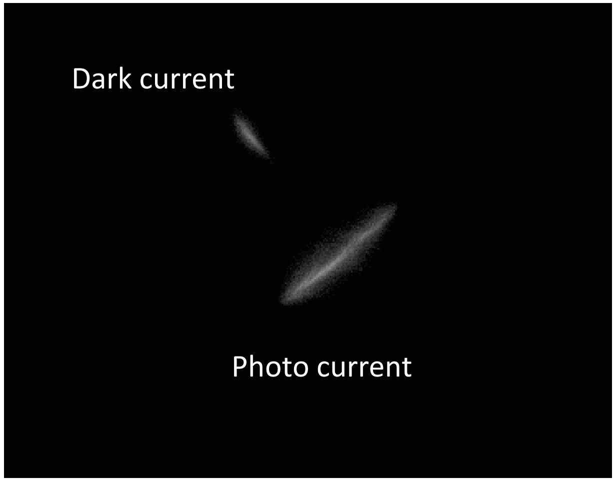


Vacuum at 1.6E-10 torr

Cathode performance in the gun

- We tested a 3.8% QE K_2CsSb cathode in the 704MHz SRF gun.
- The cathode survives well the gun and stalk RF conditioning.
- The cathode QE inside the gun (cold) is 1%. We didn't see any QE degradation after two days of high bunch charge operation. The vacuum at the gun exit is at 10^{-9} scale during gun operation.
- After extracting the cathode out of the gun, the QE is still at 3.8%.
- 8uA@1MV dark current may due to good cathode. (Small QE cathode only get 1.2uA@1.2MV.)





Cathode rejuvenation after bad vacuum exposure

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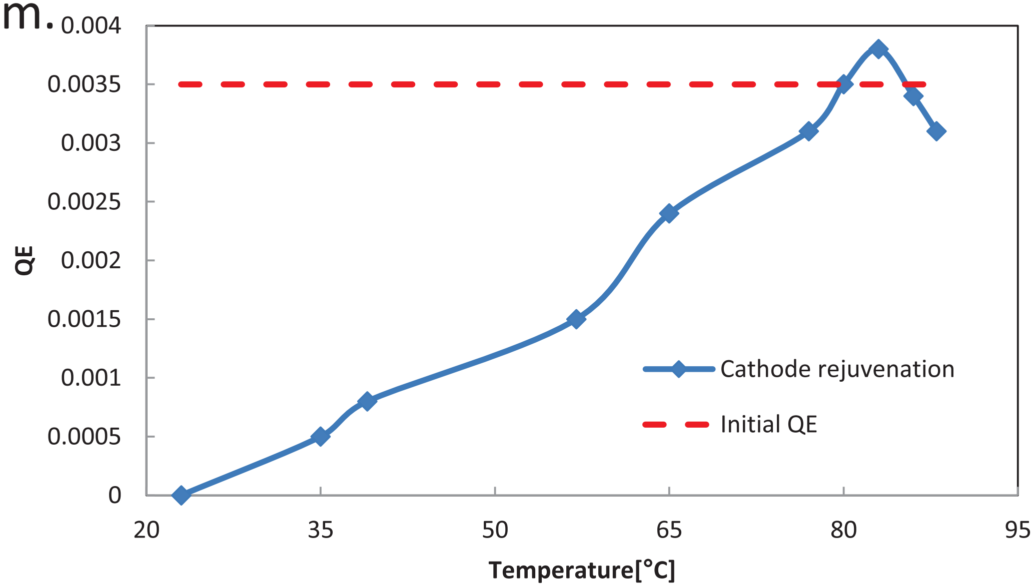
•Last year, during low current beam test, the cathode was exposed to a bad vacuum (10^{-6} torr) due to a cryogenic accident at end of the day shift. The cathode was damaged.

•The QE was zero when it was extracted from the gun.

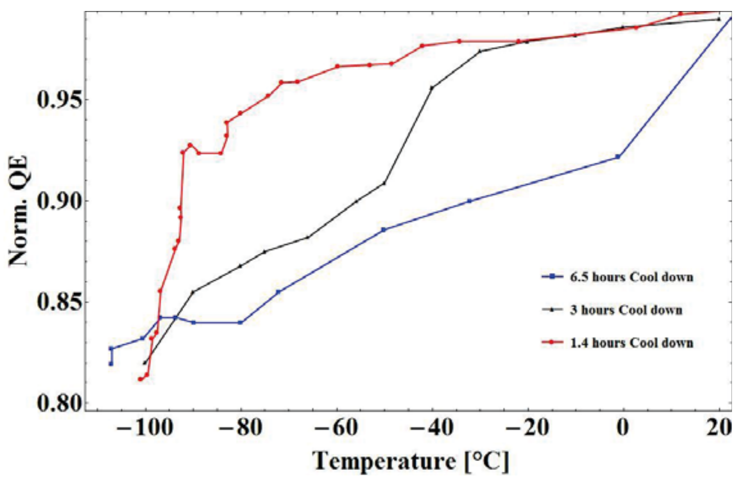
•After we heated the cathode up to 80°C, 80% of QE was recovered.

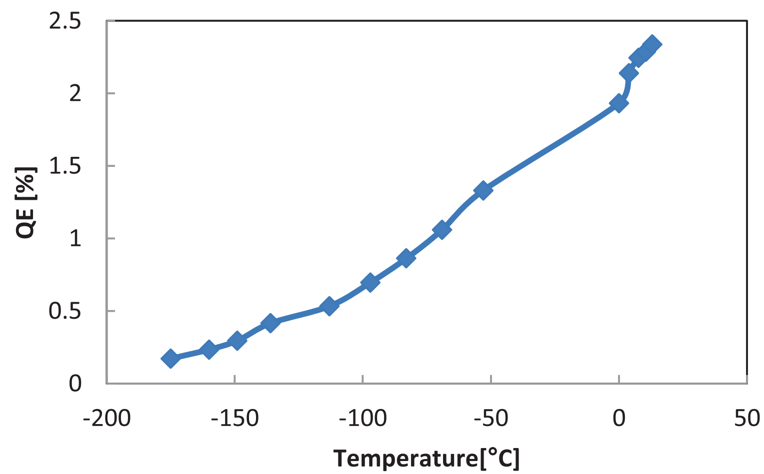
•We conclude that the cathode will not be damaged by 10^{-6} torr vacuum.



QE degradation due to cooling

•We observed that the cathode QE will drop when cooled down. We carried out multiple cooling tests and saw the QE will drop factor of 8~10 (at 532nm) when the cathode cools down to LN_2.
•In the SRF gun, the cathode is either cooled by LN_2 or water.
•QE could fully recovery if the cathode warms up back to room temperature.





Why does the QE decay?

•Mechanism: Surface gas trapping at cryogenic temperatures and generating a surface potential barrier.

➢Solution: Cool the cathode after environment's temperature drop to 2K.

•Reduction in electrical conductivity due to decreased carriers' density at cryogenic temperature. C. Ghosh J. Appl. Phys., Vol. 49, No.8, August 1978

➢The reduction of the number of electrons filling donor levels lying on Fermi level having energies large enough to be excited above the photoemission threshold.($E_{photon}<E_g+E_a$) W.E. Spicer, Phys. Rev. 112, 114 (1958) ; L. Cultrera, Arxiv. 1504.05920(2015)

•Increase in work function due to change in lattice structure at low temperature.

➢Band gap change from 1.42eV to 1.5eV while cathode cool down to LN2 temperature measured by Spectral photoluminescence.

V. Beguchev J. Phys. 0: Apl. Phys. 26 (1993) 4499-4502.

Schottky effect compensates the band gap change

Surface barrier change due to Schottky effect:

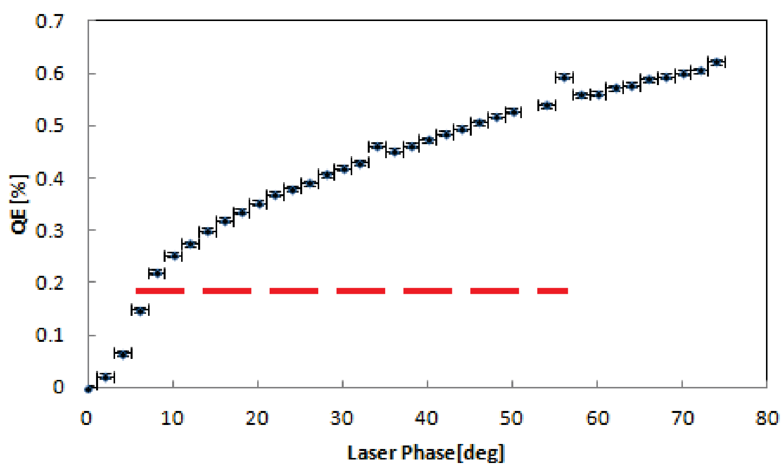
$$\varphi s = \sqrt{\frac{eE_s}{4\pi\varepsilon_0}\left(\frac{\varepsilon-\varepsilon_0}{\varepsilon+\varepsilon_0}\right)}$$

K_2CsSb relative permittivity: 9.2

L. Kalarasse, B. Bennecer Journal of Physics and Chemistry of Solids Volume 71, Issue 12, December 2010, Pages 1732–1741

$$\varphi_{s=}0.034\sqrt{E\left(\frac{MV}{m}\right)}\,[eV]$$

With 20MV/m gradient , from the Schottky effect induced potential change is above 0.08eV



Peak current 1.65A
Gradient 10 MV/m

Monte-Carlo simulation

- To understand the K_2CsSb photocathode photoemission, we developed a python-based 2D Monte-Carlo simulation code based on Spicer's three step model. We want to learn:

➢ How does the density of states affect the electrons excitation?

➢ How do the carrier scattering and the electron-phonon scattering affect the electrons transportation?

➢ Momentum conservation at emission ?

➢ Could we know the thermal emittance and temporal response from the code?

➢ Get the beam initial distribution for Parmela or Astra

Electrons excitation

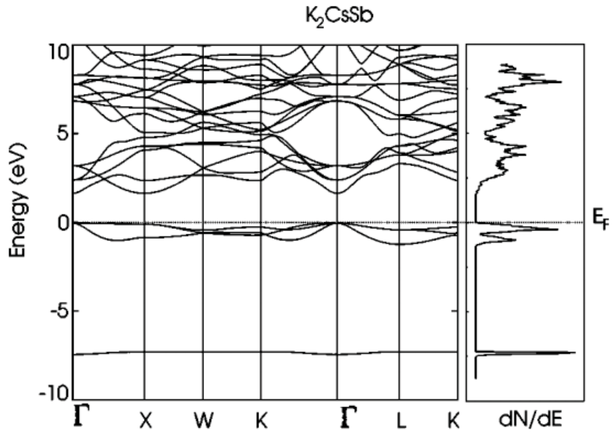


FIG. 3. The dispersion of the energy bands in K$_2$CsSb (left-hand side) and the corresponding state density (right-hand side).

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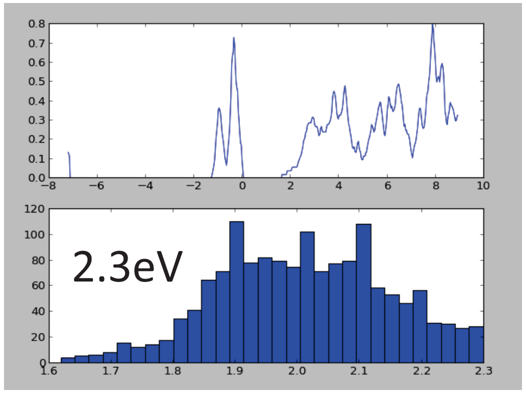
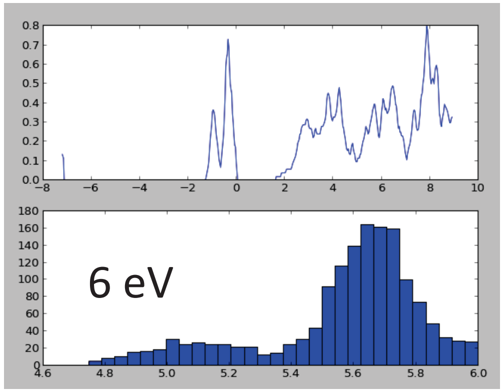
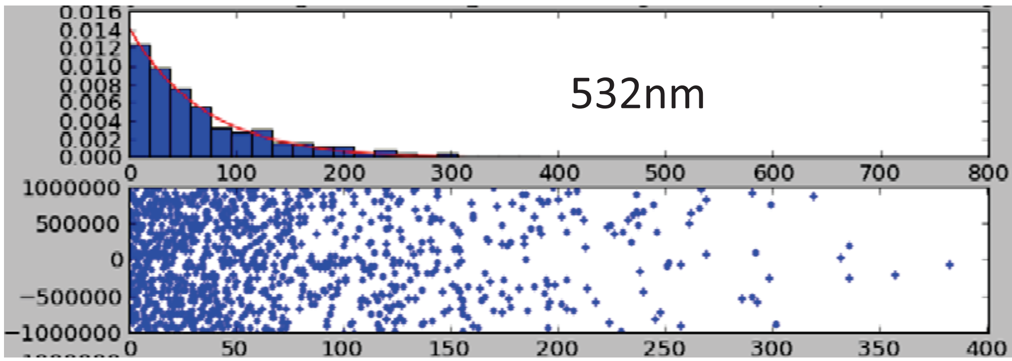




- We used K$_2$CsSb density of state.(Original data provided by J. Smedley)
- The energy distribution of excited electron is $DoS_{VB} \otimes DoS_{CB}(h\nu)$
- Energy gap is 1.6eV
- Absorption length=((19.82-27.95*ep+11.15*ep^2)0.001)$^{-1}$



Scattering in electrons transport

•Electron phonon scattering:

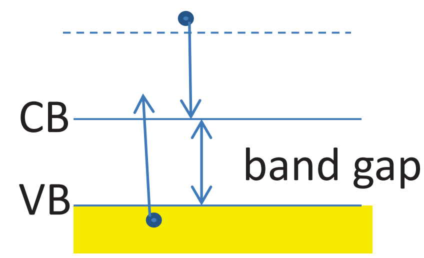
Electrons scatter from one valley to another by absorbing or emitting an optical phonon of energy.

$E_{k'} = E_k \pm h\omega$ where hw is the phonon energy (0.027eV)

V. Beguchev J. Phys. 0: Apl. Phys. 26 (1993) 4499-4502

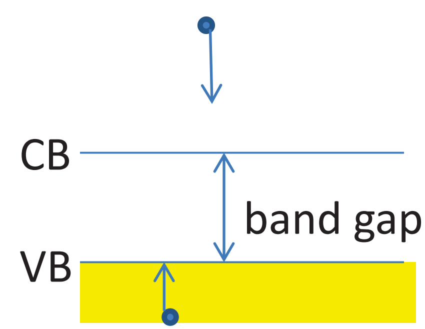
•Electron-electron scattering:

$E_e - E_{CB} > E_{bandgap}$



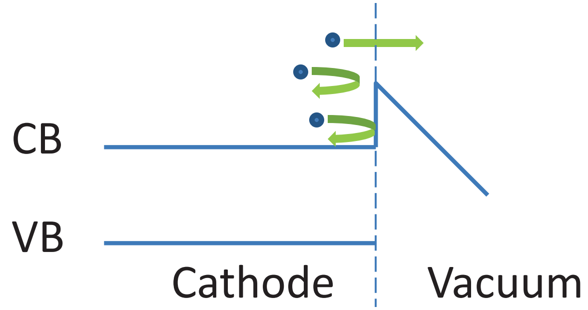
•Electron-hole scattering:

P doped material like surface over-Cesiation



Emission

•If the electron's energy is less than the electron affinity, electrons come back and encounter another diffusion iteration.



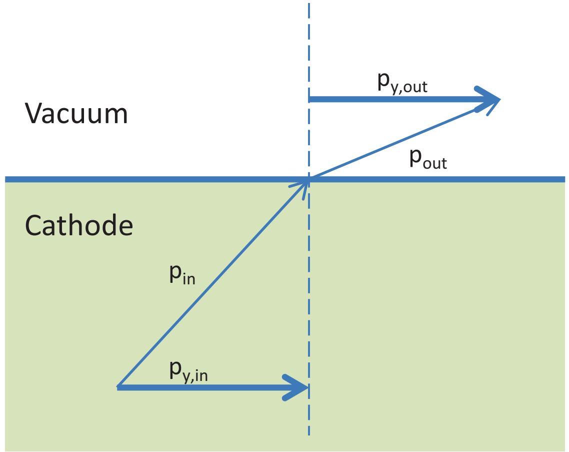
•If the electron's energy is more than the electron affinity, consider the transverse momentum continuity.

$$p_{out} = \sqrt{2m(E_k - ea - \varphi_{eff})}$$

$$p_{y,in} = p_{y,out}$$

$$\frac{Sin\ \theta_{out}}{Sin\ \theta_{in}} = \frac{p_{in}}{p_{out}} = \sqrt{\frac{(E_k - ea - \varphi_{eff})}{E_k}}$$

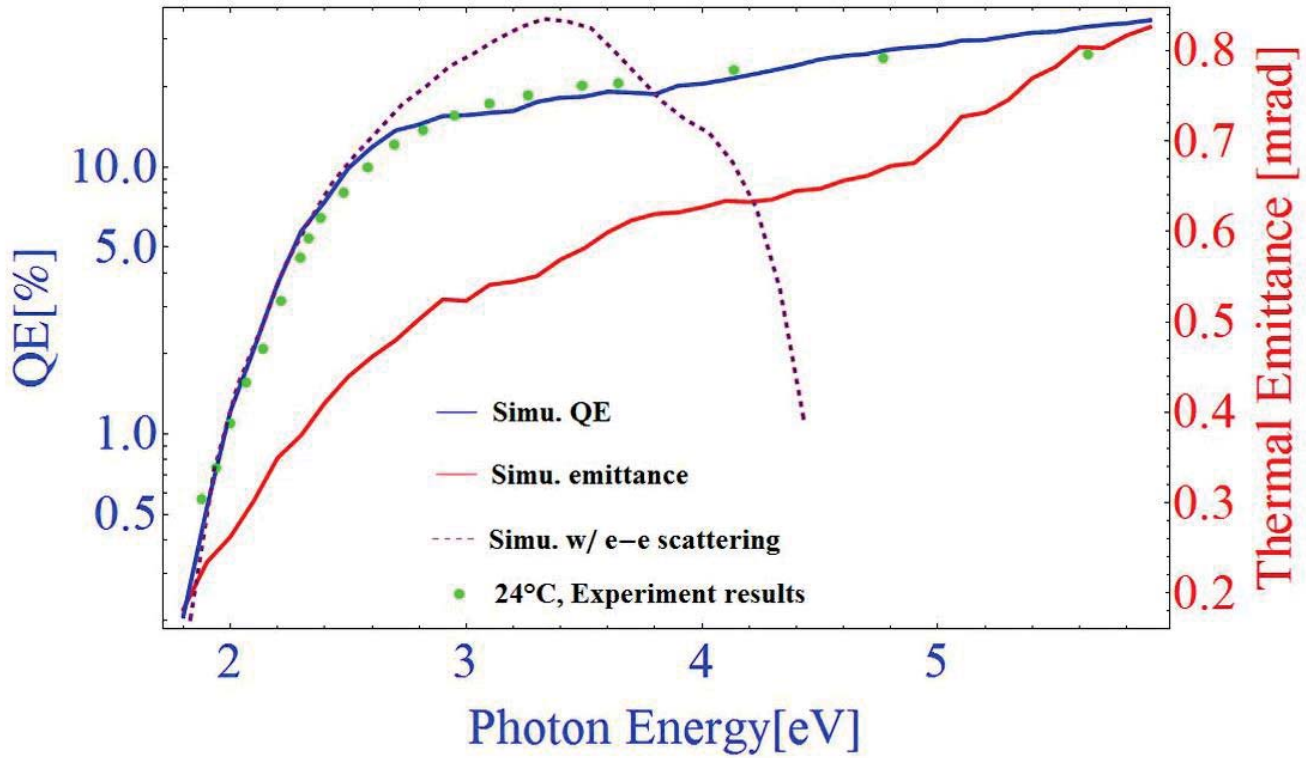
$$Sin\theta_{in,max} = \sqrt{\frac{E_k}{(E_k - ea - \varphi_{eff})}}$$



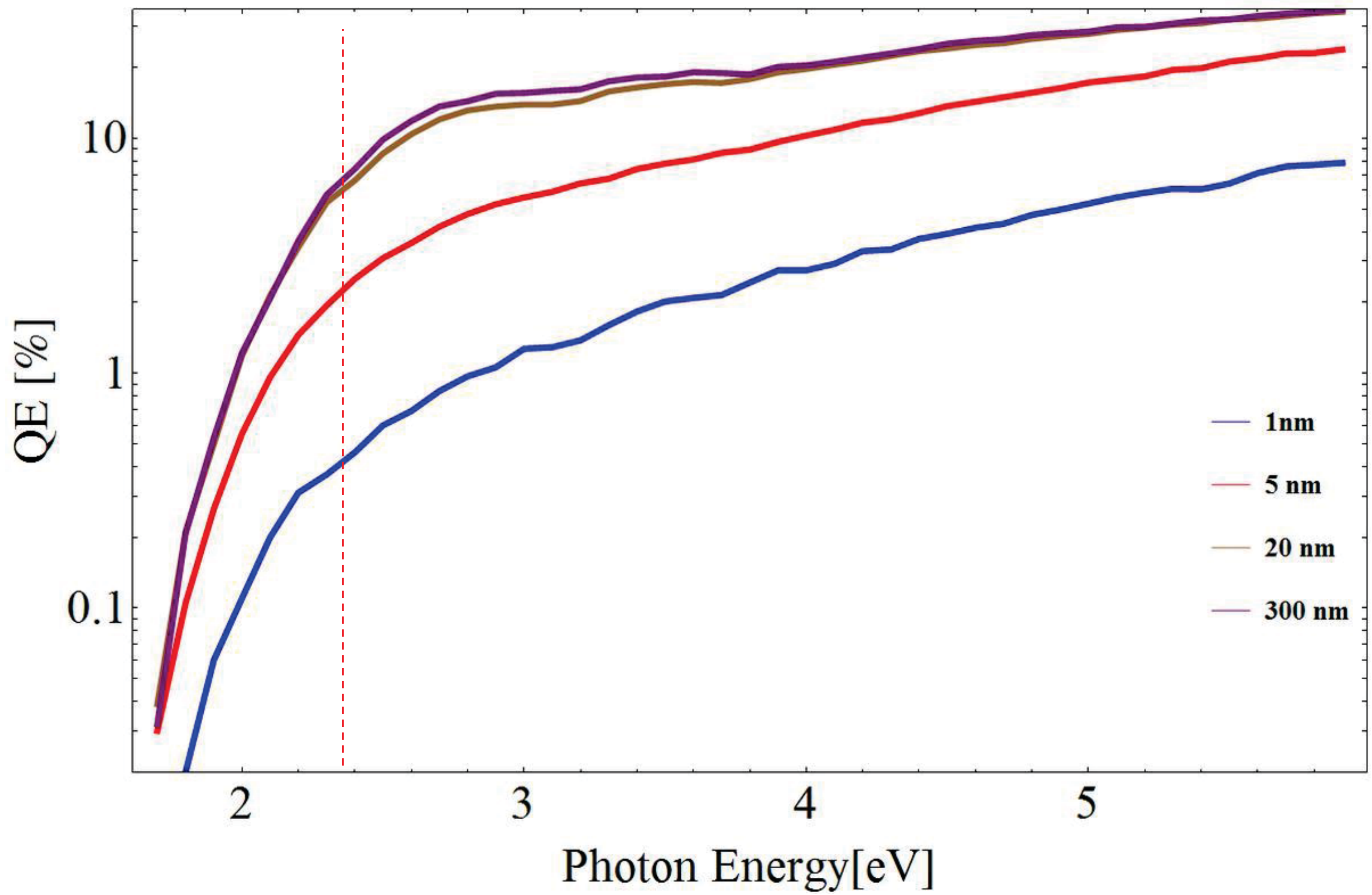
QE , thermal emittance vs wavelength

- QE: # emitted electrons / # incident photons

- Thermal Emittance: $\frac{\epsilon_n}{\sigma_x} = \frac{\sqrt{\langle v_x^2 \rangle}}{c} [mrad]$

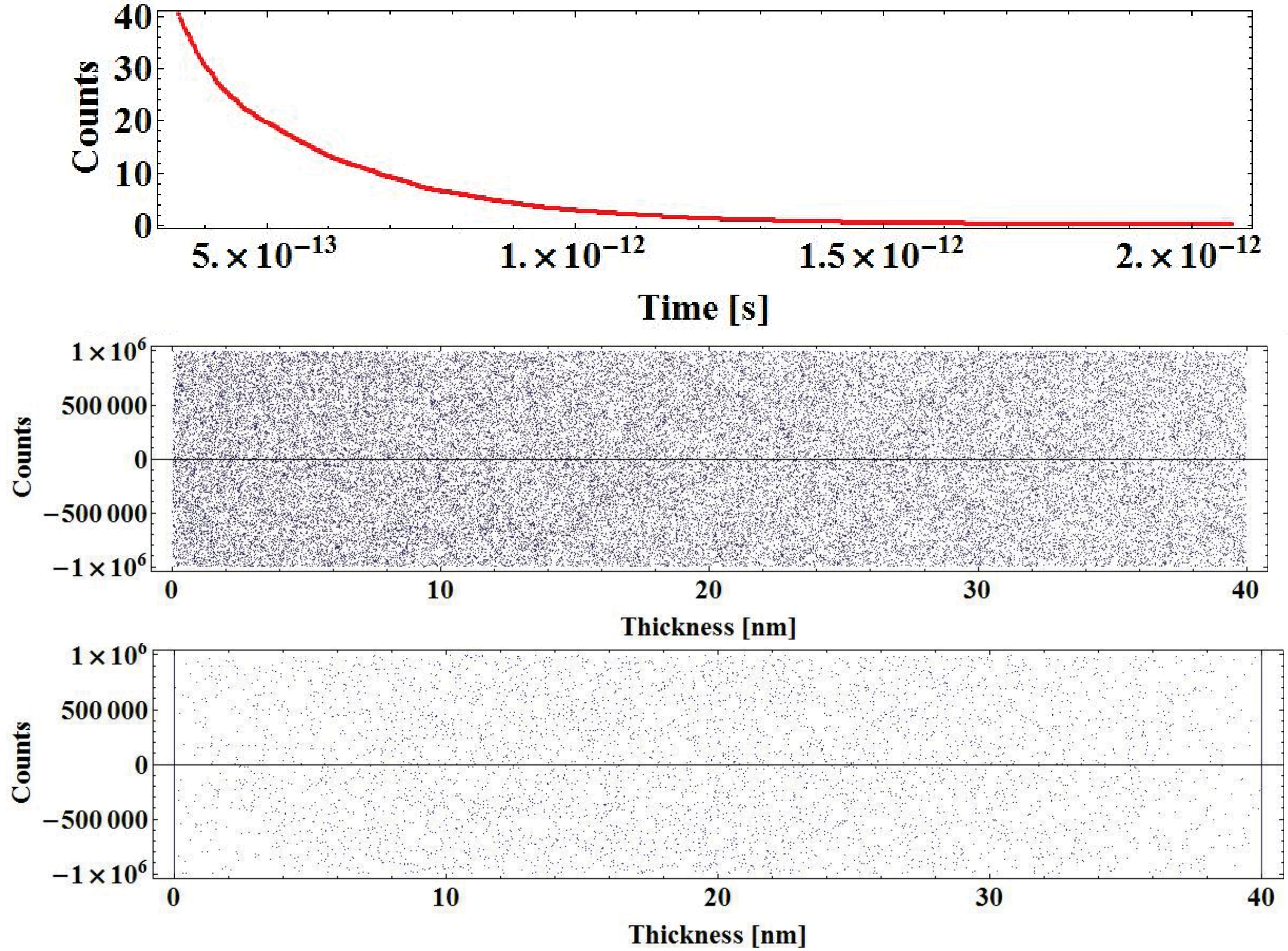


QE vs thickness



Above 20nm, cathode QE will not change.

More results



40 nm thickness photocathode, 532nm laser, delta function
100,000 electrons , run 2 hours on PC

Conclusion

- We are capable to provide high quality K_2CsSb photocathodes to both the CeC and ERL projects.
- The 704MHz SRF gun generated high bunch charge from K_2CsSb cathode. In two days operation, no QE decay was observed.
- The QE degradation due to cold cathode was studied. We observed the Schottky effect by scanning the RF phase.
- One Monte-Carlo code was developed to understand the multi-alkali photocathode photoemission.

Acknowledgements

- ERL group on cathode researches and test in SRF gun

I. Ben-zvi; T. Rao; S. Belomestnykh; B. Sheehy; J. Skaritka; D. Kayran; H. Xie; T. Xin; W. Xu; L. Hammons; R. Kellerman; C. Liaw; V. Litvinenko; G. McIntyre; T. Miller; T. Seda; R. Than; D. Weiss.

- J. Smedley and D. A. Dimitrov on cathode modeling discussion

Thanks for you attention!