High Yield Structured X-ray Photo-Cathode Development and Fabrication

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October 7, 2015

This work was done by National Security Technologies, LLC, under Contract No. DE-AC52-06NA25946 with the U.S. Department of Energy. DOE/NV/2594--2631.

Outline

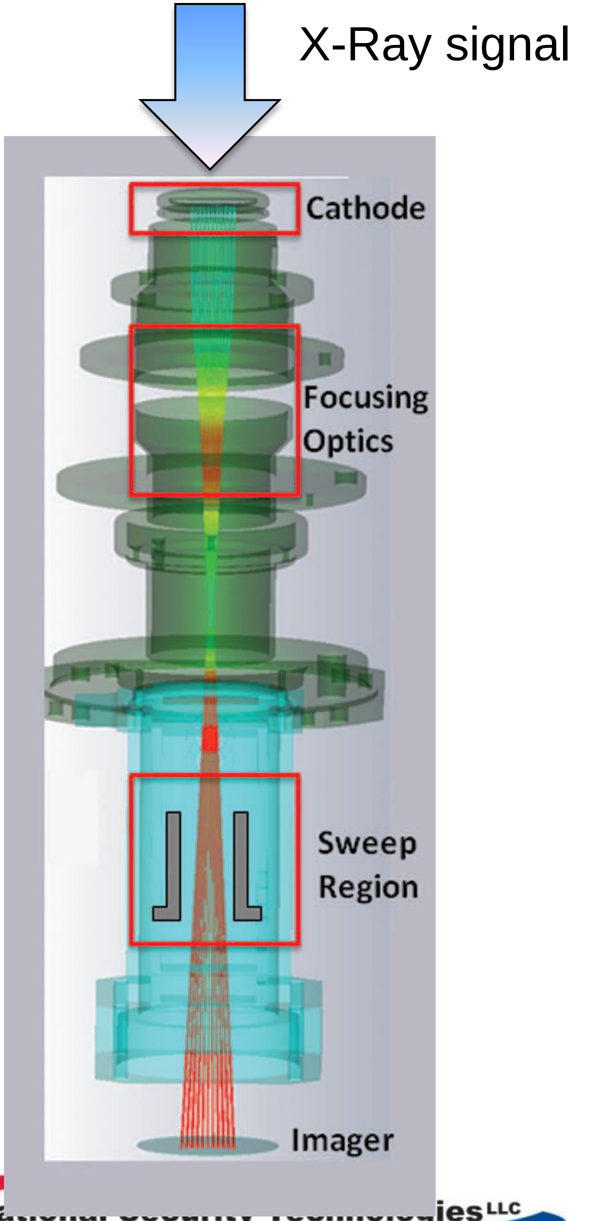
- **Overview**
  - Motivation for the project.
  - Yield enhancement at grazing incidence.
  - Utilization of 3-D structures.

- **Photocathode Design and Fabrication Details**
  - Photocathode design considerations and requirements for X-ray imagers.
  - Recessed cavity design and expected yield.
  - Fabrication details and results.
- **Recent measurements show an increase in yield**
- **Project Accomplishments**
- **Future work**

Future diagnostics will need a high QE photocathode in the 10 – 50 keV range

Diagnostic Insertion Manipulator Imaging Streak Camera (DISC) and **Streaked Polar Instrumentation for Diagnosing Energetic Radiation (SPIDER):**

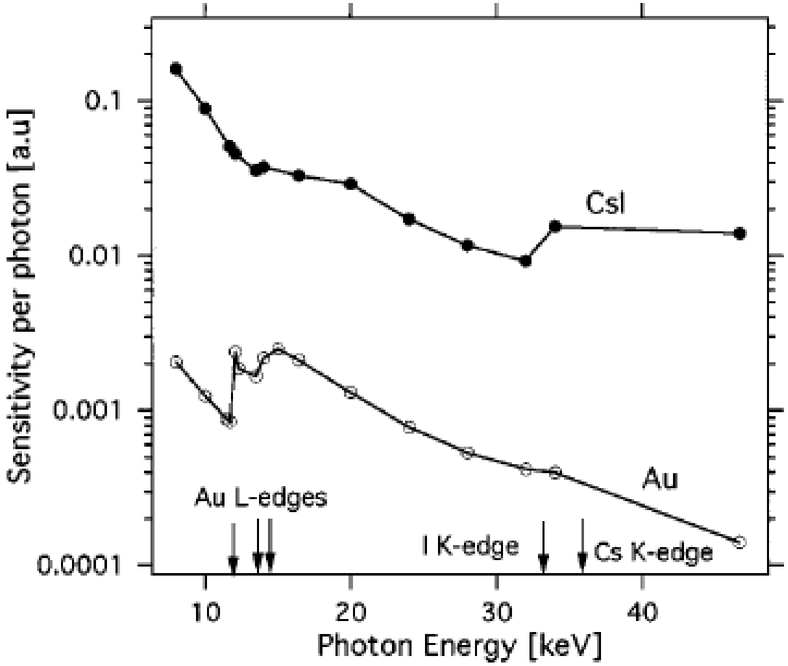
- Kentech low magnification streak camera.
- Best temporal resolution (10 ps).
- Best spatial resolution at focus 90 µm.
- Uses CsI and Au photocathodes.
- Used in the 1 - 8 keV X-ray range.

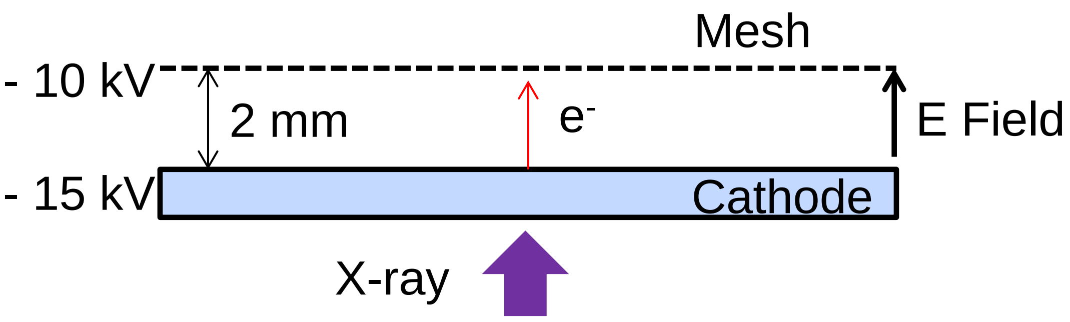


New imaging sources will be generating X-ray photons at energies >10 keV, maybe a potential complication for current detectors.

A drop in sensitivity is seen above 10 keV for most cathode materials

T. Hara RSI Vol. 71 (10) p 3624

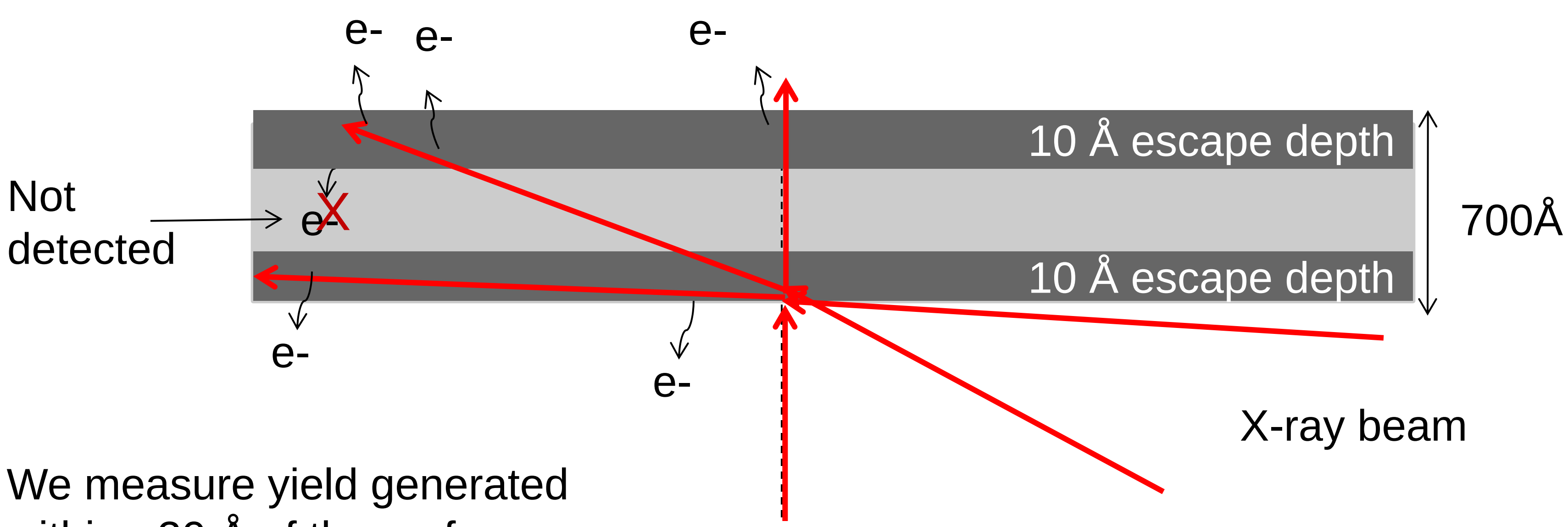




- **Yield drops above 10 keV.**
- **Difficult to use due to low signal levels.**

Yield can be increased by going to the grazing incidence geometry.

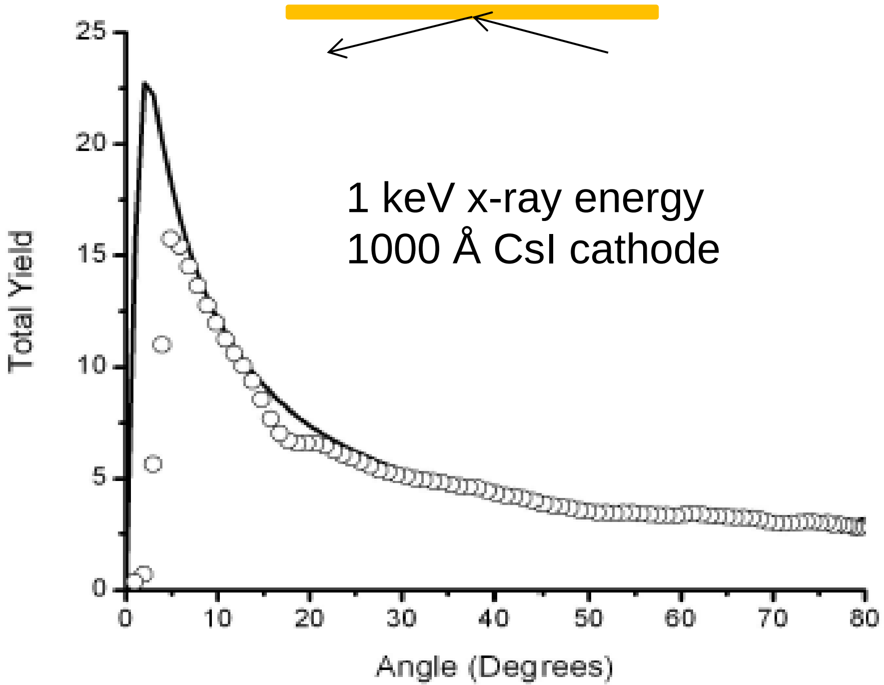
Matching the X-ray path length to the escape depth at grazing incidence increases the electron yield



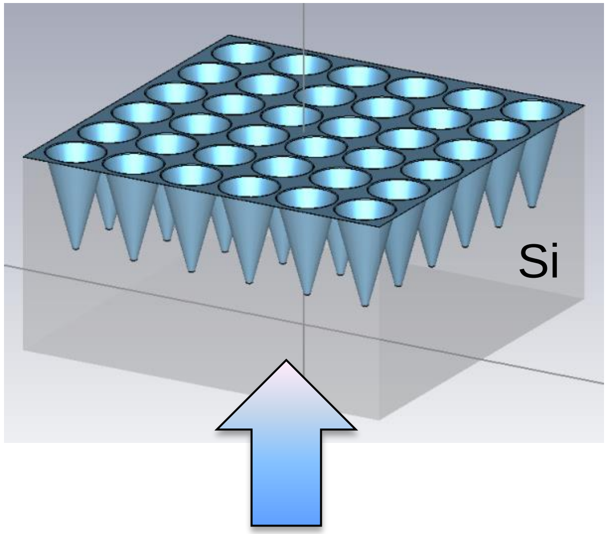
We measure yield generated within ~20 Å of the surface (photoelectron escape depth limited)

Shallow incidence angles are needed to increase X-ray path length through the top most emission surface.

Previous measurements show ~4x increase in yield at grazing incidence



Recessed Cavity Design



From: D. Lowney, *Proc. SPIE* **5194** (2004) 139.

Recessed cavity structures utilize this effect to improve yield.

Photocathode design considerations for time – dilated and streaked X-ray imagers

Geometry:

-Self supporting, large area cathodes are needed.

Spatial Resolution:

-The spatial resolution requirement is ~50 µm for DISC. <200 µm for DIXI.

Temporal Resolution:

-The temporal resolution must be within the current best NIF X-ray diagnostic resolution. Current resolution is ~10 ps (for DISC).

High E - Field:

-Structure must not field emit in large voltage gradients (as high as 10 kV/mm).

Cathode Materials:

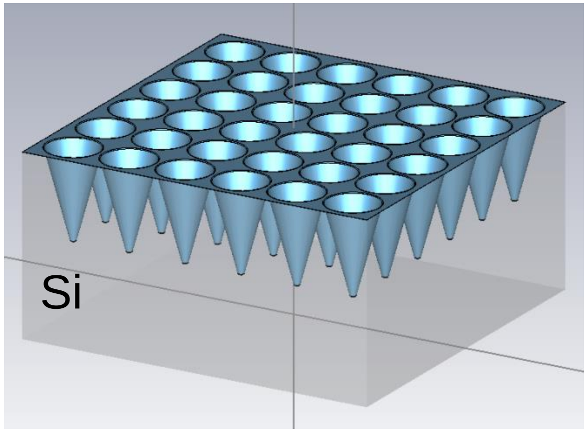
-Currently Au and CsI are used and must be supported by the structure design.

Last year we showed that the recessed structures satisfy these requirements.

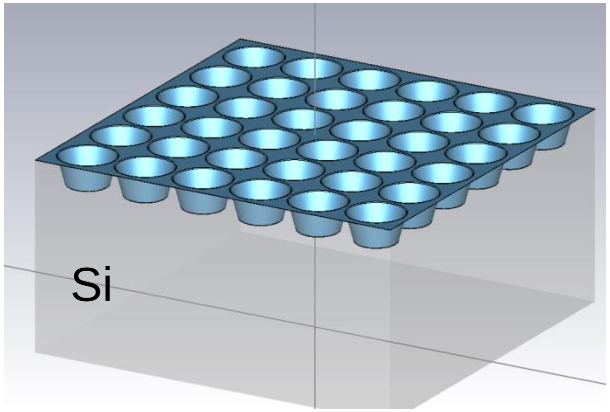
Total yield enhancement expected to be 1.2-3 times at 10 keV

Energy (keV)	Recessed Geometry	Incidence Angle	Diameter (µm)	Depth (µm)	Δt (psec)	Au Rel. Increase
10	Cone	10 - 15	9	3	1	1.6
10	Cone	10 - 15	9	8.4	~10	2.36
10	Cone	10 - 15	9	16.8	~200	2.81

Full Depth



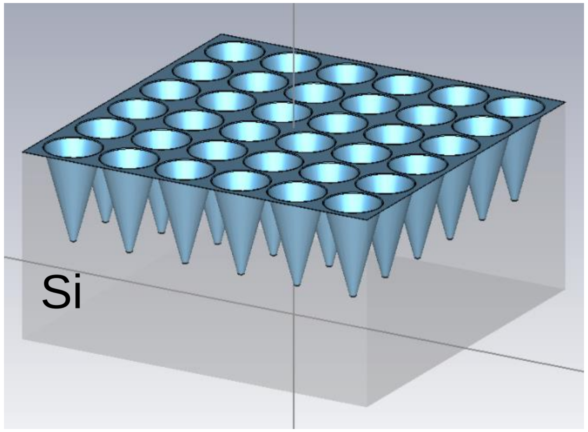
Shallow Depth



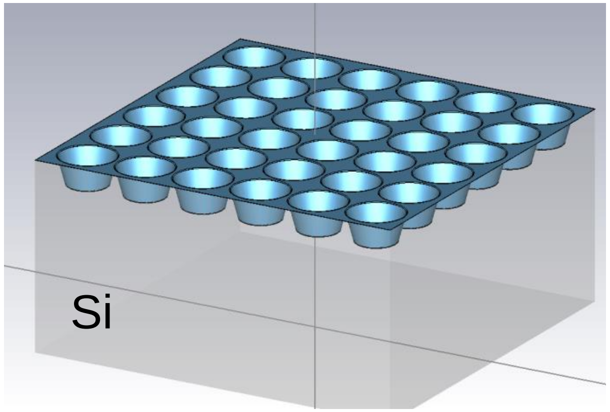
- 9 µm diameter chosen for ease of fabrication
- 10 - 15 degree wall angle chosen to increase enhanced surface area

Prototype requirements were based on recessed cavity modeling results

Full Depth

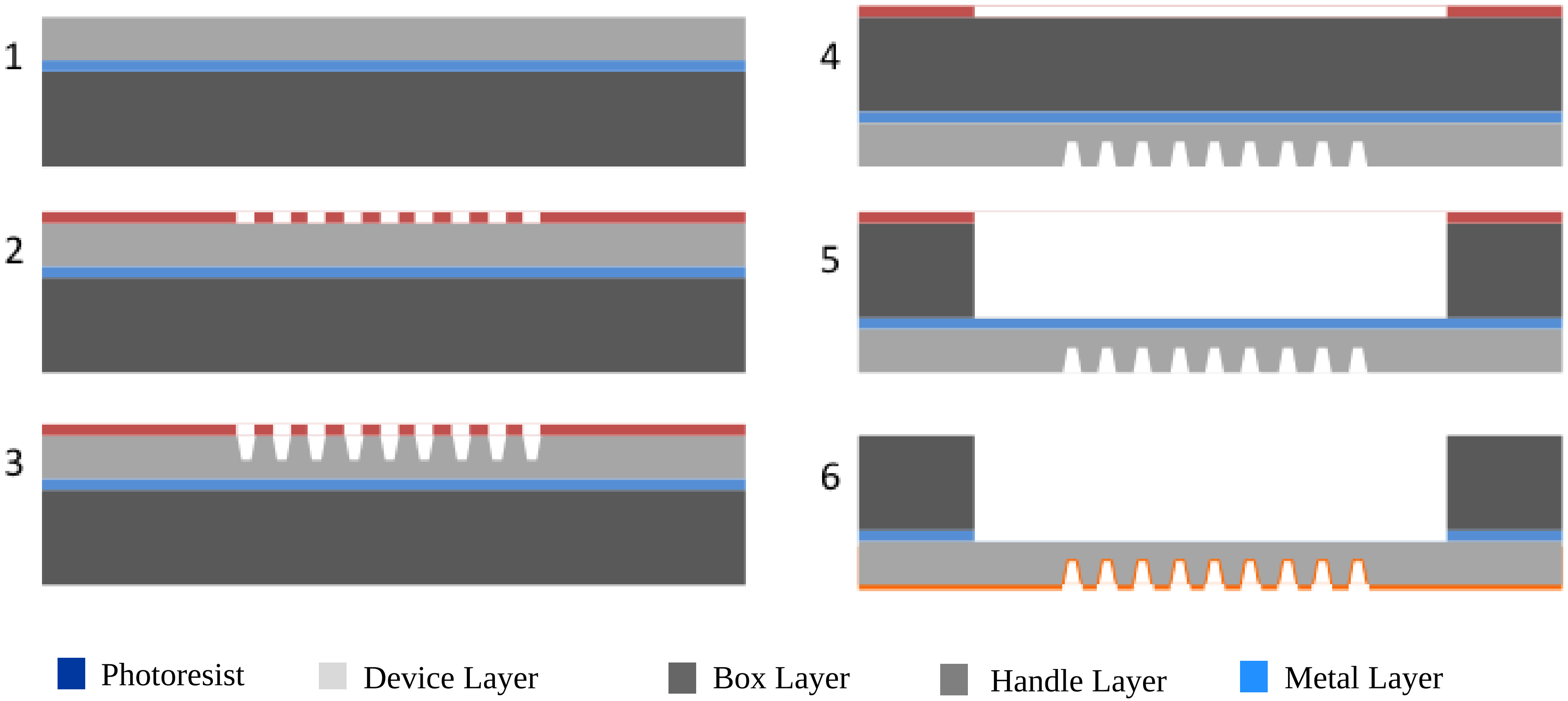


Shallow Depth



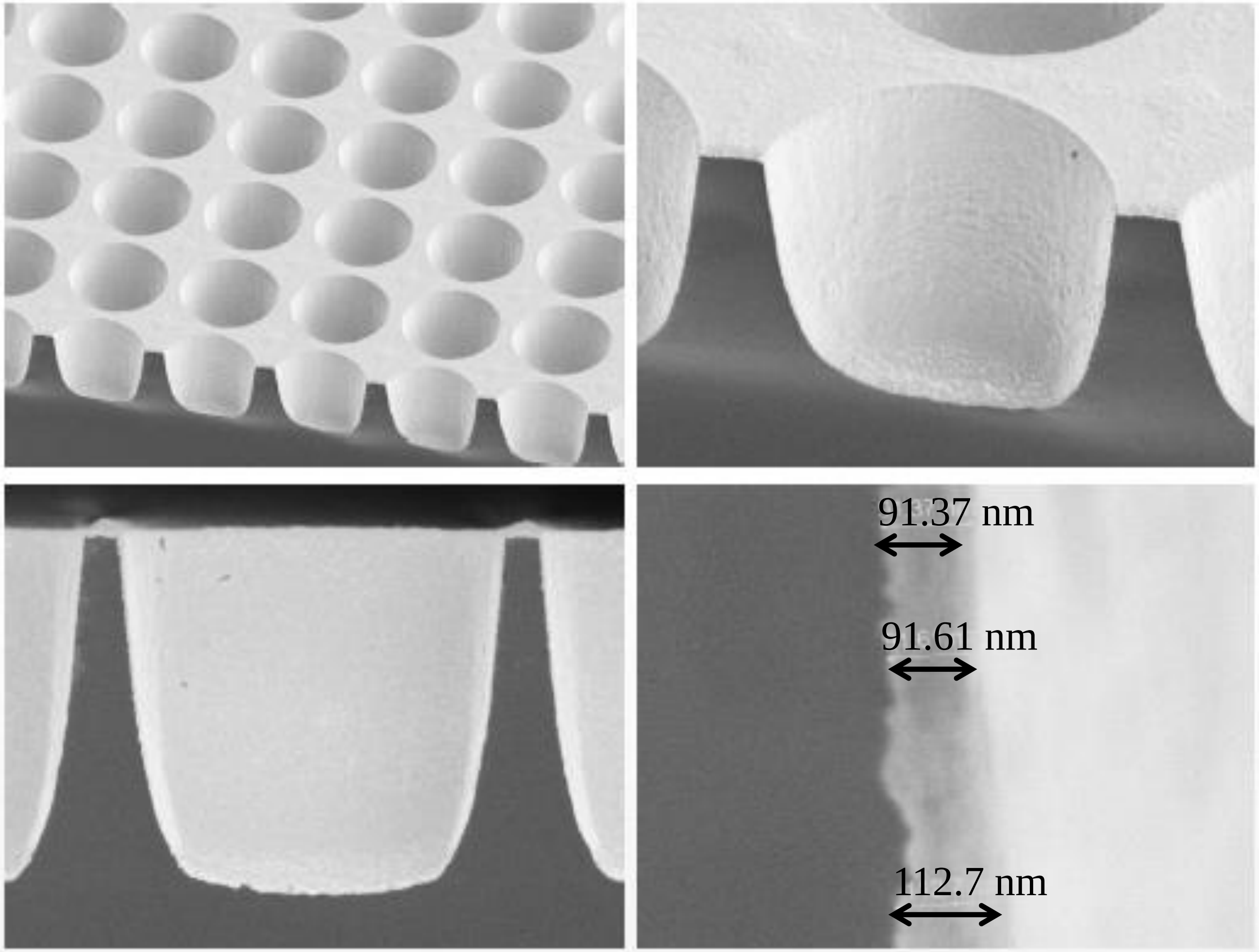
Requirement #	Description	Value	Tolerance
1	Wall Angle	12º	±2.5°
2	Depth	3/8.4/16.8 (µm)	±2 (µm)
3	Pitch	2 (µm)	±0.2 (µm)
4	Width	9	±0.2 (µm)
5	Coating Thickness	20 Å Ti / 700 Å Au	±200 Å
6	Coating Roughness	200 Å	
7	Substrate Thickness	150 (µm)	±2 (µm)

The fabrication recipe developed by NanoShift, LLC includes 6 Deep Reactive-Ion Etching (DRIE) steps



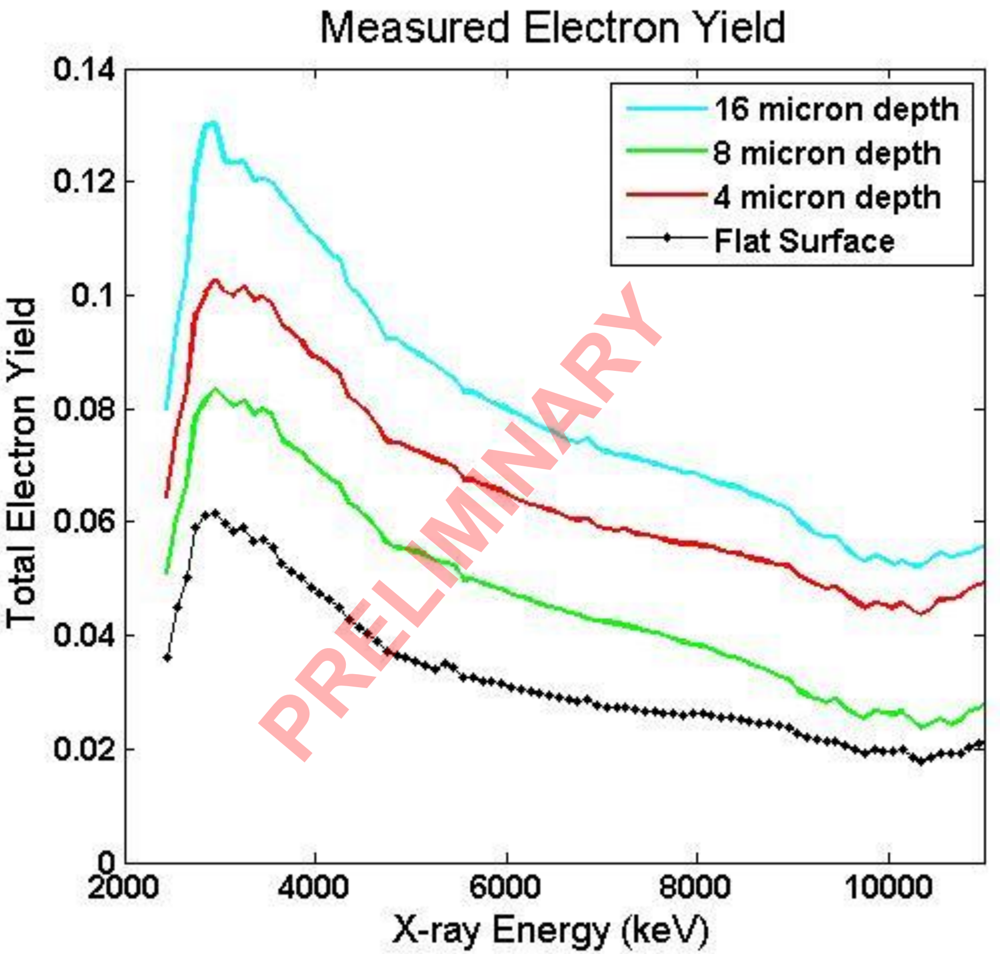
Substrates coated with Ti+Au using sputter deposition.

Final prototypes meet the fabrication requirements



Prototypes with all 3 depths were received at the end of FY 15.

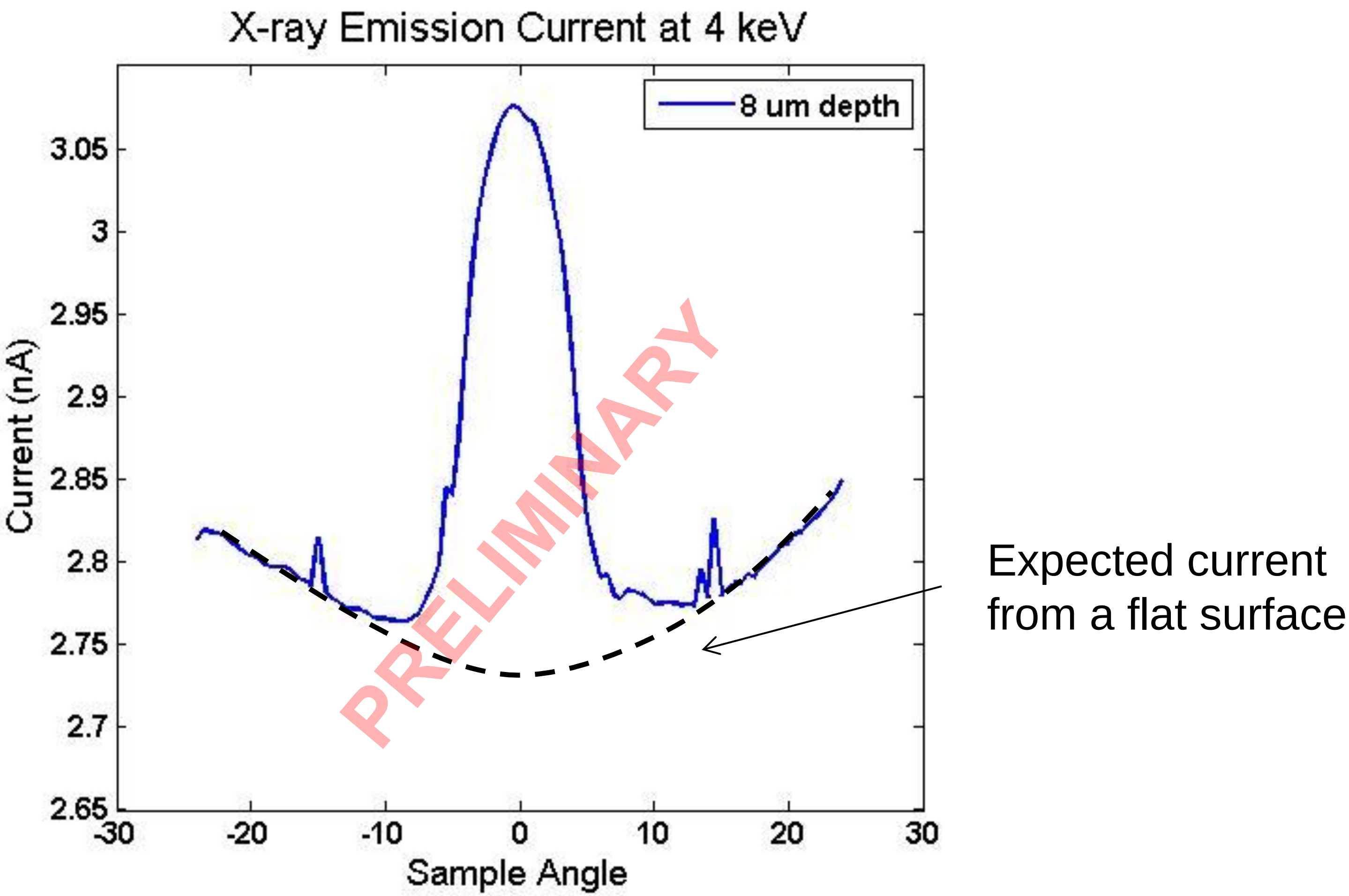
Recent measurements show an enhancement in yield of up to 2.7 times.



Relative yield increase:

- 2.7 times for full depth (16µm)
- 2.3 times for mid depth (8 µm)
- 1.3 times for shallow (4 µm)

Yield as a function of incidence angle shows structure is symmetric and introduces an increase in yield at 0°



Project accomplishments

Photocathode Model and Computer Simulation

• Used Fraser's model to predict yield for CsI and Au in the 10 - 50 keV Range. (FY 14)

• Built a CST Studio Suite model to test structured cathode designs. Predicts field strength, spatial resolution and temporal resolution. (FY 14)

Device Fabrication and Testing

• First set of prototypes built in FY 15.

• Device performance characterized at a synchrotron facility in FY 15. Devices show clear evidence of yield improvement.

Further work

Prototype performance characterization

- Finish analysis of yield data collected in the 4 - 12 keV range.
- Collect SEM and optical images of the prototype samples.

Full scale development and testing

- Develop a full scale 5 x 31 mm photocathode for DISC.
- Fabricate prototypes with 6 and 3 degree wall angles and with varied Au thickness for high energy testing.
- Test in a calibrated DISC detector for full performance characterization.

New designs

- Continue to explore novel structures and materials.

References

Fraser, G. W. (1983). "The characterization of soft X-ray photocathodes in the wavelength band 1-300 A . II. Caesium iodide and other insulators of high photoelectric yield." Nuclear Instruments and Methods in Physics Research **206**(1-2): 265-279.

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Henke, B. L. (1972). "Ultrasoft X-ray reflection refraction and production of photoelectrons (100-1000-eV region)." Physical Review A (General Physics) **6**(1): 94-104.

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Henke, B. L., J. P. Knauer, et al. (1981). "The characterization of x-ray photocathodes in the 0.1--10-keV photon energy region." Journal of Applied Physics **52**(3): 1509-1520.

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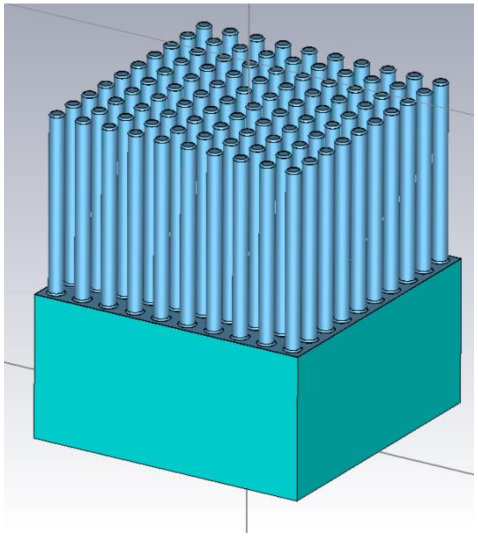
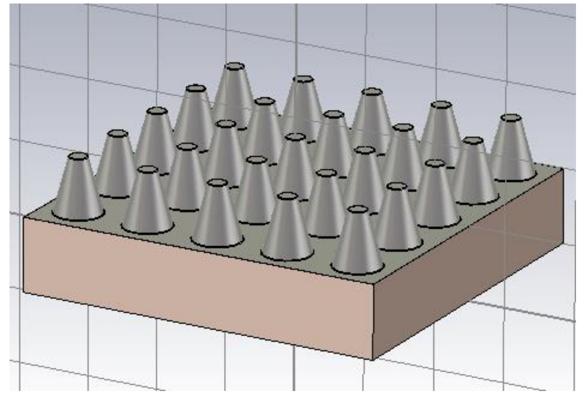
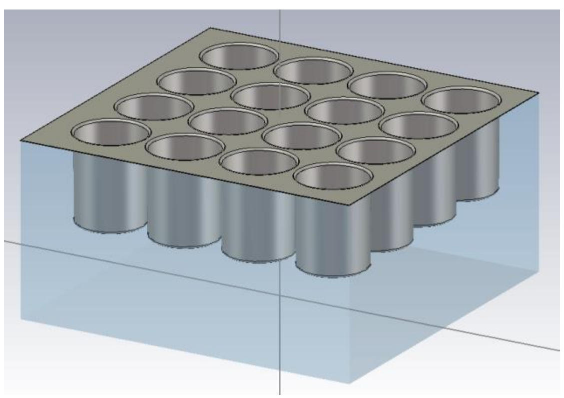
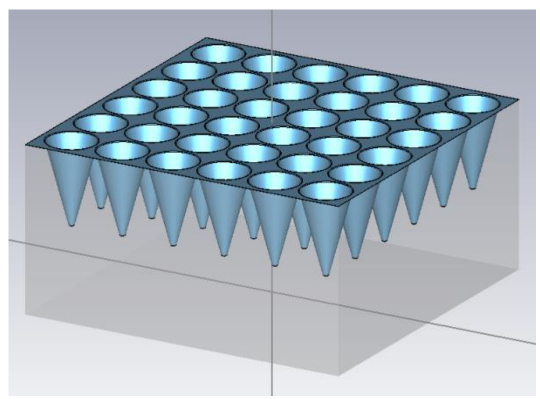
Several structures were modeled in CST Studio suite

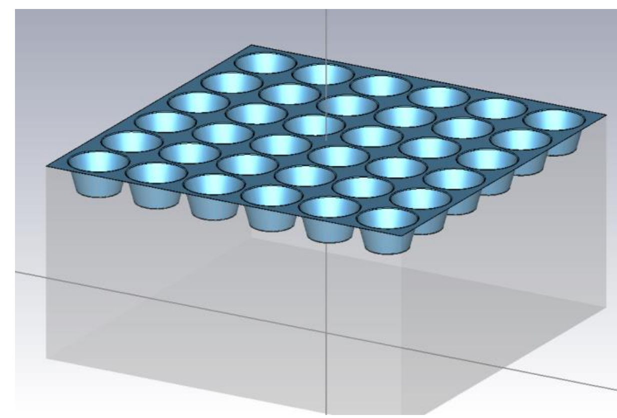




Pillar geometries



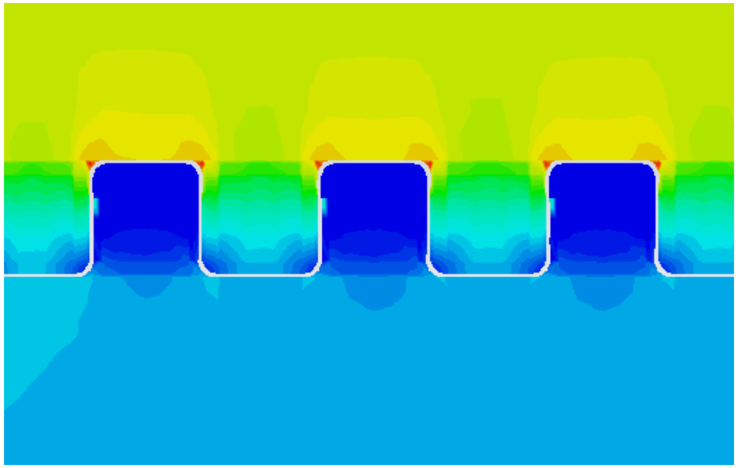




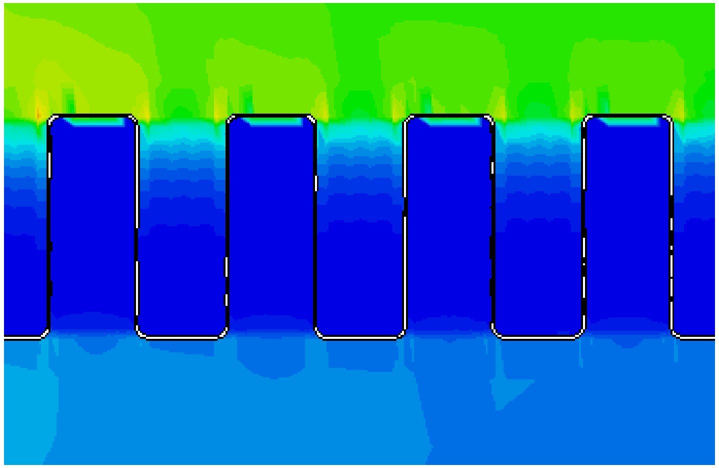
Recessed geometries

Photocathode geometry will impact the detector performance

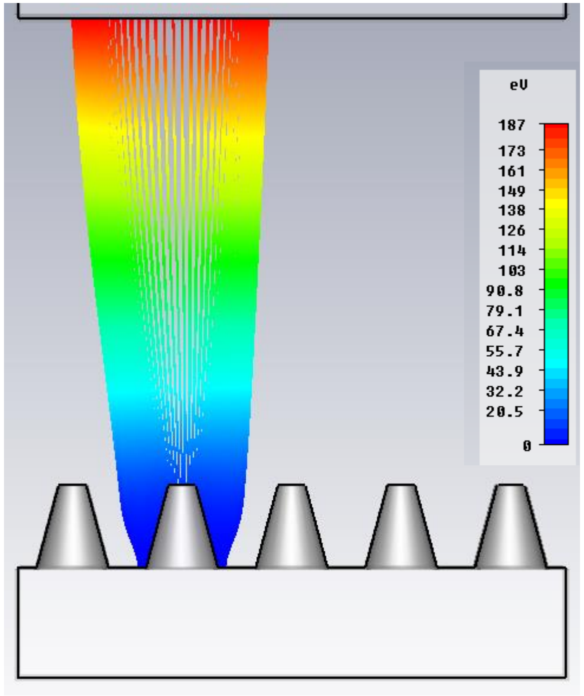
Field emission from corners



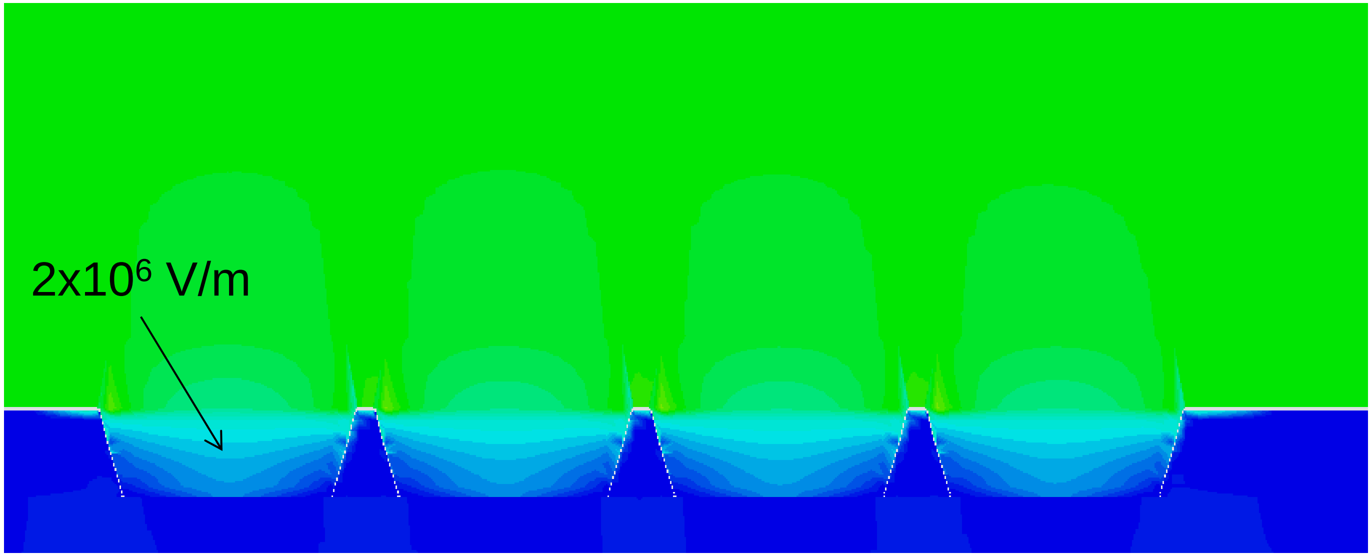
Loss of field between walls causes temporal resolution degradation



Degradation in spatial resolution depends on:
Wall angle, field strength and structure separation.

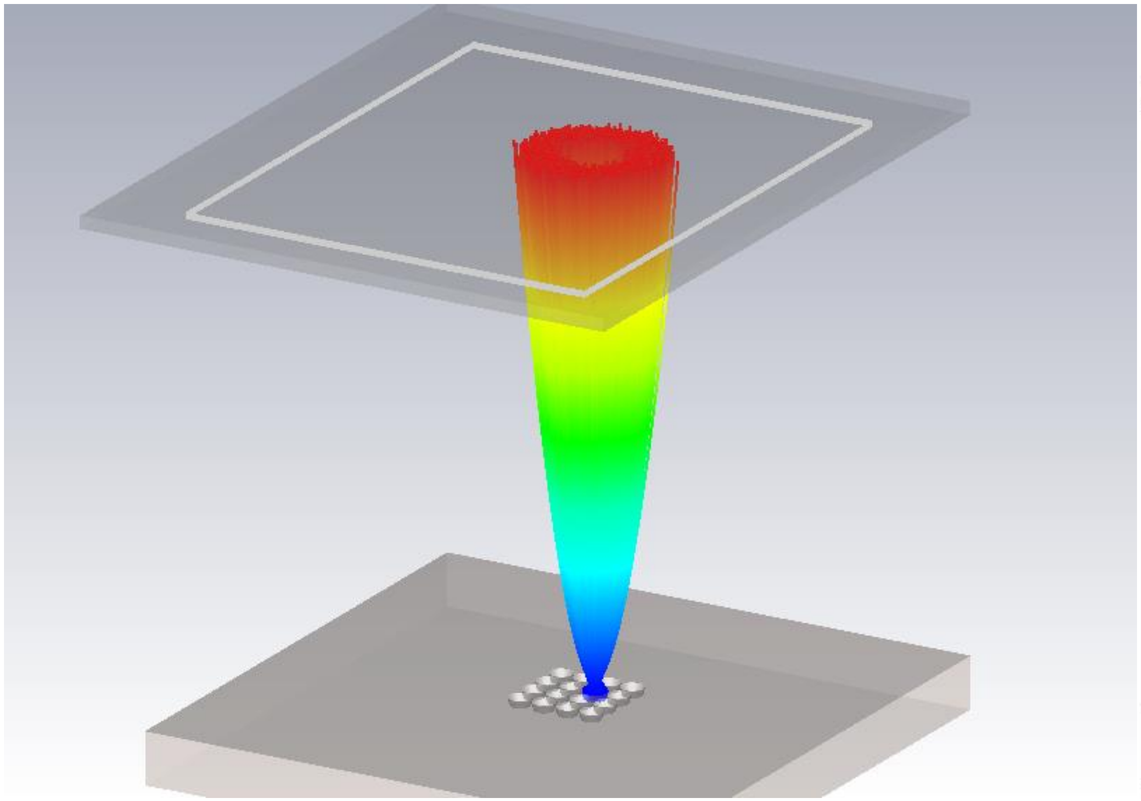


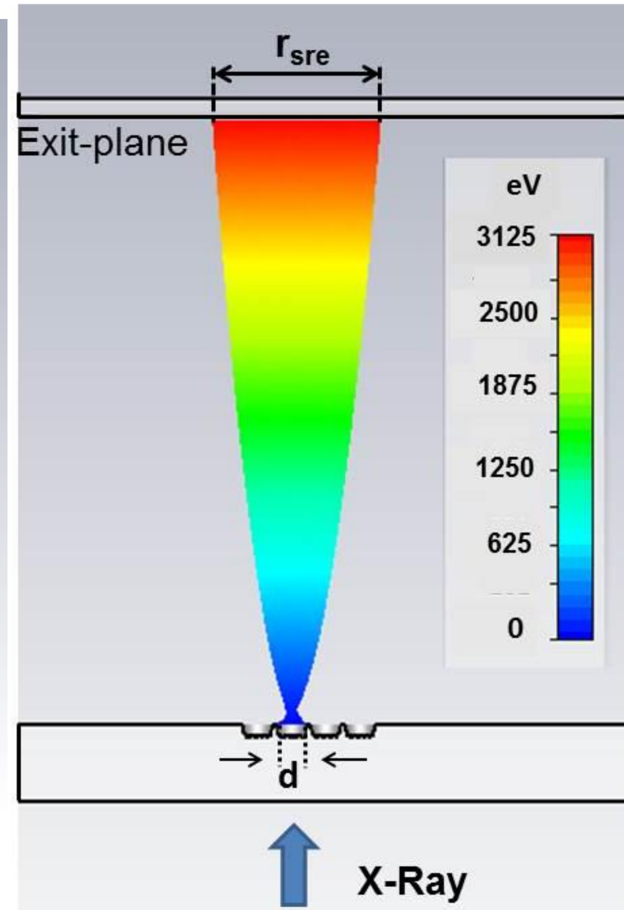
High Energy Cathode Design – Cone Cavity Structures Field Gradient Model



Field emission is suppressed and field is present within the cavity.

Spatial resolution element is limited by the emission from the structure walls and cavity diameter

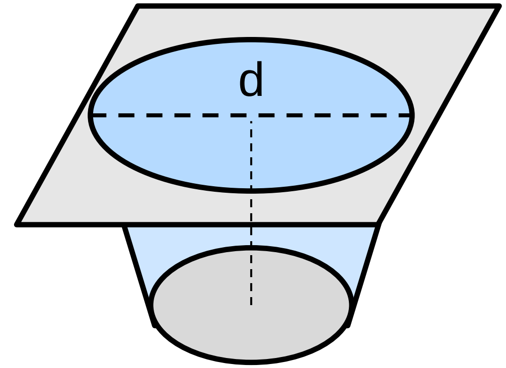


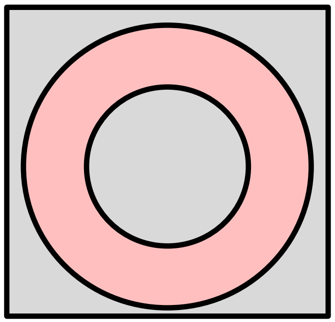


Cathode diameter and wall angle can be changed to satisfy requirements.

Total Yield Enhancement is on the order of 2-3 at 14 keV Photon Energy

Energy (keV)	Recessed Geometry	Incidence Angle	Diameter (µm)	Depth (µm)	Au TEY Rel. Increase	CsI TEY Rel. Increase
14	Cone	15	6	3	1.76	1.77
14	Pyramid	15	6	3	1.85	1.85
14	Cone	15	4	2	1.66	1.67
14	Pyramid	15	4	2	1.74	1.74
14	Cone	10	6	3	1.88	1.87
14	Pyramid	10	6	3	2.12	2.11
14	Cone	10	4	2	1.77	1.76
14	Pyramid	10	4	2	1.97	1.97





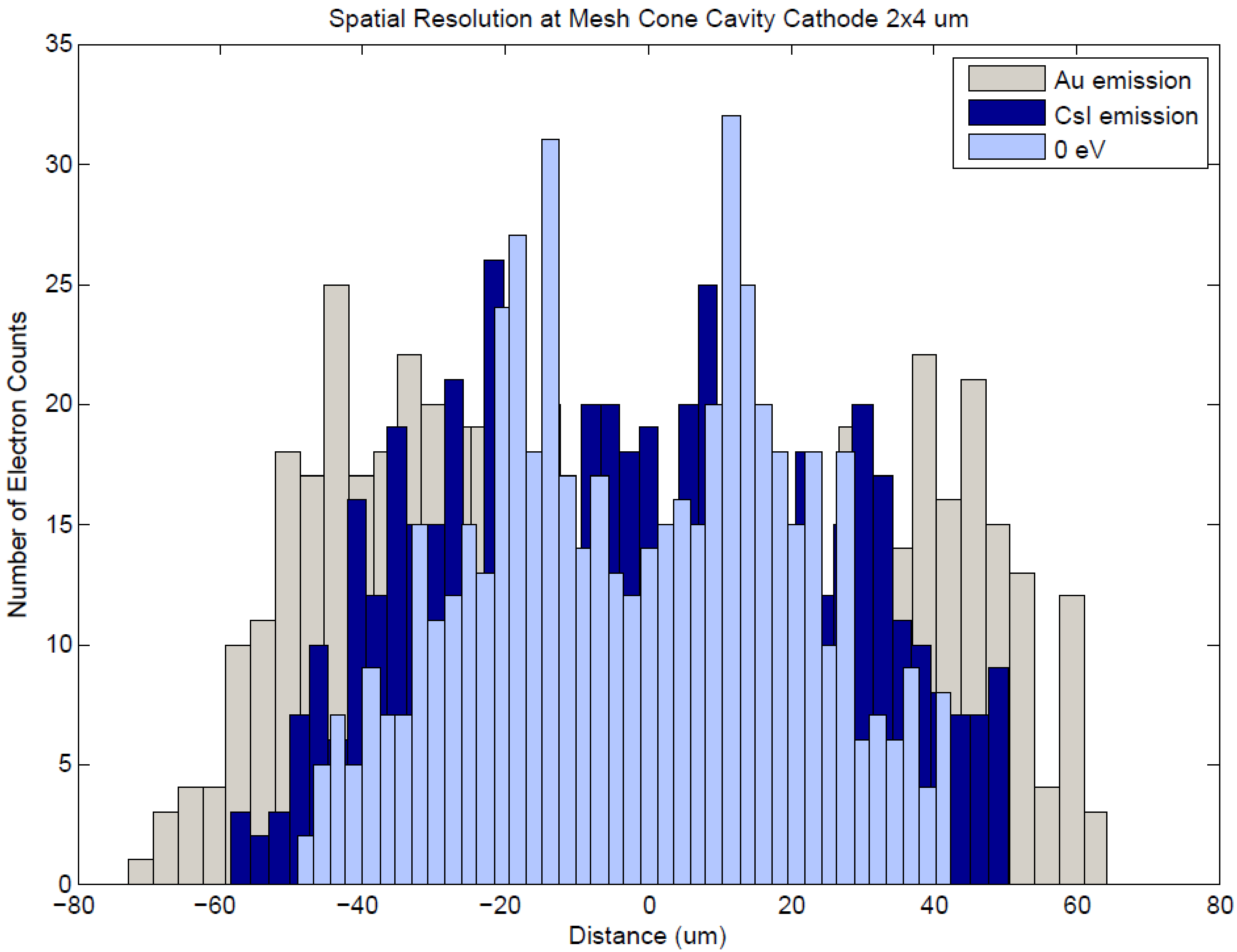
- Temporal spread from 6x3 µm geometry ~1 ps
- Temporal spread from 6x11 µm geometry ~100 ps
- Full cone geometry yield increase ~4 x

Standard emission surface area

Enhanced emission surface area

Projected enhanced surface area

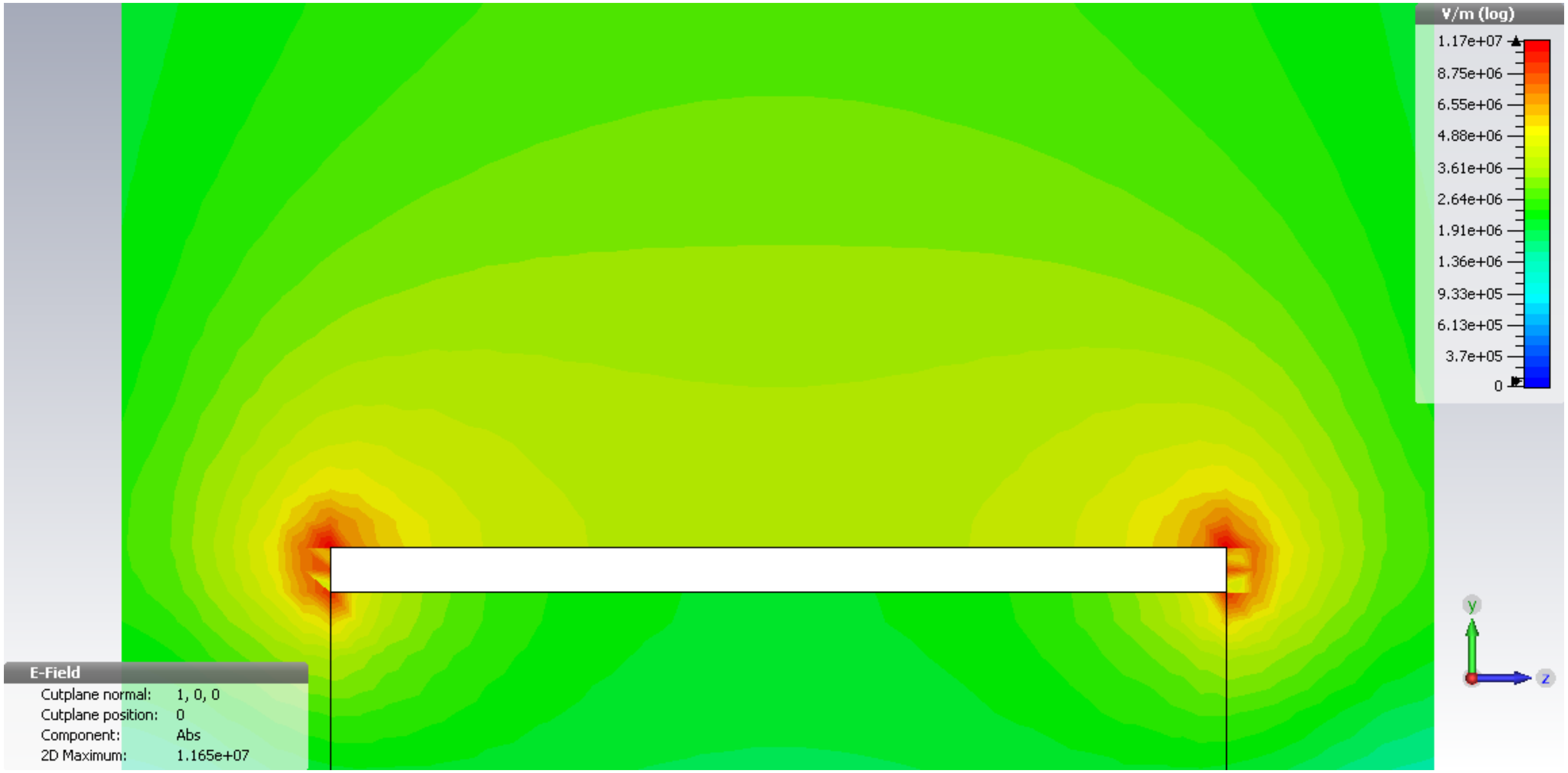
Spatial resolution shows a dependence on cathode type



Field Gradient Simulation Results

- Planar photocathode
- Pillar
- Cone (15 degree wall angle)
- Recessed pillar
- Recessed cone (15 degree wall angle)

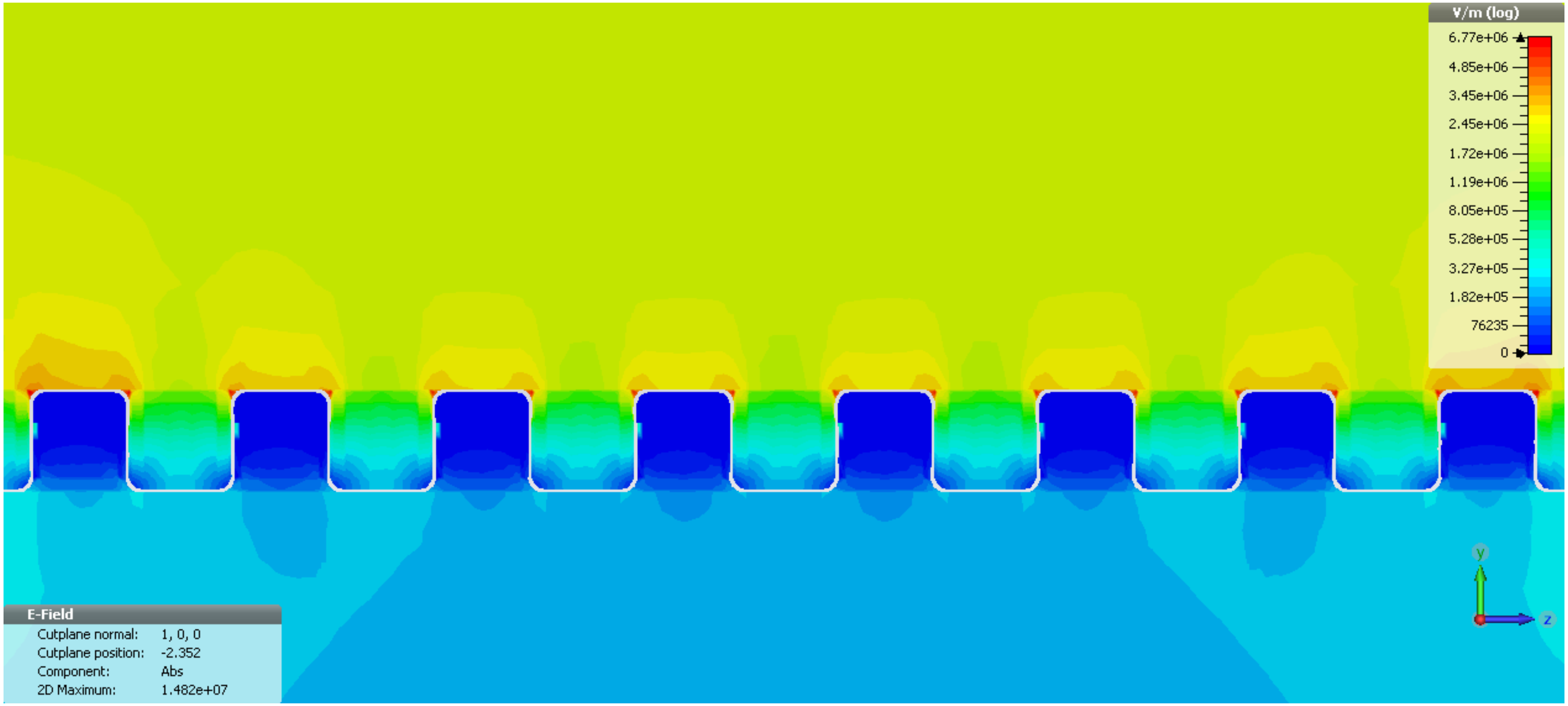
High Energy Cathode Design – Flat Photocathode Field Gradient Model



Flat photocathode geometry is currently used in NIF streak camera detectors and in the DIXIE detector

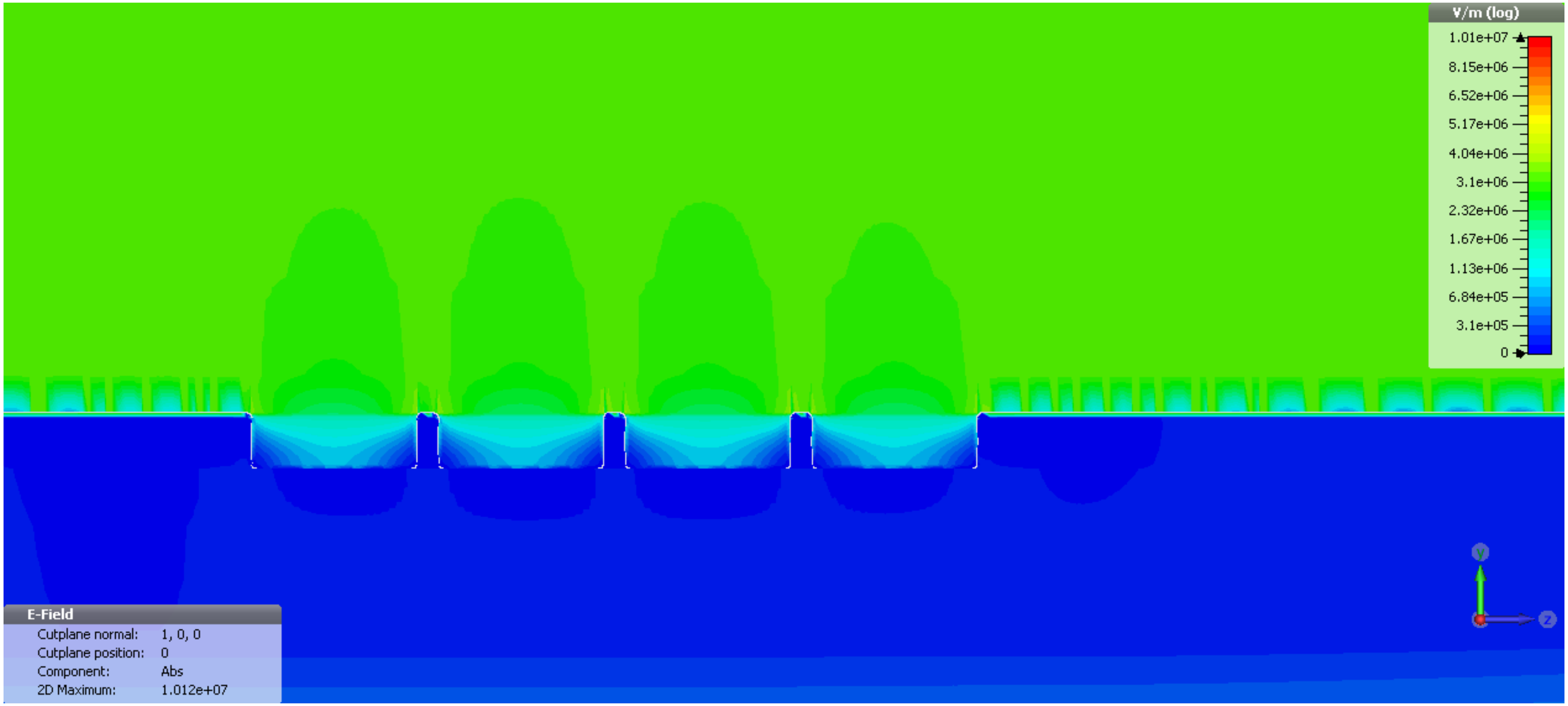
High Energy Cathode Design – Pillar Structures Field Gradient Model

Field emission at the pillar edges is seen



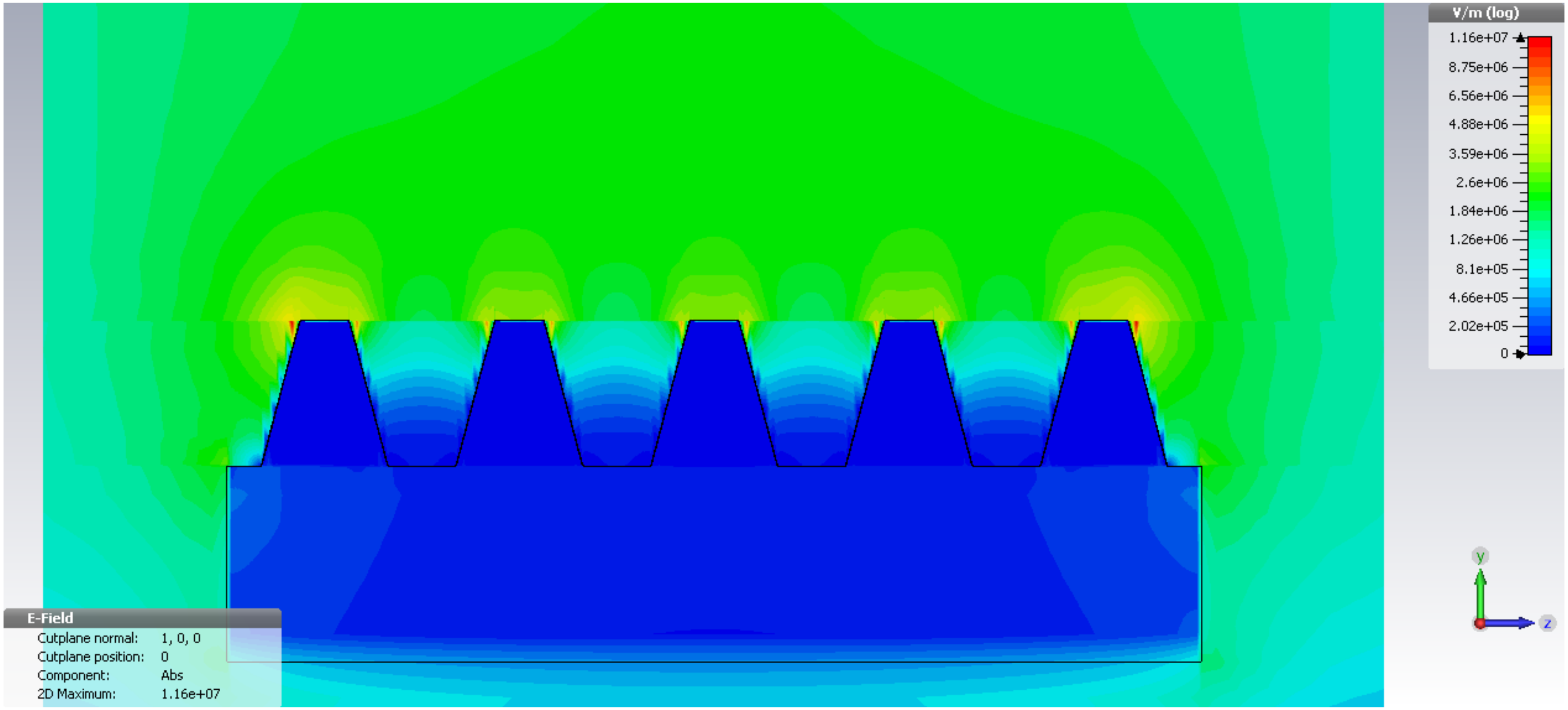
High Energy Cathode Design – Pillar Cavities Field Gradient Model

Field emission is suppressed – field present within the structure

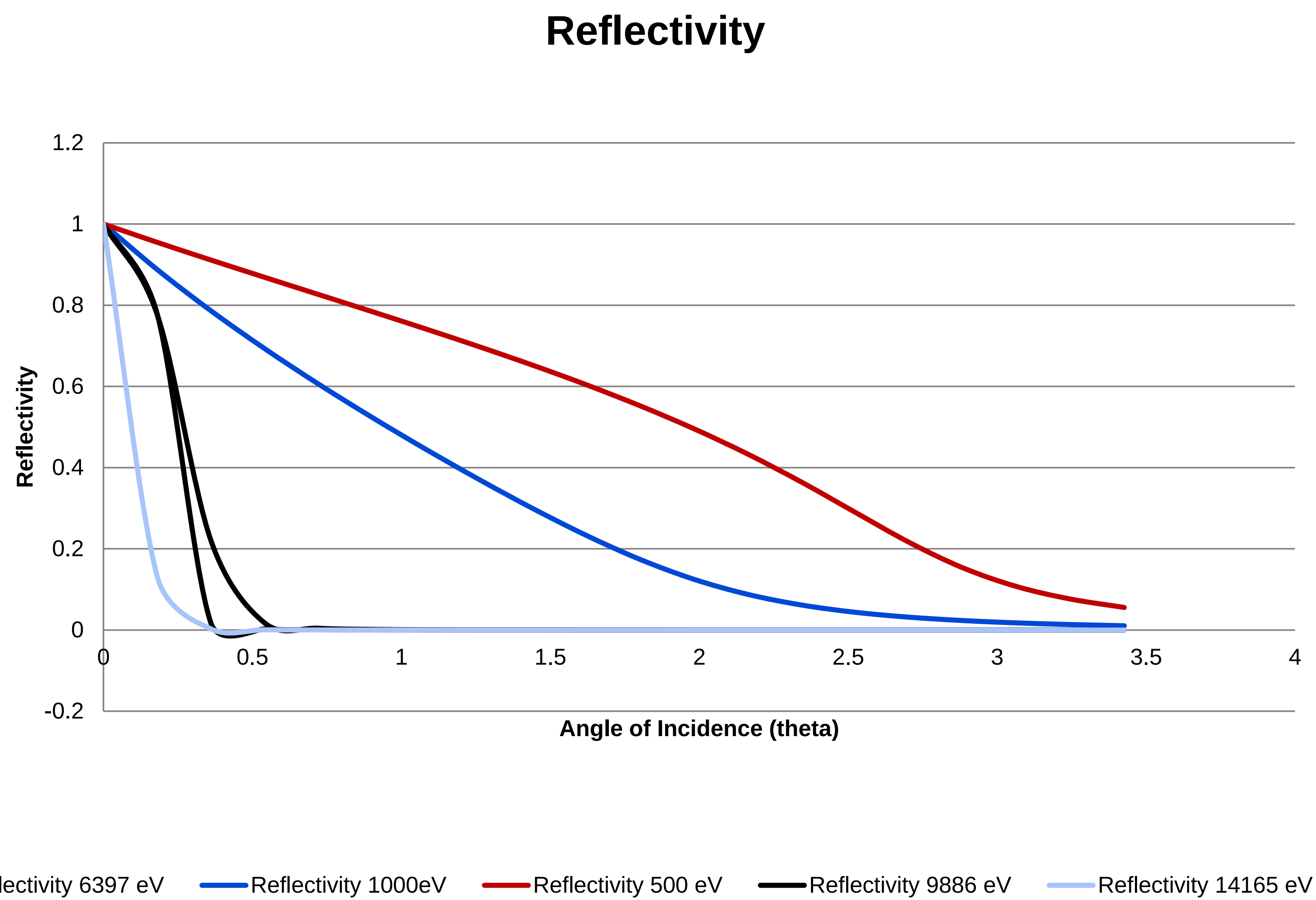


High Energy Cathode Design – Cone Pillar Structures Field Gradient Model

Field emission at the pillar edges is seen



Reflectivity



Fresnel Equations

Treat x-ray interaction as a boundary-value problem for reflection and refraction of a plane electromagnetic wave at an absorbing medium.

The reflection coefficient I/I_0 if electric vector is perpendicular to the plane of incidence:

$$R_1 = \frac{4a^2(\sin\phi - a)^2 + \gamma^2}{4a^2(\sin\phi + a)^2 + \gamma^2}$$

The reflection coefficient I/I_0 if two states of incident – beam polarization:

$$\frac{R_2}{R_1} = \frac{4a^2(a - \cos\phi \cot\phi)^2 + \gamma^2}{4a^2(a + \cos\phi \cot\phi)^2 + \gamma^2}$$

The reflection coefficient I/I_0 for an un-polarized incident beam:

$$R = R_1\left(\frac{1 + R_2/R_1}{2}\right)$$

φ is the angle of incidence, γ is the characteristic materials constant, a is the characteristic function *a*

Linear absorption coefficient

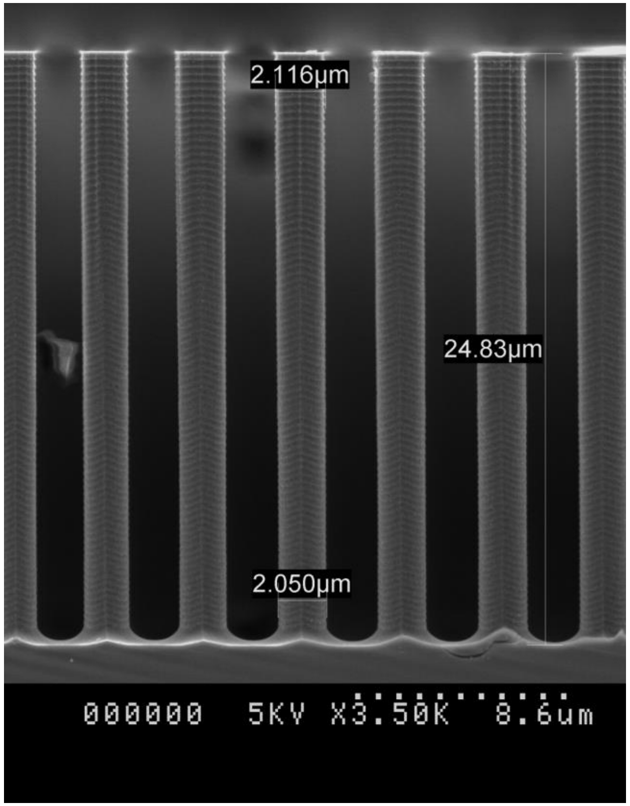
The linear absorption coefficient is given by:

$$I = I_0 e^{-\alpha t}$$

Where is the sample thickness.

Pillar Samples Available at LLNL

DBA6-33 after 1 minute Si wet etch stirred

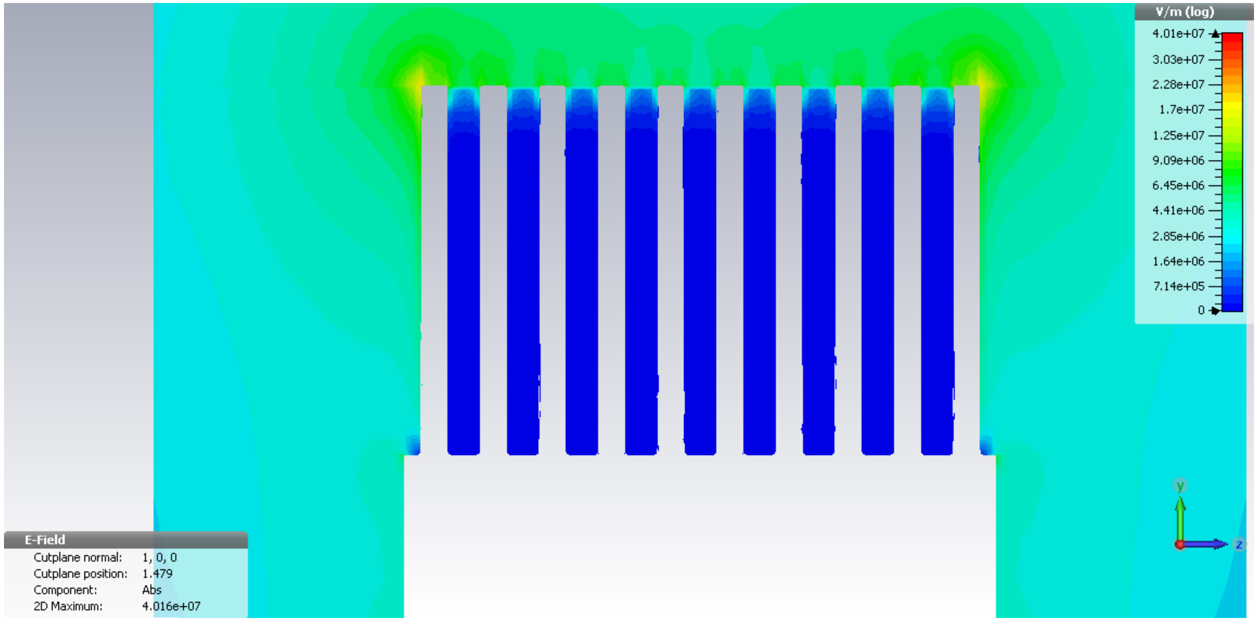


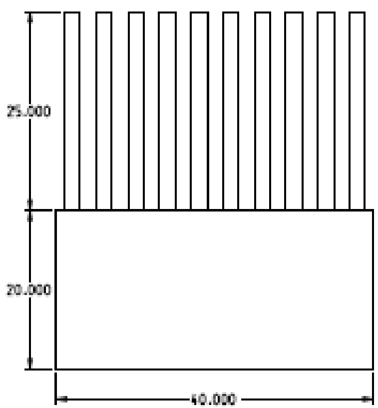
1cm x 1cm
Substrate thickness is 215 μm, pillars 25 μm
2 μm diameter and 2 μm separation –
Structure similar to the high density model

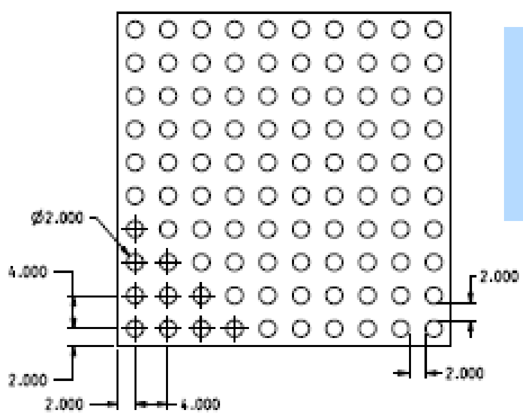
Coated with 30 Angstroms of Cr and 1000A of Au

Pillar Samples to Kathy Opachich (NIF)
Feb. 4, 2011
POC, R. Nikolic, 3-7389

High Energy Cathode Design – Pillar Geometry Results

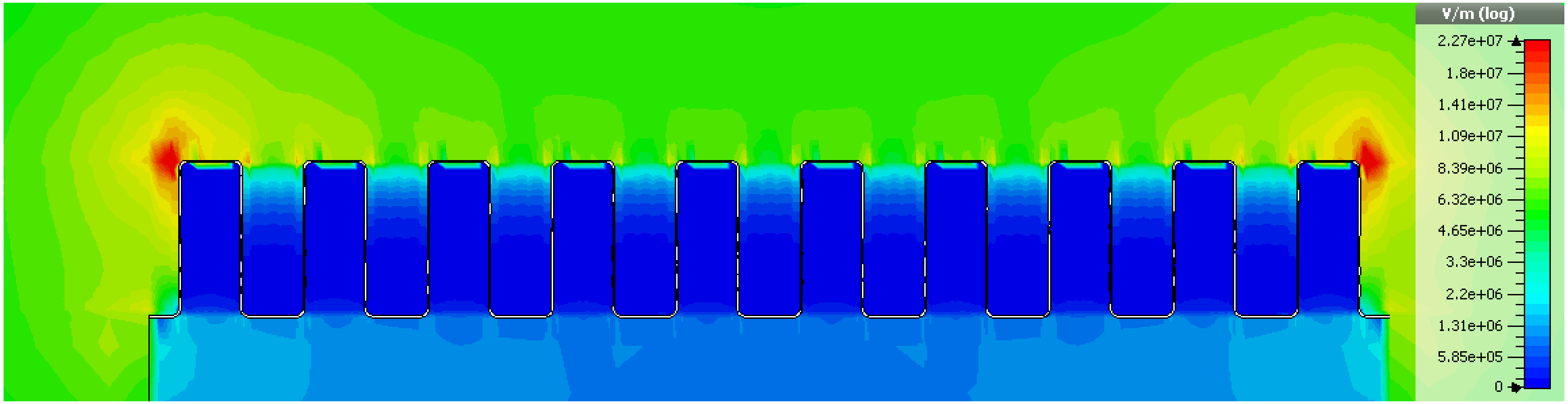






Pillar spacing either reduced the field between pillars to zero, or increase the field at the pillar tips to cause field emission.

High Energy Cathode Design – Pillar Geometry Results



Reducing the Pillar height did not increase the field gradient within the structure

Fraser's Model: used to identify incidence angle (1-30 keV)

The total electron yield is determined by considering:

•The probability of an x-ray photon being absorbed in layer z+dz

$$dE(z) = \Gamma_0 E_x [1 - R(\alpha)] \mu \operatorname{cosec} \alpha' \exp(-\mu z \operatorname{cosec} \alpha')\, dz \text{ keV} \cdot \text{cm}^{-2} \cdot \text{s}^{-1}.$$

•The number of electrons generated within a thin layer z+dz in the cathode

$$dN(z) = f(z) \varepsilon^{-1}\, dE(z) \text{ electrons} \cdot \text{cm}^{-2} \cdot \text{s}^{-1}.$$

•The probability of the secondary electron escaping to the surface

$$P_s(z) = P_s(0) \exp(-z/L_s).$$

R(α) is the Fresnel reflectivity
P_s(0) is the secondary electron escape probability (~0.2)
E_x is the x-ray energy
Γ_0 beam intensity photons/cm^2/s
ε is the energy required to promote a secondary electron from the valence band with sufficient energy to escape into vacuum (7eV)
T is the cathode thickness (1000 Angstroms)
μ is the linear absorption coefficient
α is the x-ray incidence angle
α' is the angle of the refracted x-ray
f(z) is the fraction of x-ray energy available for generation of secondary electrons
Ls is the secondary electron escape length (215 Angstroms for CsI)

Fraser's Model: used to identify incidence angle (1-30 keV)

The secondary photocurrent $(X_c)_s$ is then:

$$(x_c)_s = [1 - R(\alpha)] P_s(0) E_x \varepsilon^{-1} \times \int_0^{\mu T \operatorname{cosec} \alpha'} f(y) \exp[-(1+\beta)y] \, dy \quad (1)$$

Where:

$$\beta = (\mu \operatorname{cosec} \alpha' \cdot L_s)^{-1}.$$

Assigning conversion efficiency a value independent of depth below cathode surface (f=1) gives:

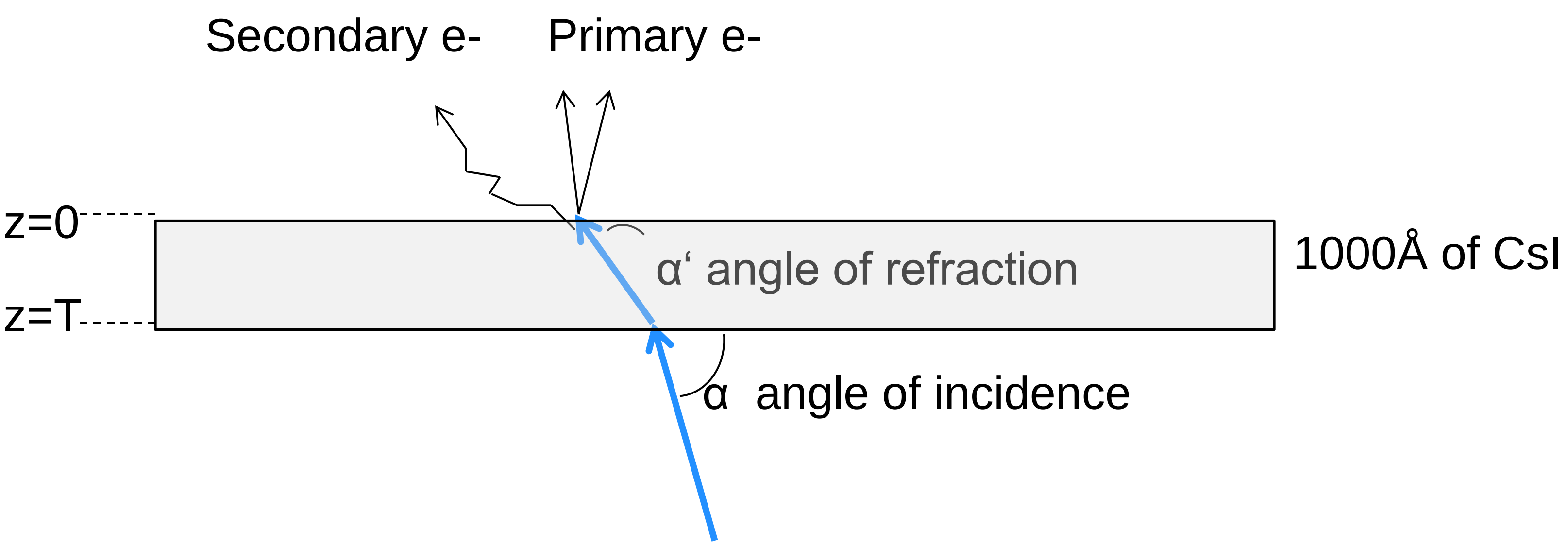
$$(x_c)_s = [1 - R(\alpha)] f P_s(0) E_x \varepsilon^{-1} (1+\beta)^{-1} Y(T)$$

Y(T) is relative yield –versus-thickness function:

$$Y(T) = 1 - \exp[-(\mu \operatorname{cosec} \alpha' + L_s^{-1}) T]$$

R(α) is the Fresnel reflectivity
P_s(0) is the secondary electron escape probability (~0.2)
E_x is the x-ray energy
ε is the energy required to promote a secondary electron from the valence band with sufficient energy to escape into vacuum (7eV)
T is the cathode thickness (1000 Angstroms)
μ is the linear absorption coefficient
α is the x-ray incidence angle
α' is the angle of the refracted x-ray
f(y) is the fraction of x-ray energy available for generation of secondary electrons
Ls is the secondary electron escape length (215 Angstroms)

Incidence Angle Definition and Yield



Does changing the incidence, and thus increasing the x-ray path-length, improve yield in reflection and transmission modes?

The angular distribution at the mesh was predicted using CST