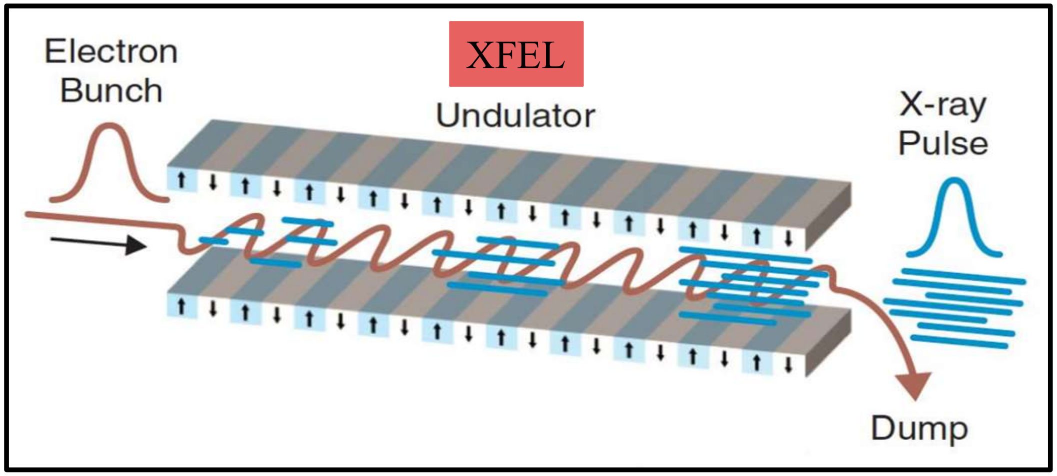
Study and Characterization of Nano-structured Electron Sources for Accelerator Applications

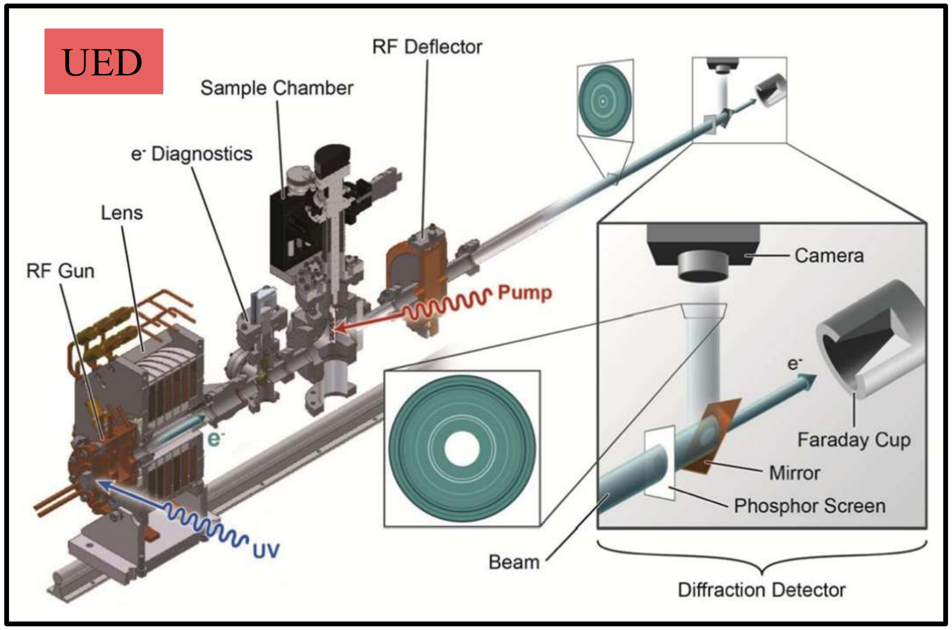
Alimohammed Samina Hussain Kachwala
Advisor: Prof. Siddharth Karkare
Arizona State University

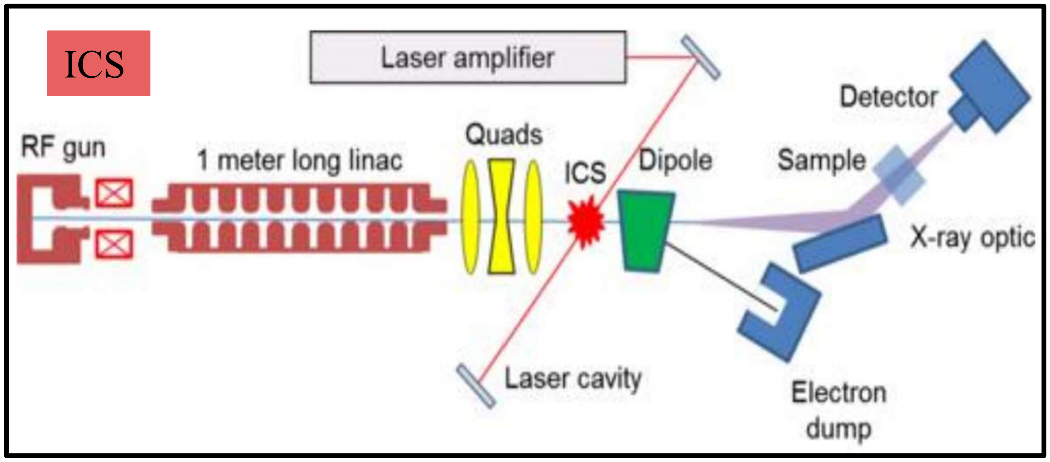
Outline

- Introduction
- Photoemission Electron Microscope (PEEM): A Tool to Characterize Photocathodes
- (N)UNCD Photocathode
- Cs_3Sb Photocathodes
- Plasmonic Spiral
- Conclusion and Future Work

Introduction







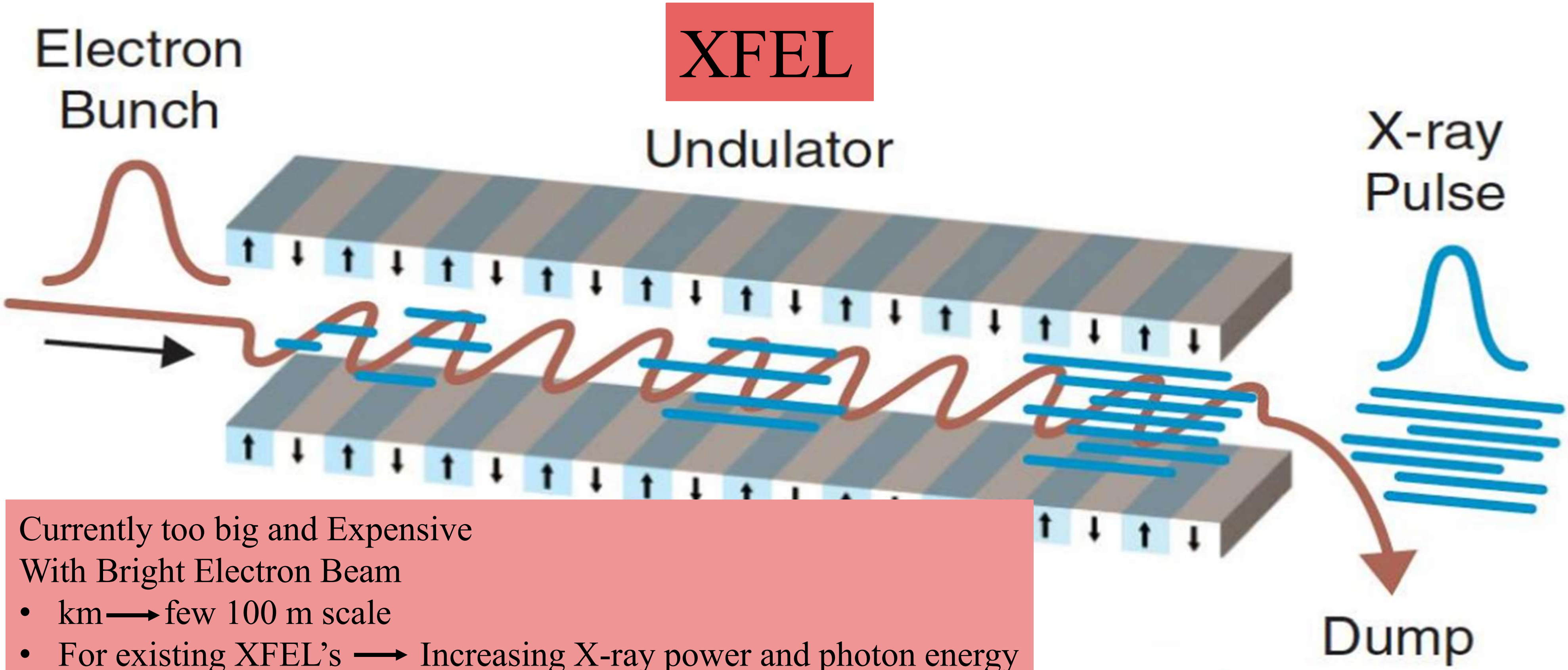
Reviews of Modern Physics 88.1 (2016): 015007.

New Journal of Physics 17.6 (2015): 063004.

Physical Review Special Topics-Accelerators and Beams 17.12 (2014): 120701.

Introduction

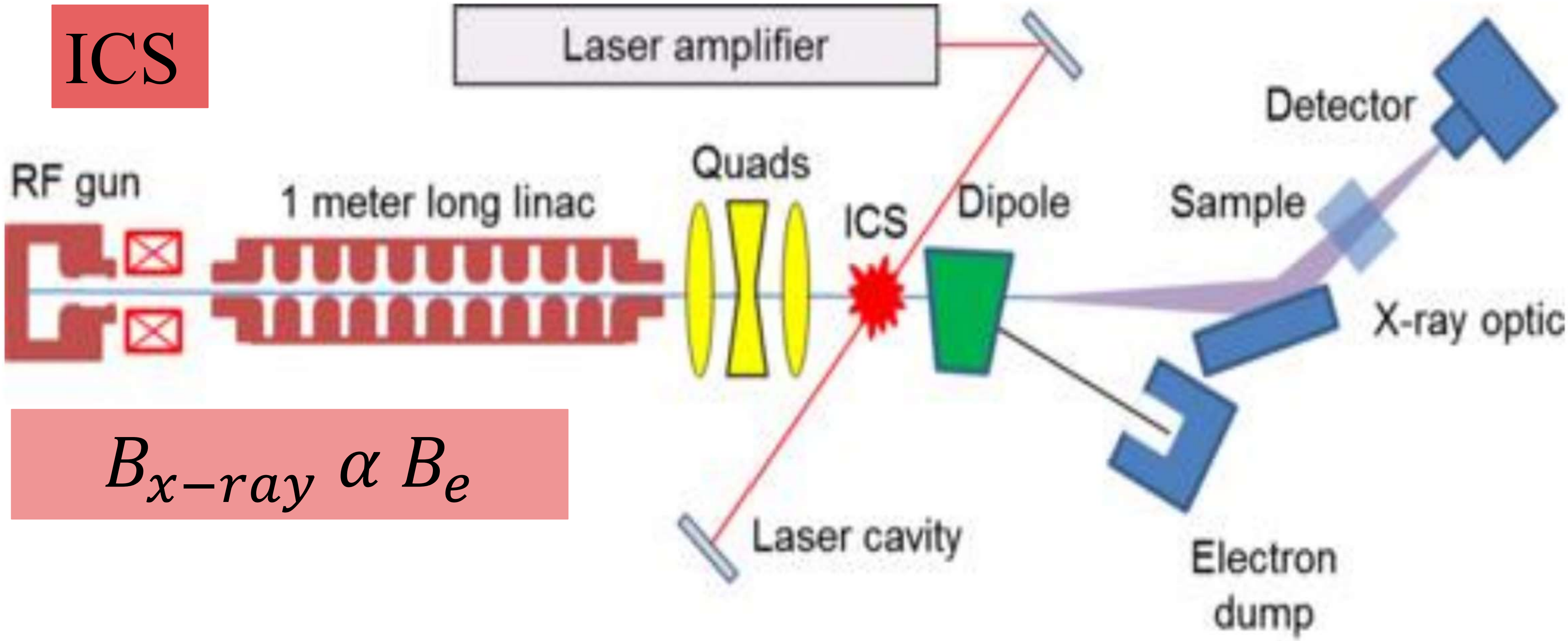
XFEL



Currently too big and Expensive
With Bright Electron Beam
- km ⟶ few 100 m scale
- For existing XFEL's ⟶ Increasing X-ray power and photon energy

Reviews of Modern Physics 88.1 (2016): 015007.

Introduction



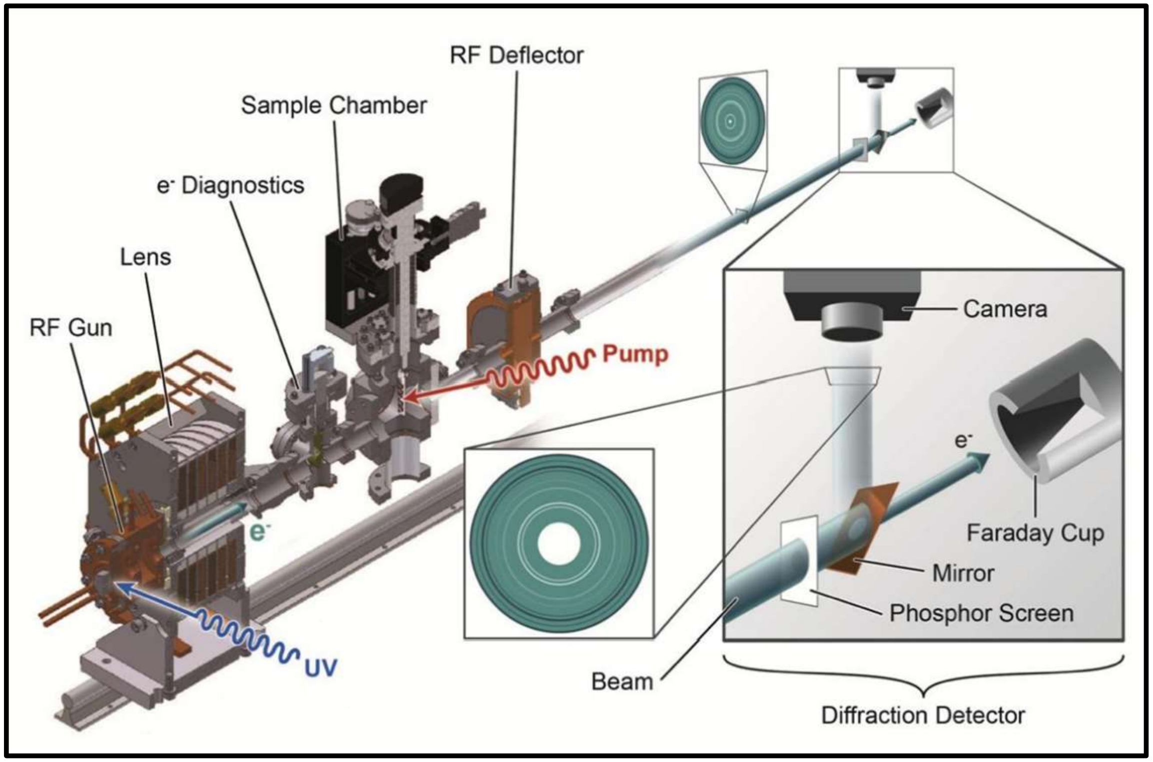
ICS

$$B_{x-ray}\ \alpha\ B_e$$

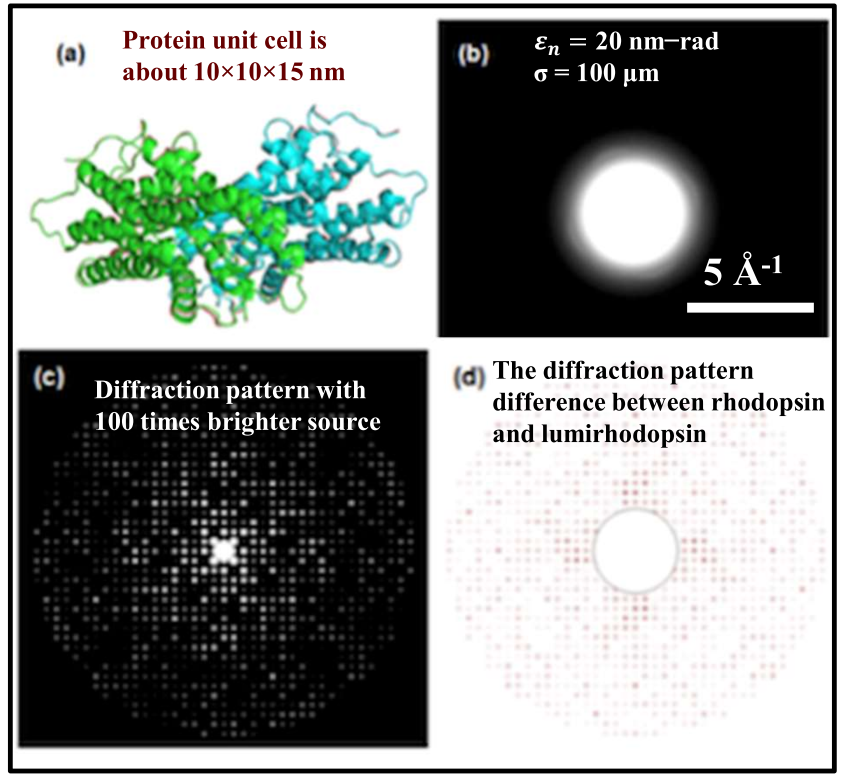
Physical Review Special Topics-Accelerators and Beams 17.12 (2014): 120701.

Introduction

UED



UED: Imaging Proteins

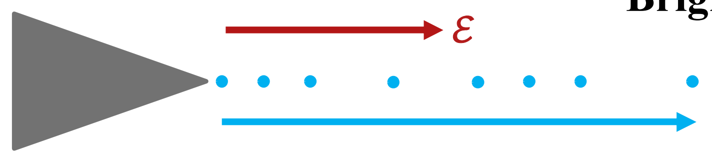


New Journal of Physics 17.6 (2015): 063004.

https://www.classe.cornell.edu/

Temporal Structure of Electron Beam

- Continuous Electron Beam
  - ➢ Steady State Microscopy Applications



Brightest Electron Source

Field Emission Tips (~nm scale emission area)

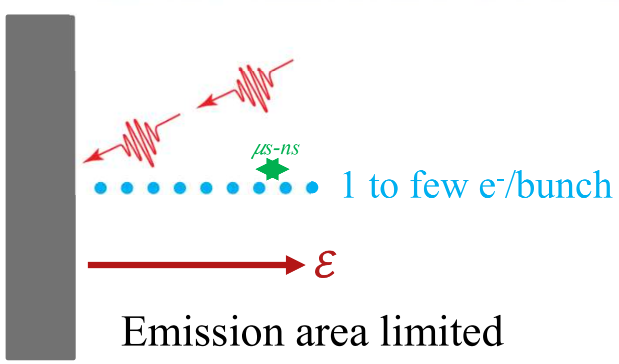
No Temporal Structure

- Pulse

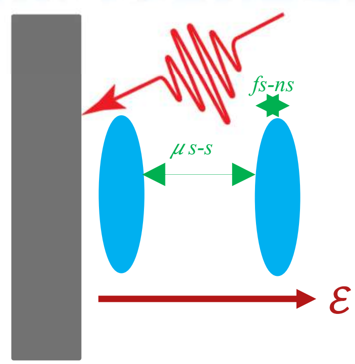
Goal: Increase Brightness of Pulsed Electron Beam

➢ Stroboscopic UED/M

➢ X-ray Sources, Colliders, Single Shot UED/M etc.



Emission area limited by laser spot



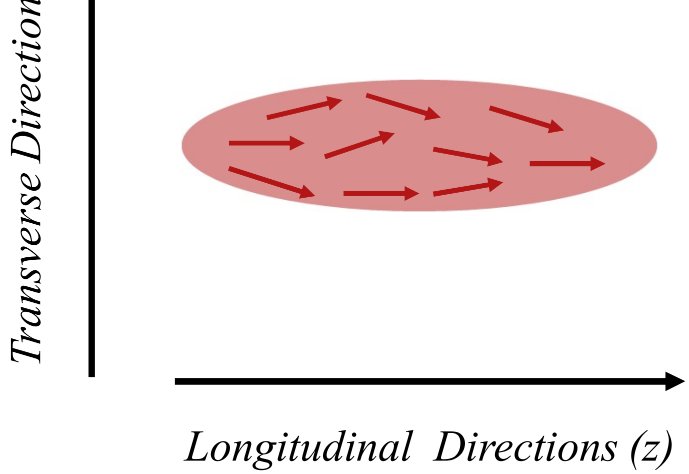
10^5-10^{10} e^-/bunch

Emission area limited by the electric field (ℰ) on the cathode

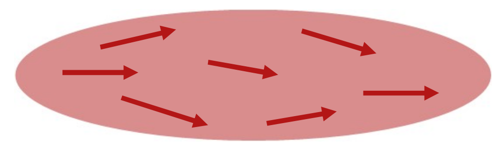
Electron Beam

What is an electron beam?
Bunch of electrons travelling in similar direction

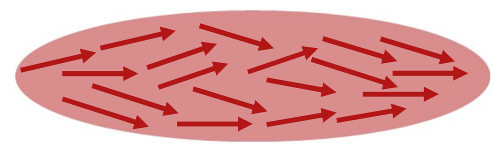
Momenta Satisfy Relation
$p_z >> p_x , p_y$



What is Bright electron beam?



Low Brightness



High Brightness

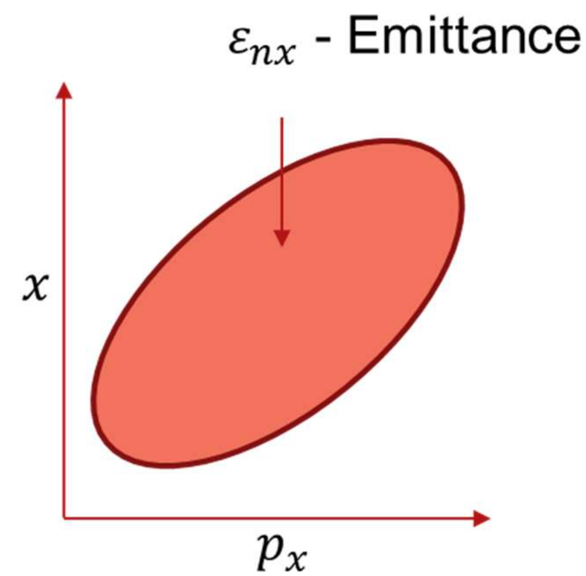
Beam Direction

Beam Brightness

Beam Brightness = Charge density in Phase space

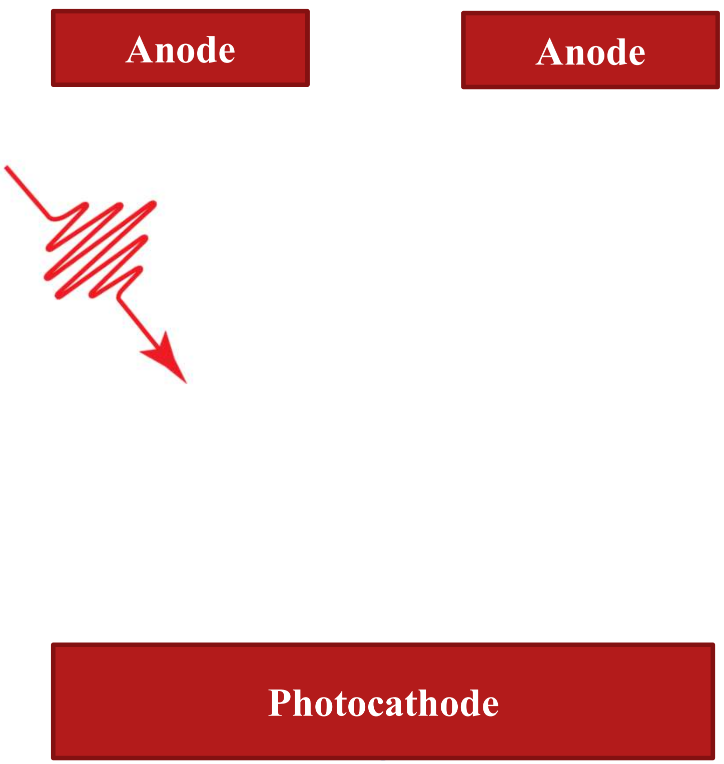
$$\mathbf{B} = \frac{I}{\varepsilon_{nx}\varepsilon_{ny}}$$

According to Liouville's theorem, Brightness remains invariant for Hamiltonian systems



Photocathode determines the maximum possible brightness

Photocathode Parameters



Photocathode Metrics

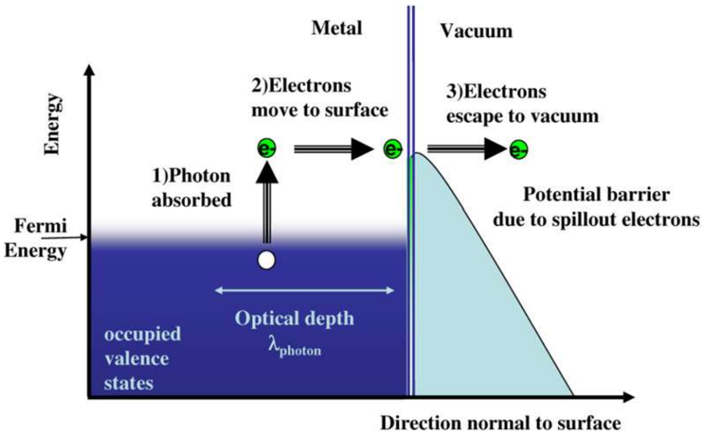
- Quantum Efficiency (QE): $\frac{Number\ of\ Electrons}{Number\ of\ Photons}$
- Response Time: Extracted electron bunch length when compared to the incoming laser pulse
- Mean Transverse Energy (MTE): Kinetic Energy of Electron Transverse to the direction of Electron Emission
- Kinetic Energy Spread

Photocathode Parameters

Quantum Efficiency

Dowell-Schmerge (DS) model

- Free Electron Gas Theory
- Spicer's Three Step Model



$$QE \propto (\hbar\omega - \Phi_{effective})^2$$

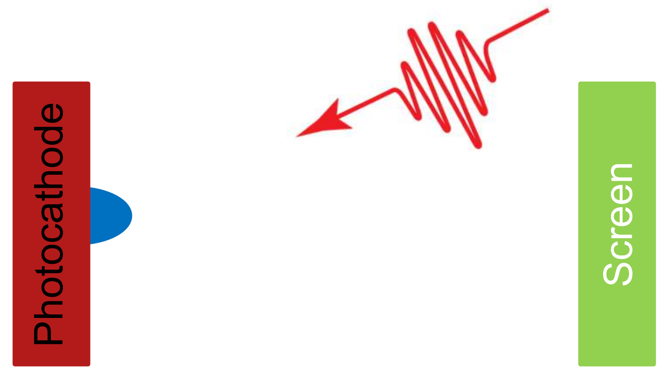
$\hbar\omega$ = Photon Energy

$\Phi_{effective}$ = Effective Work Function

Dowell et.al ,12.7 (2009): 074201.

Response Time

Response time of a photocathode is given in terms of the extracted electron bunch length when compared to the incoming laser pulse.



Fast response time (< 1 ps) Desirable for Various Photoinjector Applications

Emittance

$$\varepsilon_{nx} = \frac{1}{mc}\sqrt{\langle x^2\rangle\langle p_x^2\rangle - \langle xp_x\rangle^2}$$

$$\varepsilon_{nx} = \frac{\sigma_x \sigma_{p_x}}{mc} = \sigma_x\sqrt{\frac{MTE}{mc^2}}$$

$$MTE = \frac{1}{2}m\langle v_x^2\rangle + \frac{1}{2}m\langle v_y^2\rangle$$

$$MTE = \frac{1}{3}(\hbar\omega - \Phi_{effective})$$

MTE dependance:

- Photocathode Parameters
  - Material & Temperature
  - Surface Morphology
- Laser Parameter
  - Photon Energy ($\hbar\omega$)
  - Fluence

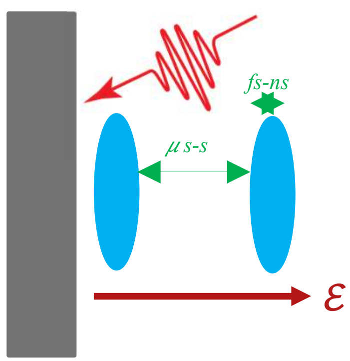
Photocathode Brightness

$$B = \frac{I}{\varepsilon_{nx}\varepsilon_{ny}}$$

$$\varepsilon_{nx} = \frac{\sigma_x \sigma_{p_x}}{mc} = \sigma_x \sqrt{\frac{\mathrm{MTE}}{mc^2}}$$

$$\mathrm{MTE} = \frac{1}{2}m\langle v_x^2\rangle + \frac{1}{2}m\langle v_y^2\rangle$$

- Pulsed Electron Beam
  - X-ray Sources, Colliders, Single Shot UED/M etc.

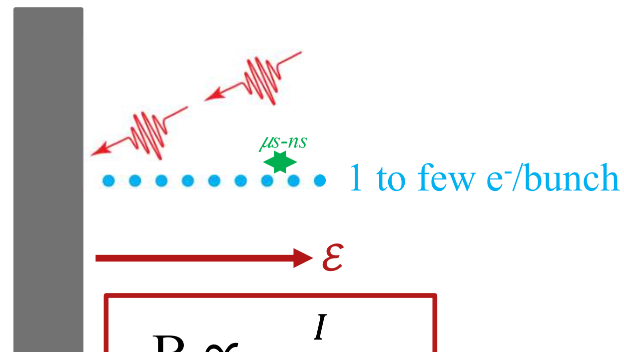


$$B \propto \frac{I}{\sigma_x^2 \mathrm{MTE}}$$

$$I \propto \sigma_x^2 \mathcal{E}$$

$$B \propto \frac{\mathcal{E}}{\mathrm{MTE}}$$

- Pulsed Electron Beam
  - Stroboscopic UED/M

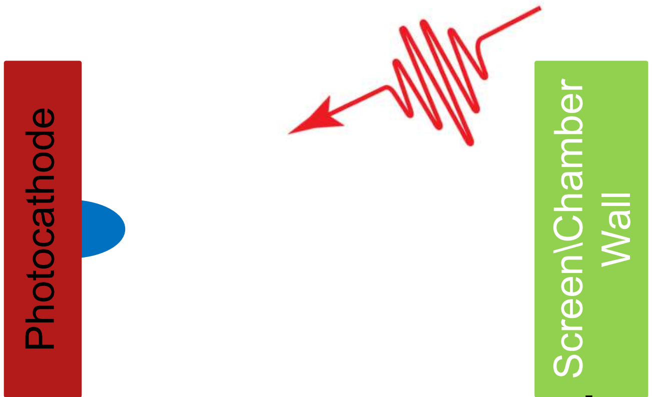


$$B \propto \frac{I}{\sigma_x^2 \mathrm{MTE}}$$

Few μm limited by the diffraction limit of light

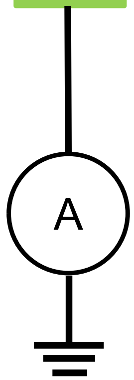
Measuring Photocathode Parameters

Quantum Efficiency

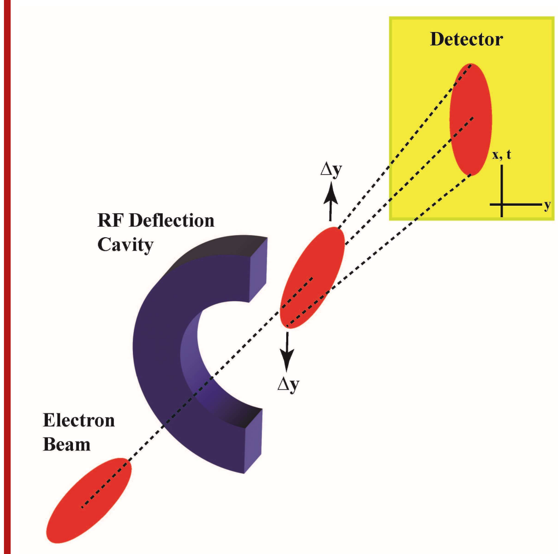


QE = (I$\hbar\omega$)/(P)

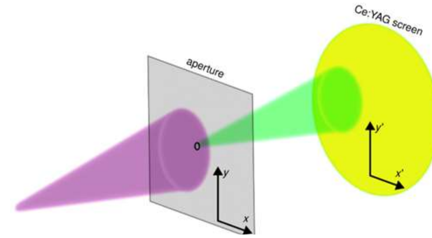
I = Average Photocurrent
P = Average laser Power



Response Time



Emittance



$$\Sigma_{4D} = \begin{bmatrix} \langle xx \rangle & \langle xx' \rangle & \langle xy \rangle & \langle xy' \rangle \\ \langle x'x \rangle & \langle x'x' \rangle & \langle x'y \rangle & \langle x'y' \rangle \\ \langle yx \rangle & \langle yx' \rangle & \langle yy \rangle & \langle yy' \rangle \\ \langle y'x \rangle & \langle y'x' \rangle & \langle y'y \rangle & \langle y'y' \rangle \end{bmatrix}$$

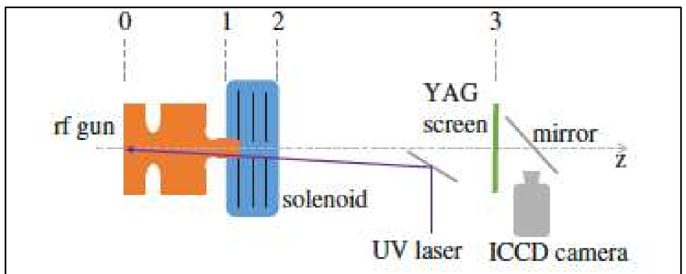
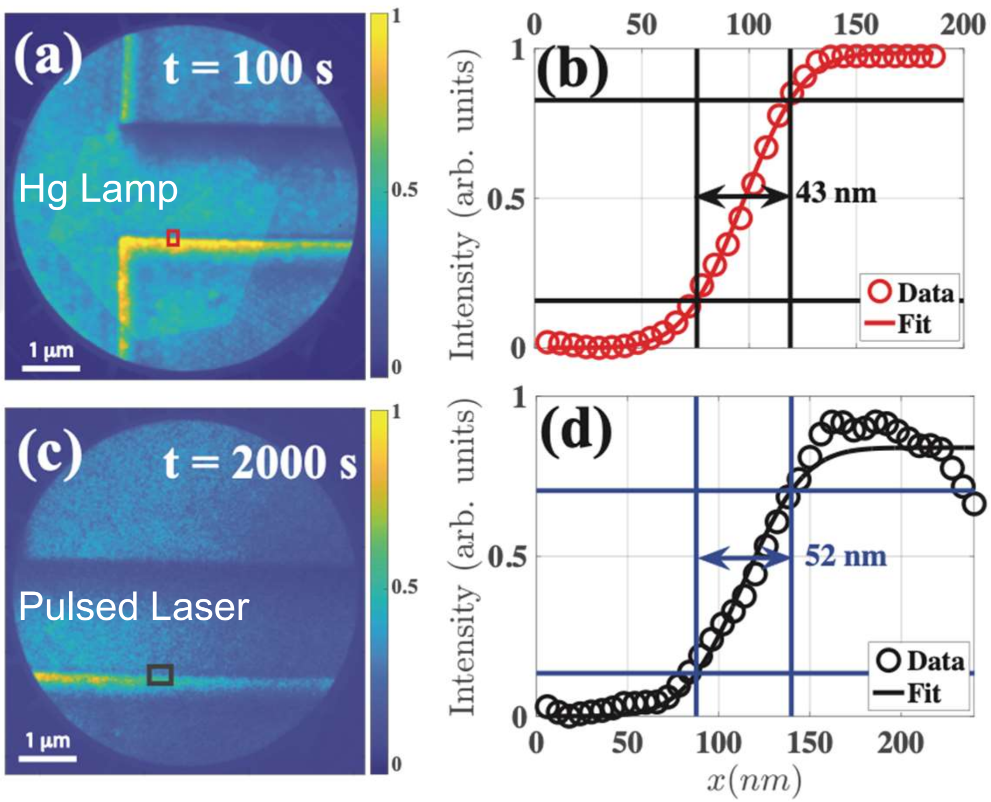


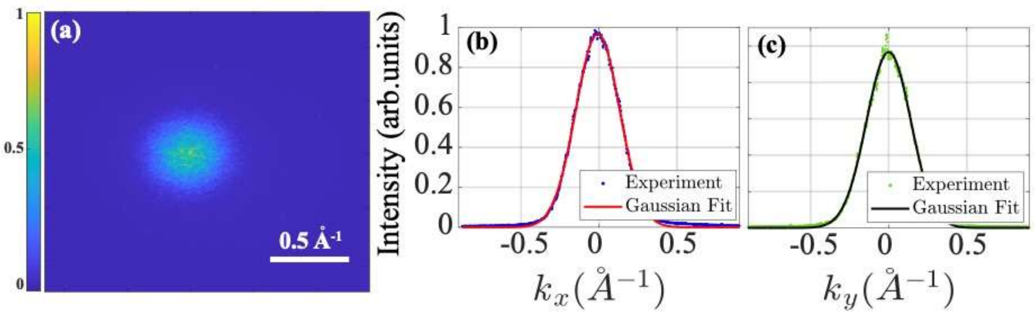
FIG. 1. Thermal emittance measurement setup at AWA.

PEEM: Characterize Photocathodes

Real Space: Measure $\boldsymbol{\sigma_x}$ and $\boldsymbol{I}$



k Space: Measure $\boldsymbol{\sigma_{p_x}}$ or **MTE**



$$\mathrm{MTE} = \frac{\hbar^2\sigma^2}{2m}$$

$$\sigma = \sqrt{\sigma_{k_x}^2 + \sigma_{k_y}^2}$$

Resolution

k Space 7.4 m$\AA^{-1}$

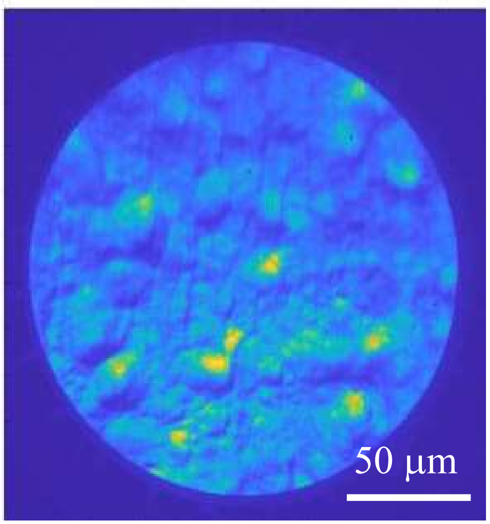
(MTE 0.2 meV for 25 meV)

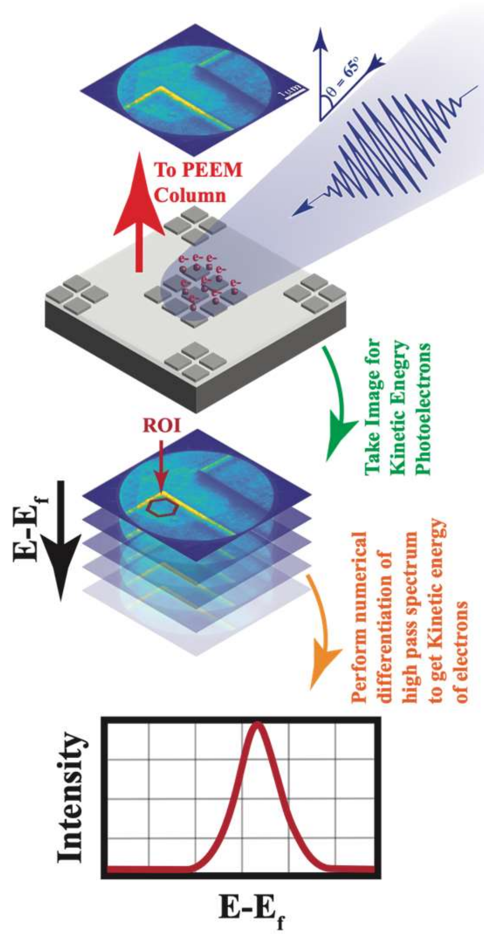
PEEM: Characterize Photocathodes

Measure Kinetic Energy

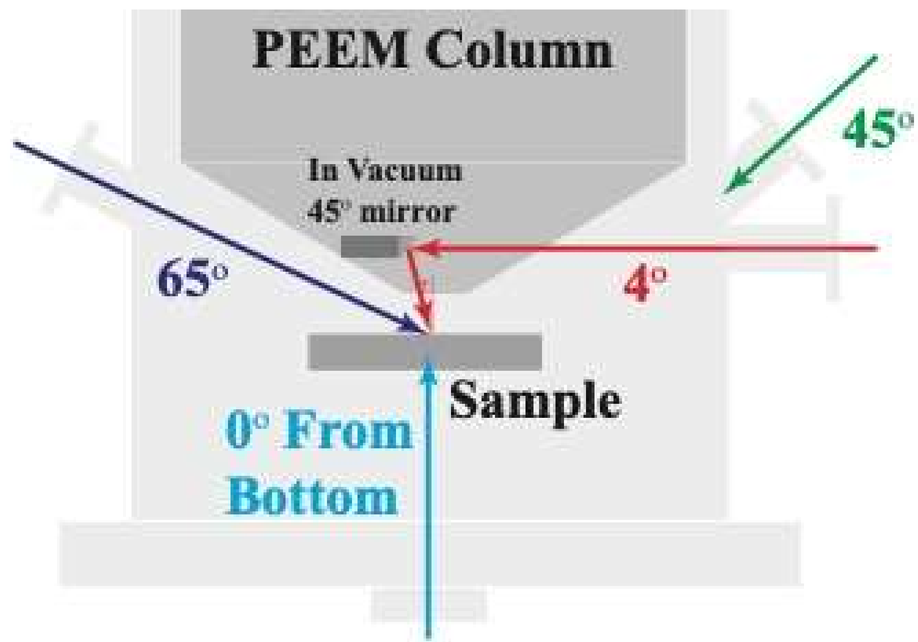
Resolution: 62 meV

Measure Photocathode Uniformity





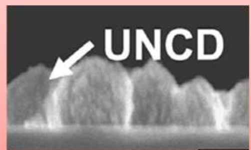
Various Angle of Incidence in Focus PEEM



Research Work: Various Photocathodes

(N)UNCD

MTE limited to 70 meV due to physical & chemical roughness

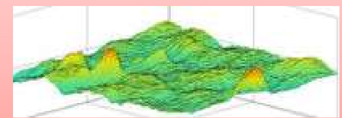


Kachwala, A., Chubenko, O., Kim, D., Simakov, E. I., & Karkare, S. (2022). Quantum efficiency, photoemission energy spectra, and mean transverse energy of ultrananocrystalline diamond photocathode. *Journal of Applied Physics*, *132*(22).

Cs_3Sb

Work function = 1.5 eV

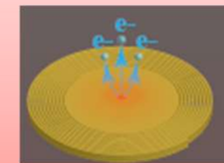
<u>Record low</u> MTE ~ 30 meV



Kachwala, A., Saha, P., Bhattacharyya, P., Montgomery, E., Chubenko, O., & Karkare, S. (2023). Demonstration of thermal limit mean transverse energy from cesium antimonide photocathodes. *Applied Physics Letters*, *123*(4).

Plasmonic spiral

<u>Record low</u> emittance ~40 pm-rad

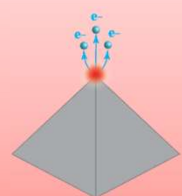


Kachwala, A., *et. al., IPAC 2023/2024.*

arXiv preprint arXiv:2406.08678 (2024).

(N)UNCD Tip

Thermalized electron emission



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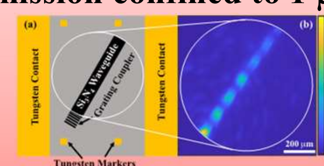
Photonics Integrated Cathodes

<u>Record</u> evanescent mode photoemission confined to 1 μm spot



Kachwala, A., *et. al., NAPAC 2022.*

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Manuscript Under Preparation.

Applied Physics Letters 120.19 (2022): 194102.

Chemical Physics Letters 430.4-6 (2006): 345-350.

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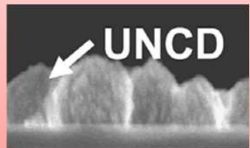

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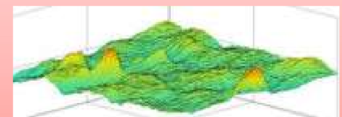

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Plasmonic spiral

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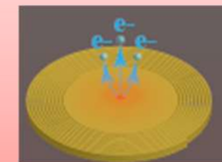

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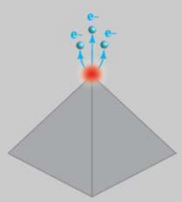
Thermalized electron emission



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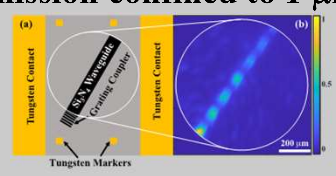

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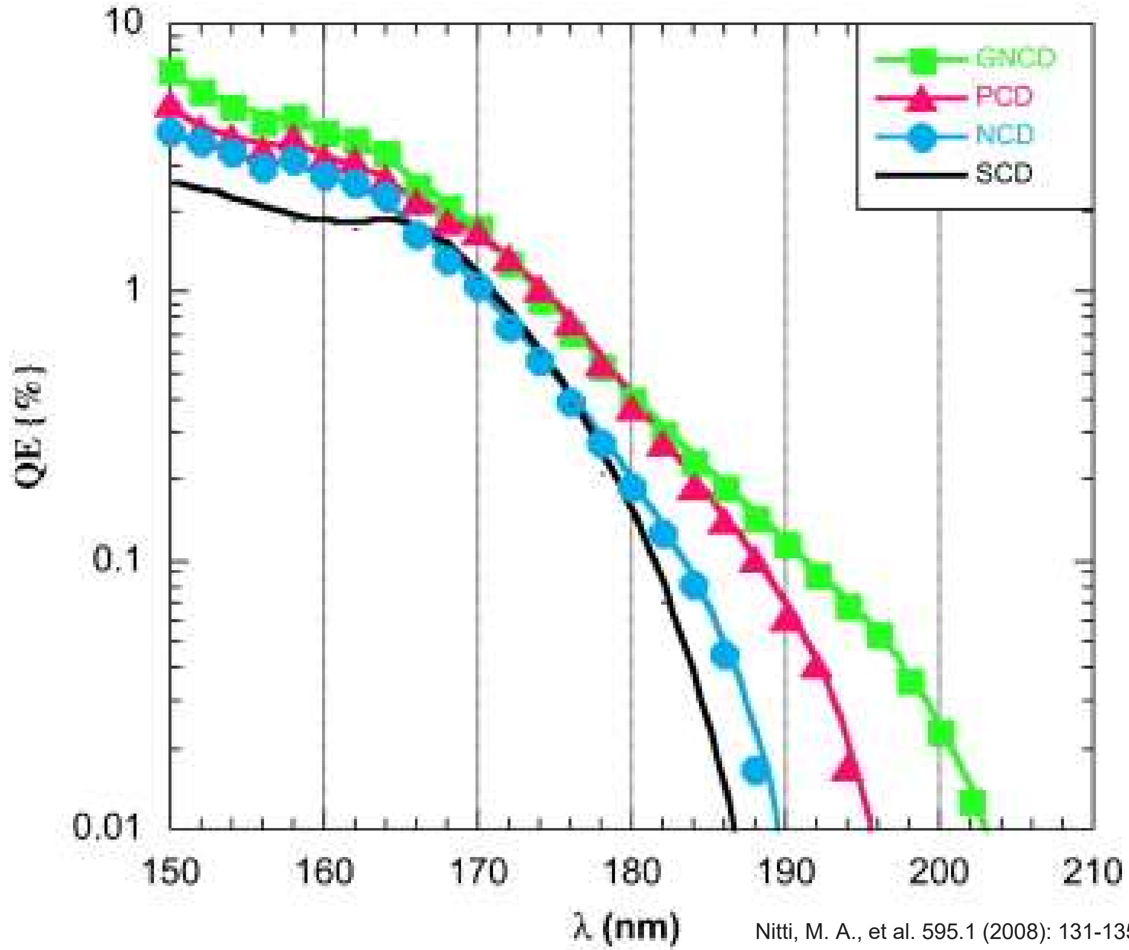
Chemical Physics Letters 430.4-6 (2006): 345-350.

(N) UNCD Photocathode

- Mechanical
- Vacuum Stability

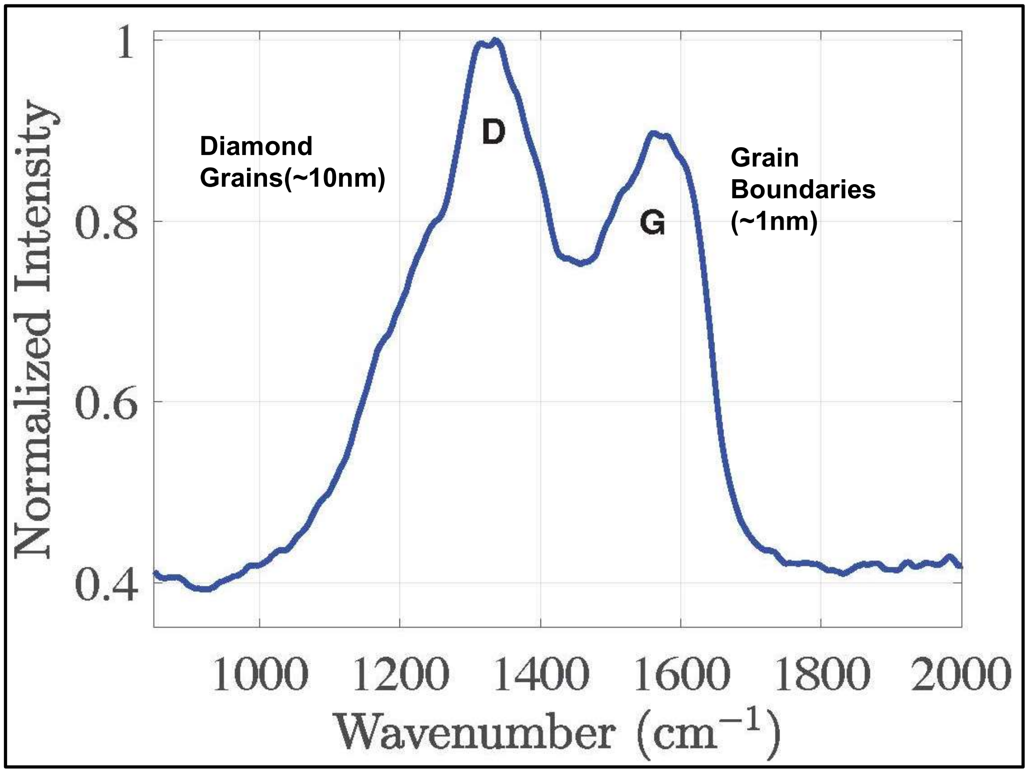
Improve performance at λ > 200 nm

Introduce Negative Electron Affinity by *n*-doping of diamond films and surface treatment in hydrogen environment



Nitti, M. A., et al. 595.1 (2008): 131-135.

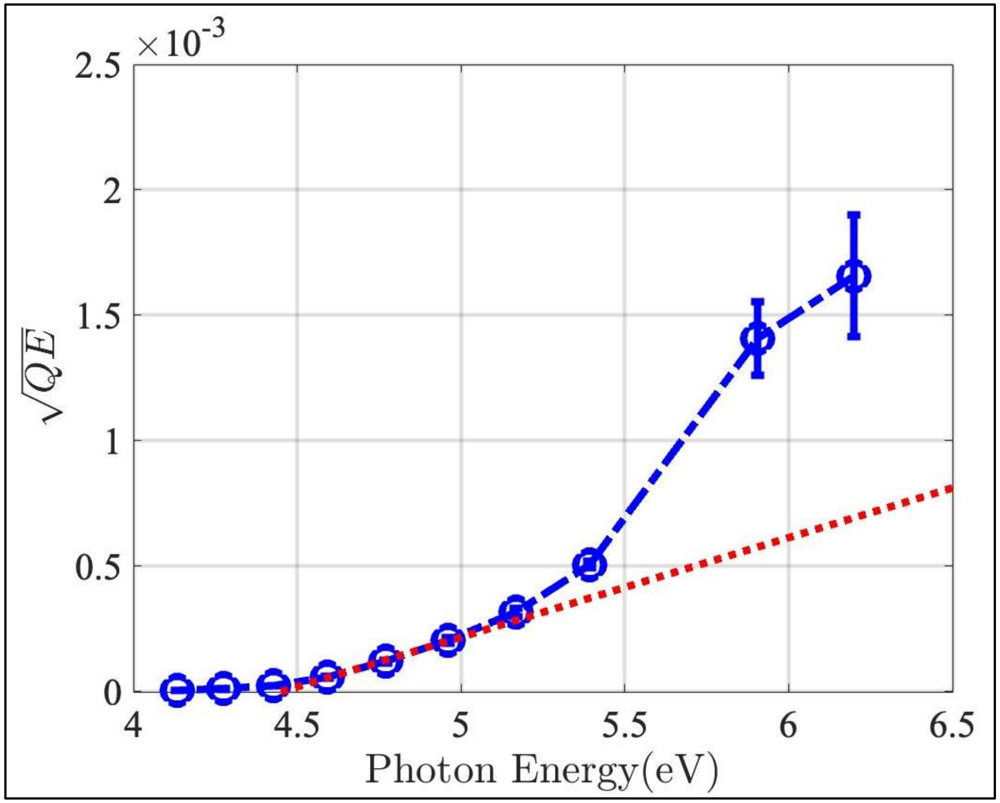
(N) UNCD Photocathode



Raman spectrum of the (N)UNCD sample showing a characteristic disordered diamond (D) peak and graphite (G) peak.

- λ: 200 – 300 nm
- Laser spot size: approx.100 µm X 250 µm (AOI: 65°)
- Extraction Field: 5 kV/m - 500 kV/m

(N) UNCD Photocathode: QE Measurement



$$QE \propto (\hbar\omega - \Phi_{effective})^2$$

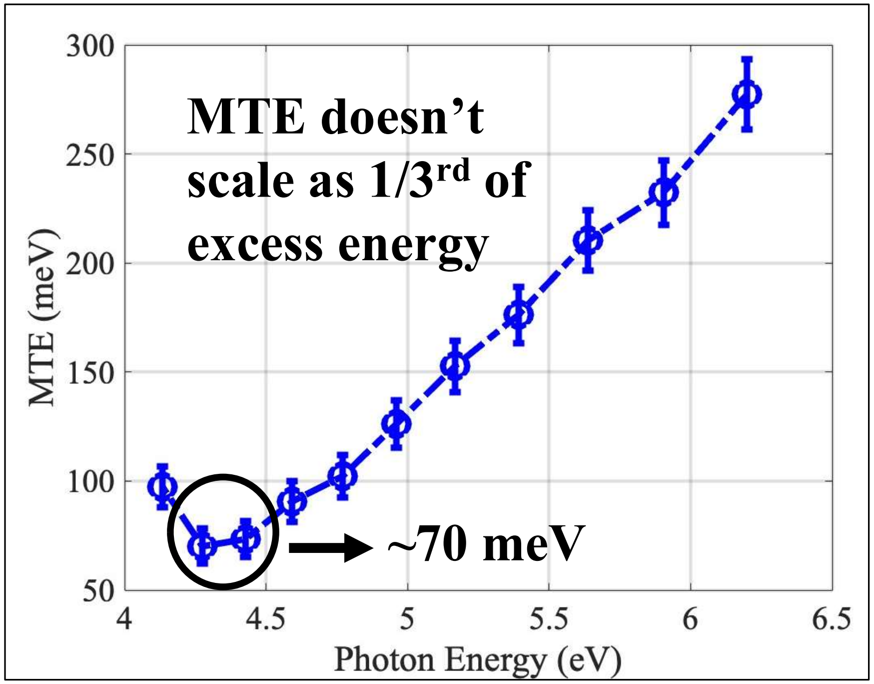
$$\Phi = 4.4 \pm 0.1 \text{ eV}$$

Comparable to Previously Reported Values

Comparable to Metal Photocathodes

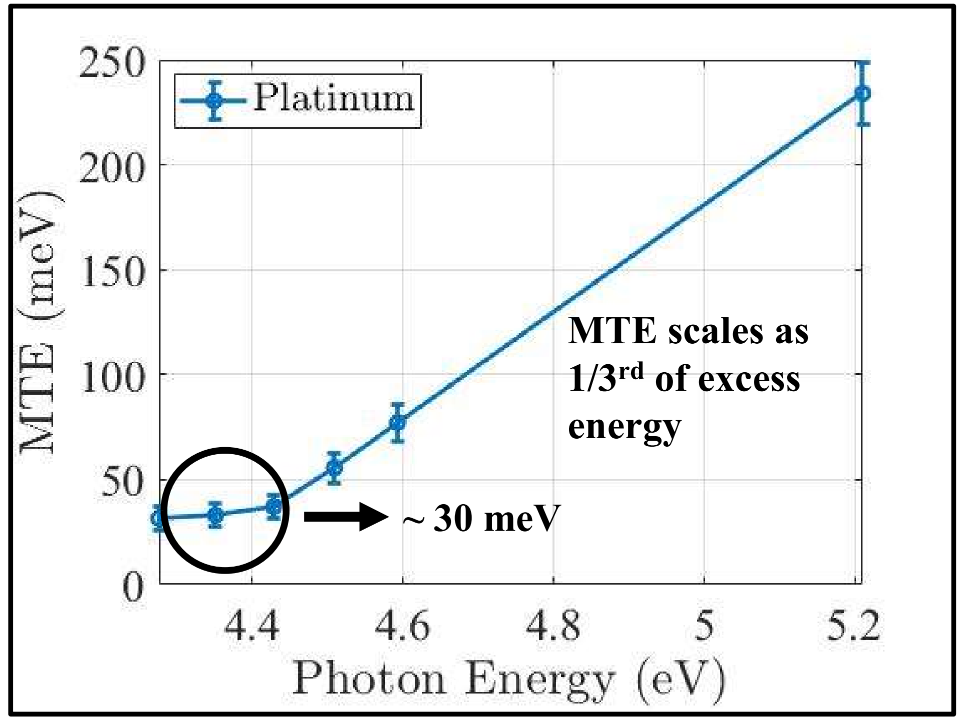
Quintero et al. *Applied Physics Letters* 105.12 (2014) Chen, et al. *Applied Physics Letters* 114.9 (2019) Chen et al. *Applied Physics Letters* 117.17 (2020)

(N) UNCD Photocathode: MTE Measurement

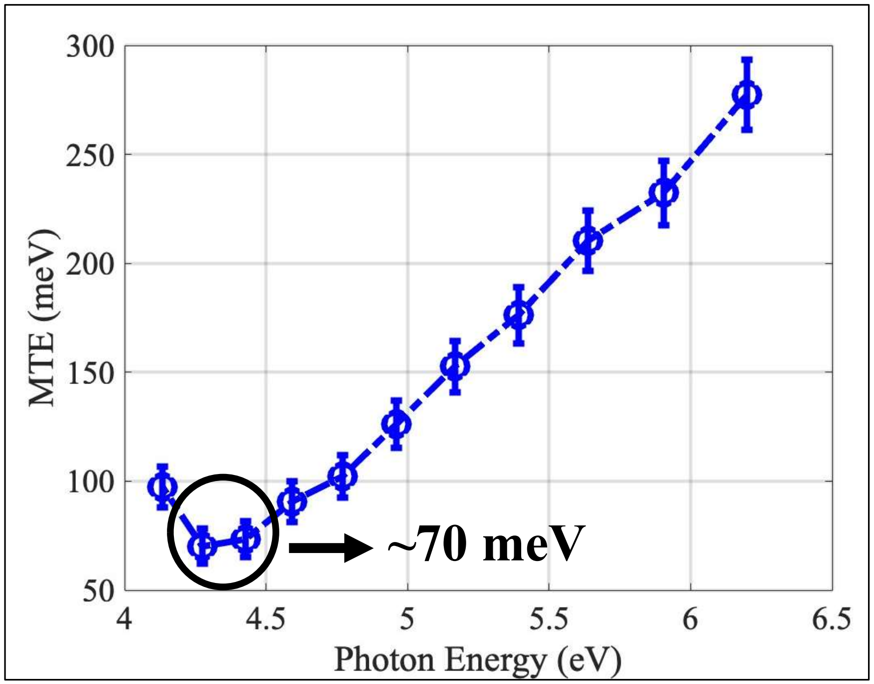


Why is MTE limited to 70 meV at threshold?

Let us Check for Metal Photocathode



(N) UNCD Photocathode: MTE Measurement



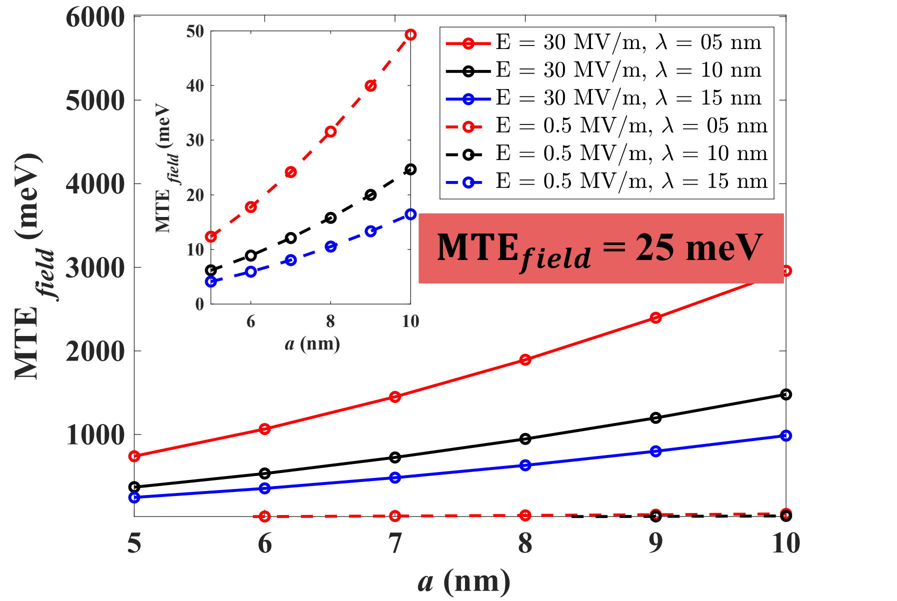
Why is MTE limited to 70 meV at threshold?

Physical Roughness

$$\text{MTE}_{field} = \frac{\pi^2 a^2 E_0 e}{2\lambda}$$

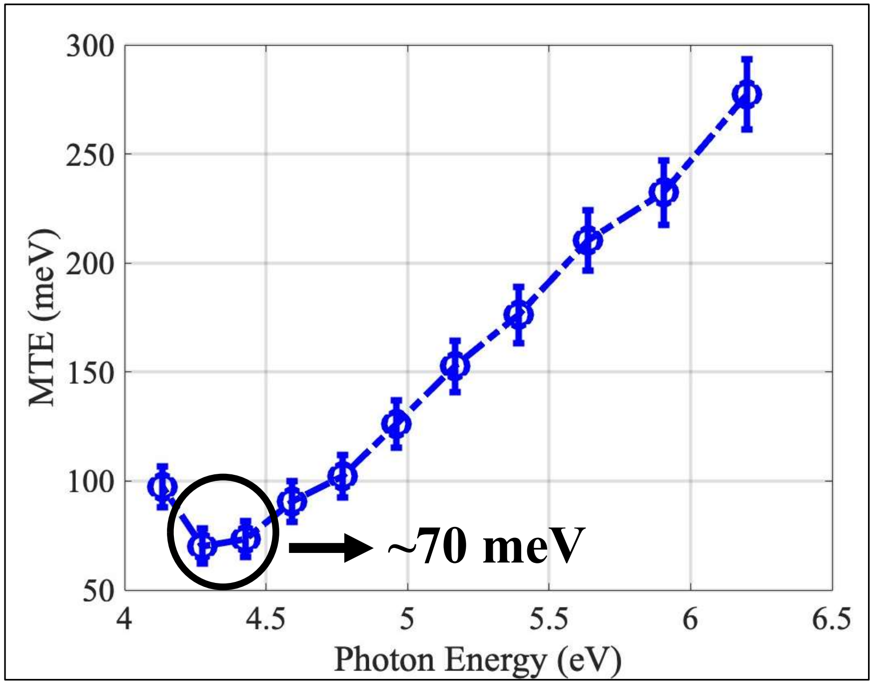
a = 5 - 10 nm,
λ = 5 - 15 nm

J. Appl. Phys. 121, 044904 (2017).



Chen, et al. *Applied Physics Letters* 117.17 (2020)

(N) UNCD Photocathode: MTE Measurement



Why is MTE limited to 70 meV at threshold?

Chemical Roughness

$$\mathrm{MTE}_{wf} = \frac{\pi^2 h^2 e}{4\sqrt{2} a E_0}$$

Φgraphite = ~4.4 eV
Φdiamond = ~5.4 eV

Phys. Rev Applied, 4, 024015 (2015).

$$\mathrm{MTE} = \mathrm{MTE}_{kT} + \mathrm{MTE}_{field} + \mathrm{MTE}_{wf}$$

$\mathrm{MTE}_{kT} \sim 25$ meV at 300 K

$\mathrm{MTE}_{field} \sim 25$ meV

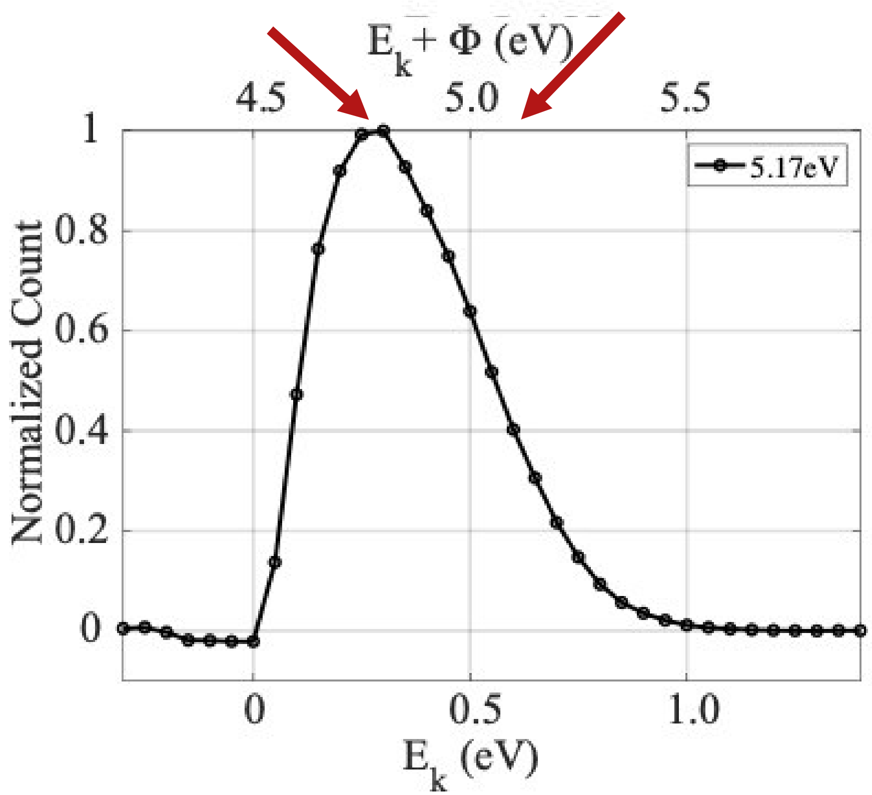
$\mathrm{MTE}_{wf} \sim 20$ meV

Chen, et al. *Applied Physics Letters* 117.17 (2020)

(N) UNCD Photocathode: Electron Energy Spectra

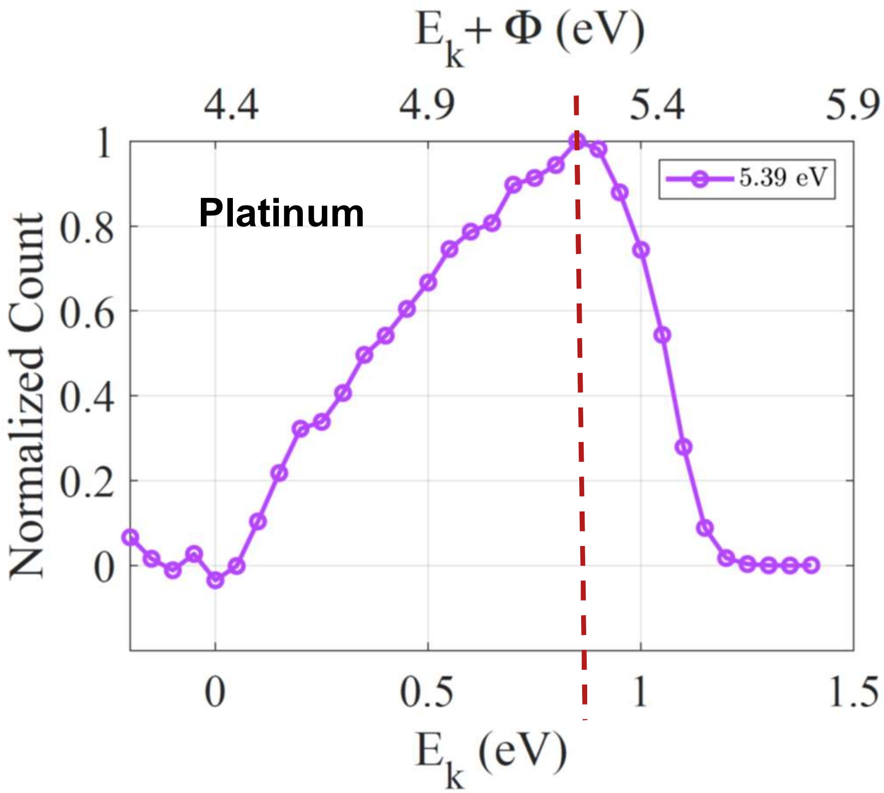
$\Phi = 4.5$ eV

Electron Scattering during transport



$\Phi = 4.4$ eV

NO Electron Scattering during transport



(N)UNCD: Conclusion

Parameter	Measured
Φ	4.4 ± 0.1 eV
MTE	~70 meV
QE	$\sim 10^{-6}$

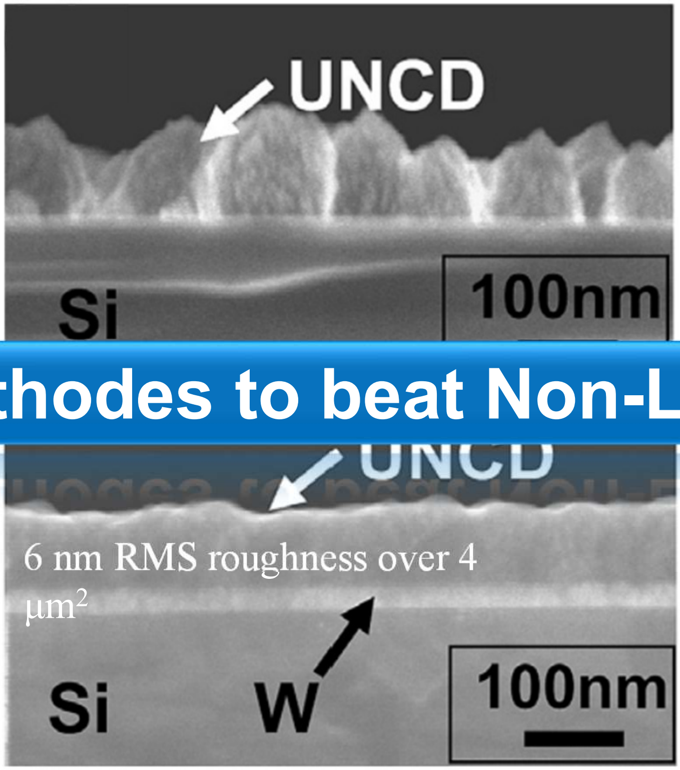
(N)UNCD: Conclusion

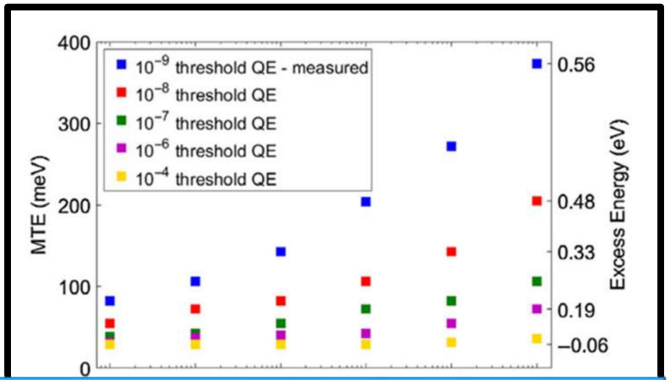
Fast Response Time (~1 ps)

Long Operational Lifetime

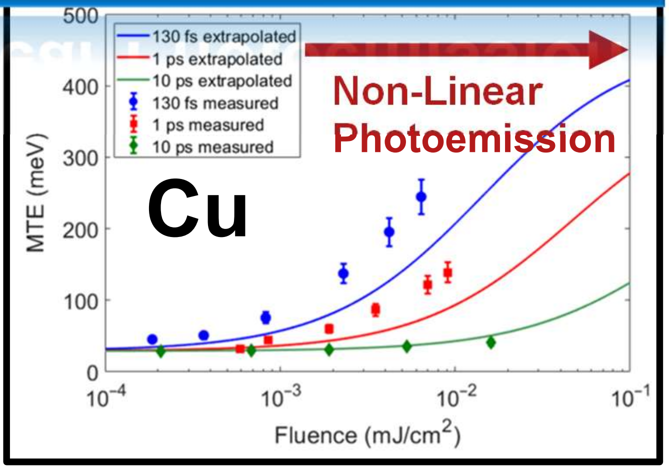
Can have Low MTE

LOW QE





Need High QE cathodes to beat Non-Linear Photoemission



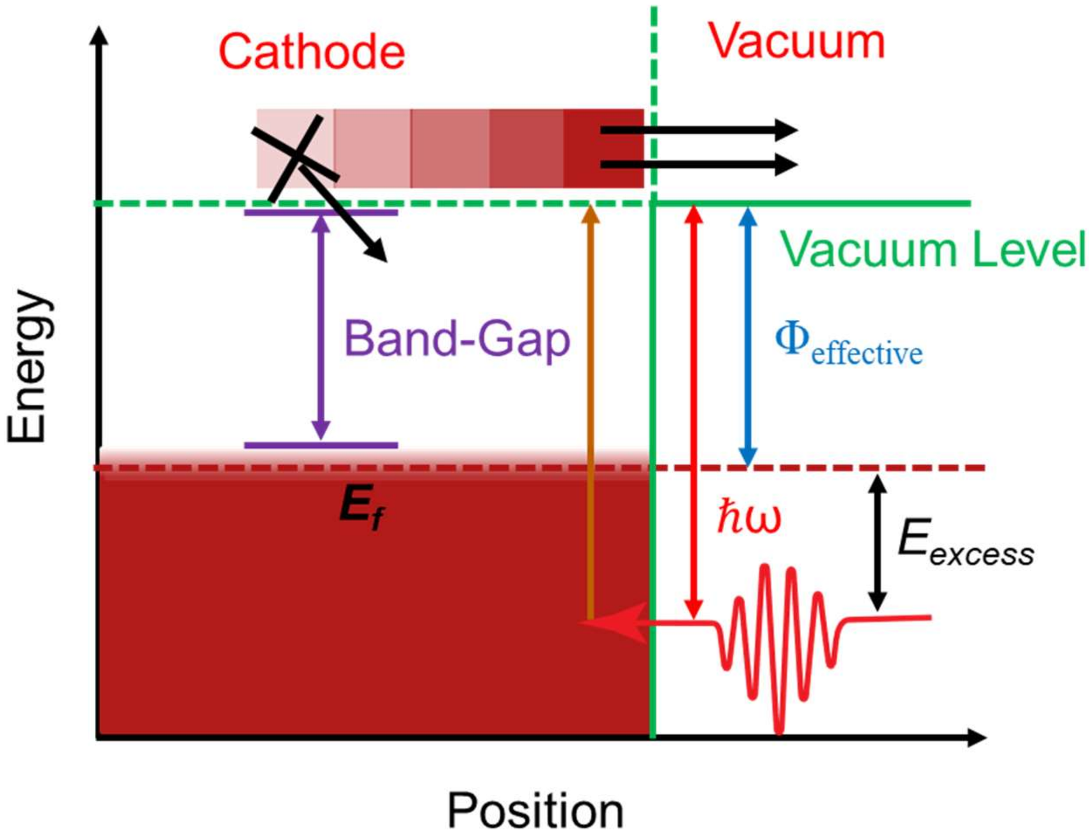
Naguib, et al. *Chemical Physics Letters* 430.4-6 (2006): 345-350.

Physical Review Accelerators and Beams 26.9 (2023): 093401

Physical review letters 125.5 (2020): 054801

High QE Photocathodes

Low Electron Affinity Semiconductors

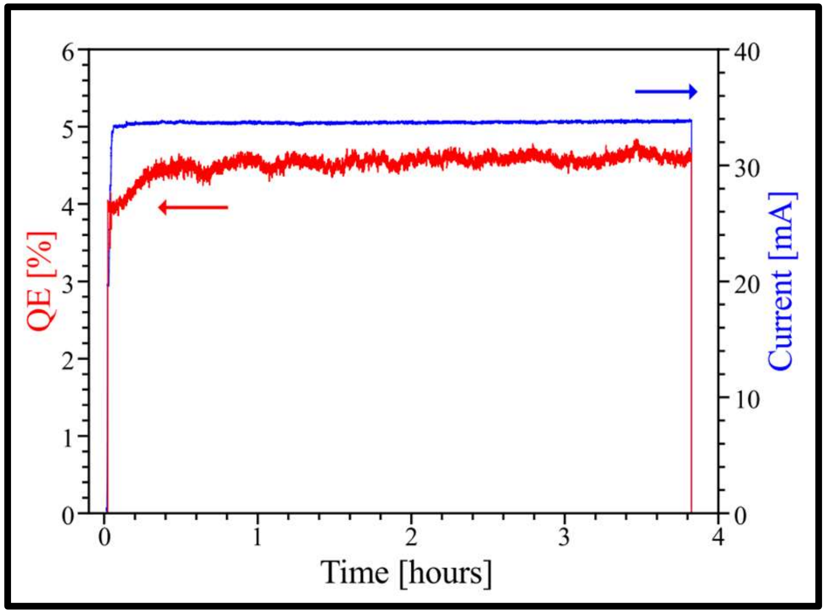


Alkali Antimonide Photocathodes

- K_2CsSb
- Na_2KSb
- Cs_3Sb

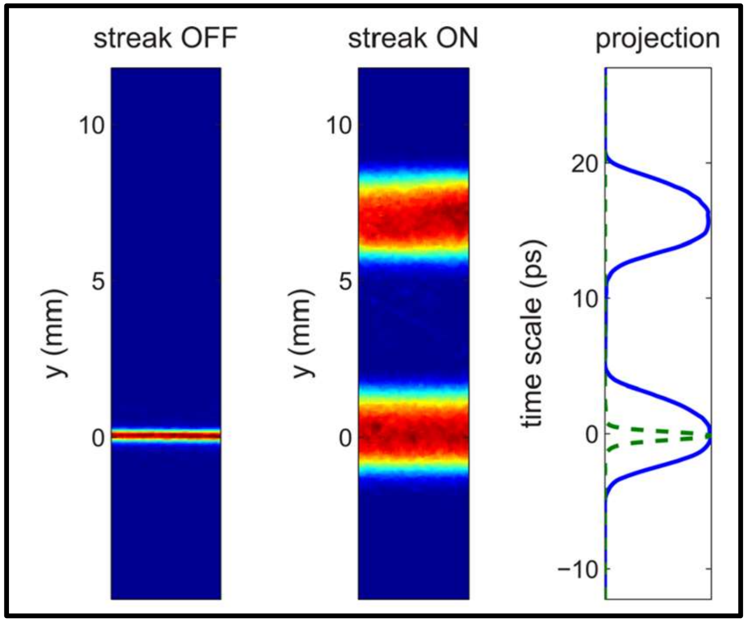
Cs_3Sb for High Brightness Applications

Operational Lifetime



Applied Physics Letters 102.3 (2013).

Response Time

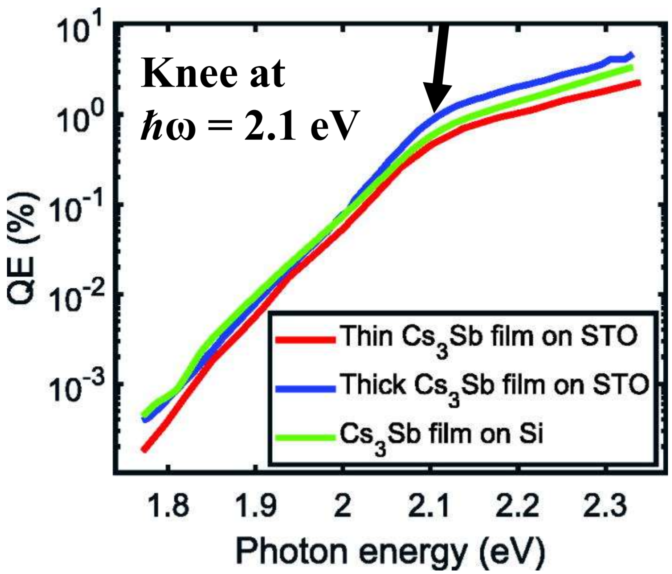


Sub pico-second response time with $\lambda = 520$ nm

Applied Physics Letters 99.15 (2011).

Cs_3Sb for High Brightness Applications

High QE



Orders of Magitude Higher than Metal Photocathode

Applied Physics Letters 120.19 (2022): 194102.

Physical Review Special Topics-Accelerators and Beams 18.11 (2015): 113401.

Low MTE

MTE of ~40 meV (> 25 meV at 300 K)

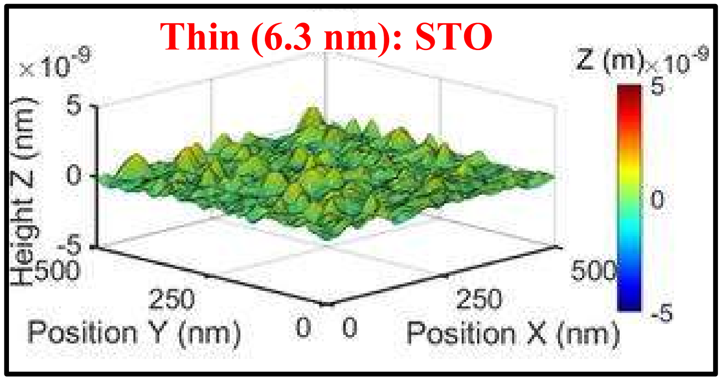
- Physical Surface Roughness
- Work Function Variation ("Chemical Roughness")

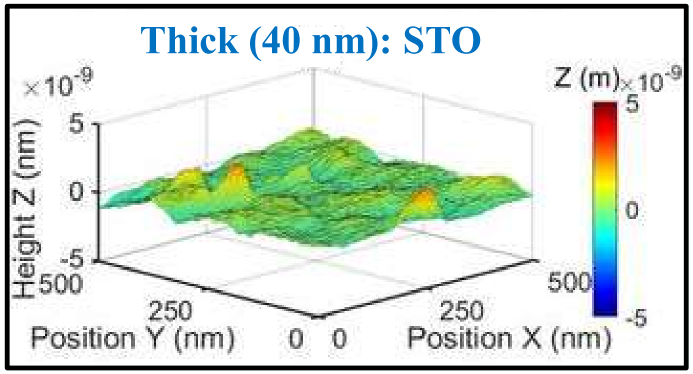
40 meV at 300K (Expected 25 meV)

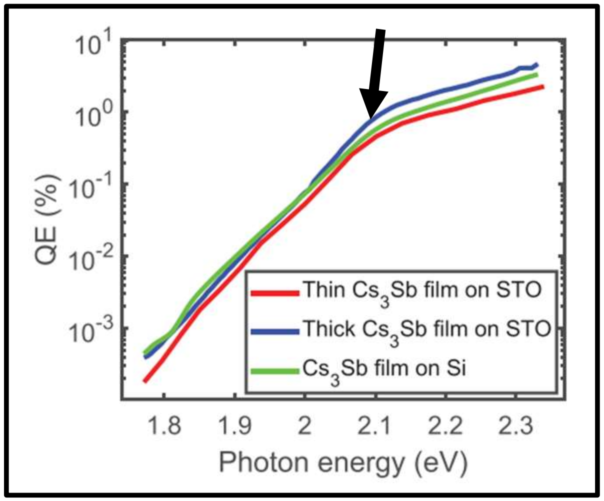
22 meV at 90K (Expected 8 meV)

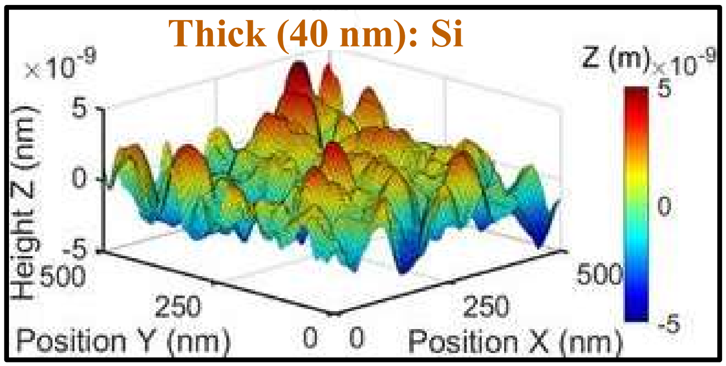
Cs_3Sb: Efforts to Grow Smooth Films

Co-Deposition on Lattice Matched Substrate









Thin STO: RMS surface roughness = 0.3 nm
Average spacing b/w peaks = 60 nm.

Thick STO: RMS surface roughness = 0.6 nm
Average spacing b/w peaks = 100 nm.

On Si: RMS surface roughness = 1.4 nm
Average spacing b/w peaks = 100 nm.

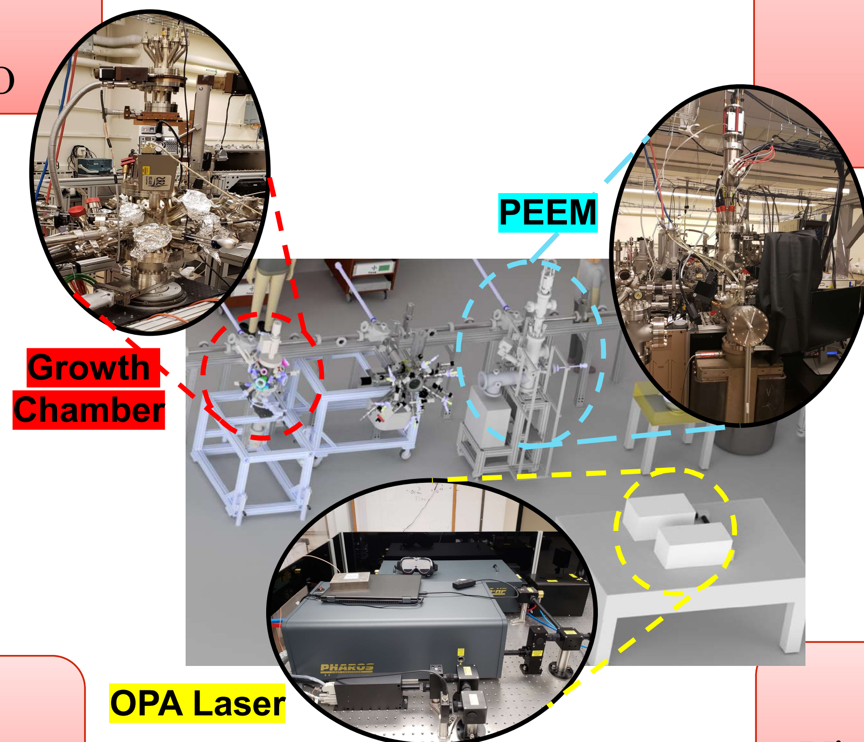
Observe Knee at $\hbar\omega = 2.1$ eV ($\lambda = 620$ nm)

Applied Physics Letters 120.19 (2022): 194102.

Cs_3Sb: Experiment

Growth
Thickness: ~40 nm
Substrates: Si and Nb doped STO

Measurements
$\hbar\omega$: 1.45 – 2.33 eV
Repetition rate: 500 kHz
Pulse length: 150 fs

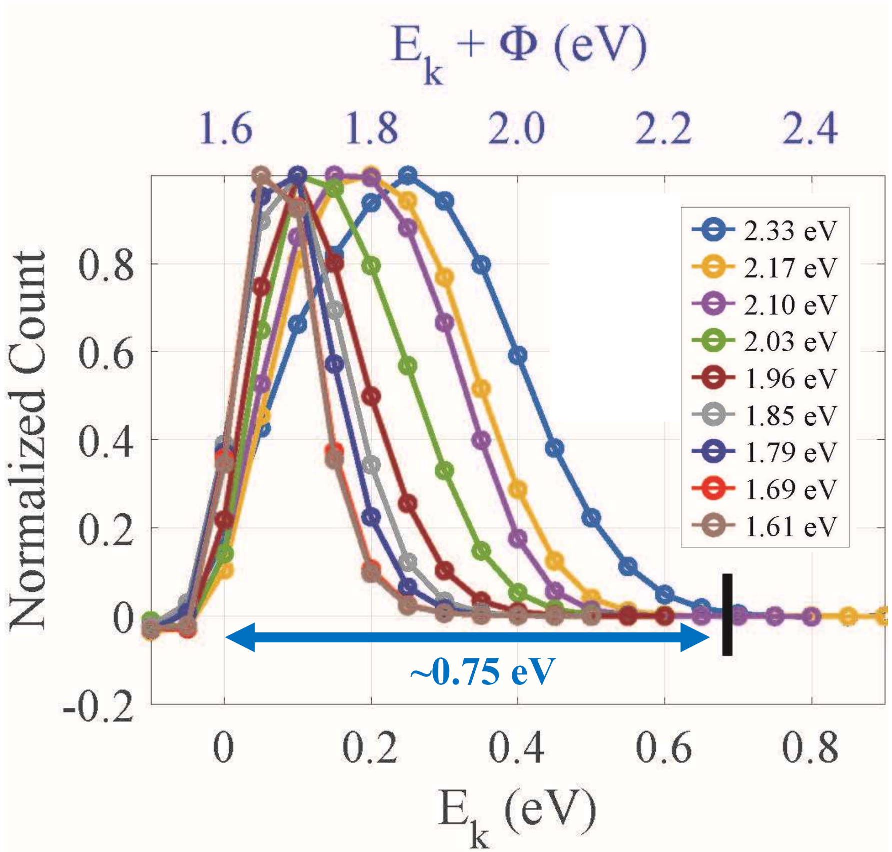


QE
3% - 4%
λ = 530 nm

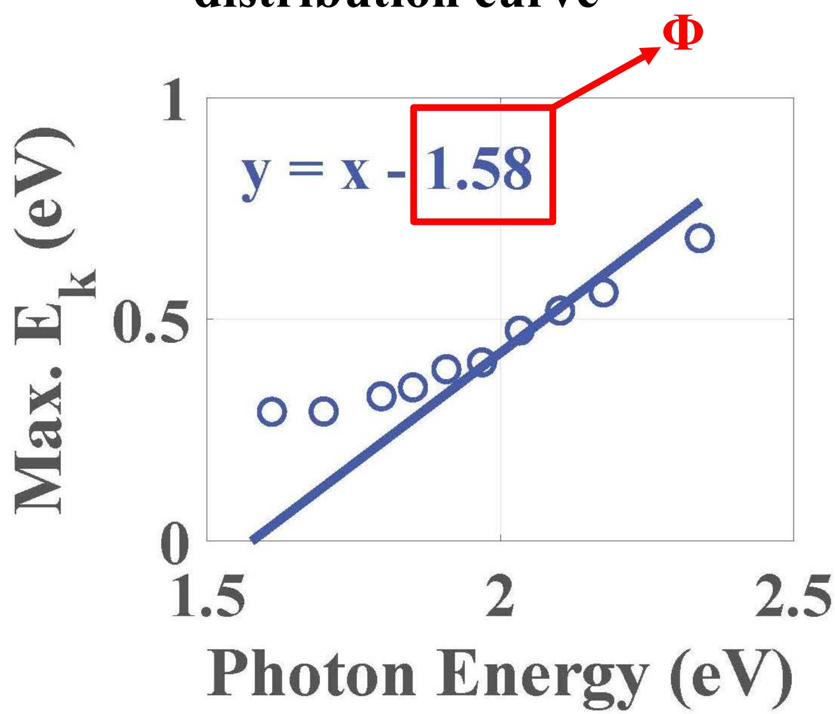
Transfer
Via UHV transfer line in PEEM
Measured: PEES, MTE & QE

Cs_3Sb: Photoemission Electron Energy Spectra

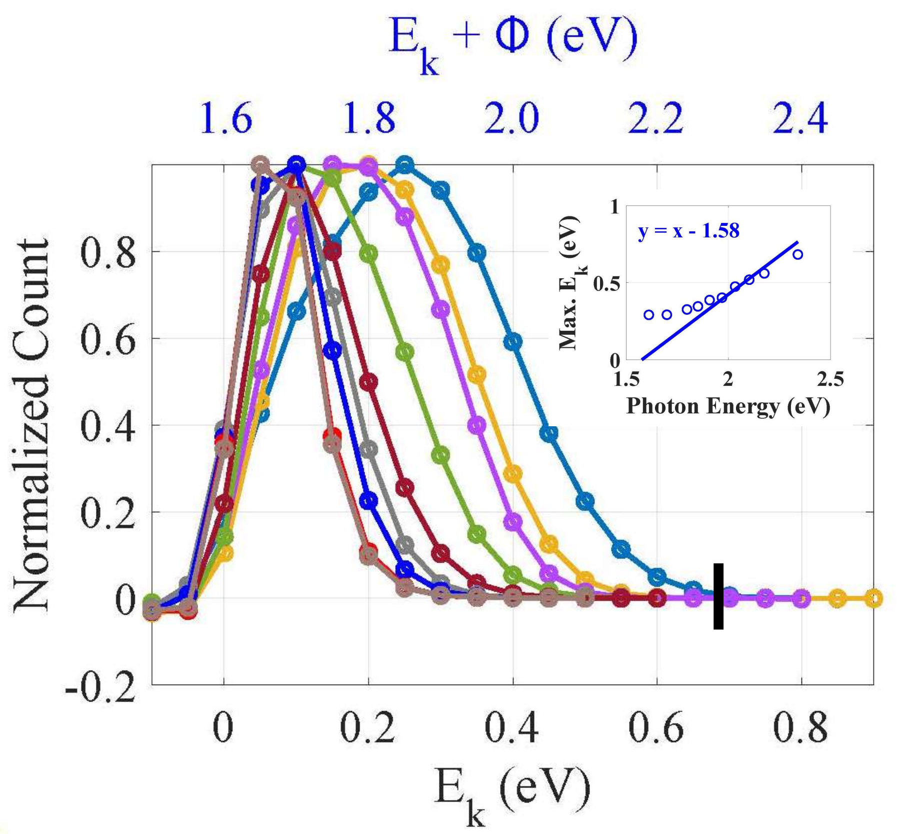
Substrate: Doped Si



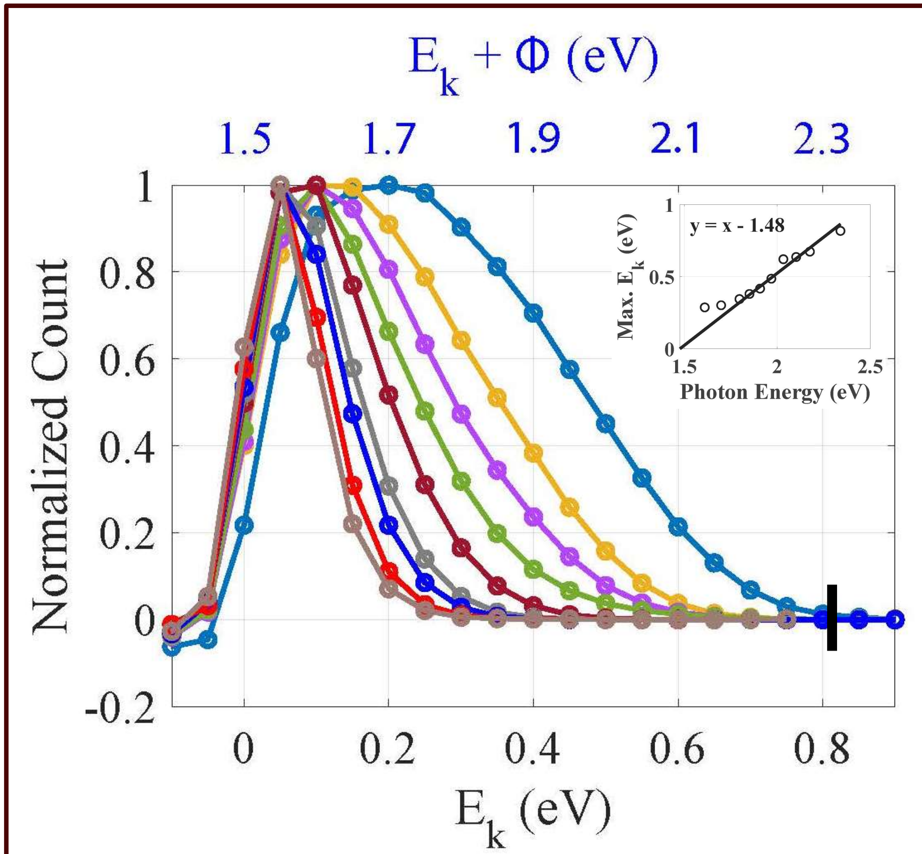
Maximum E_k = 1% of the maxima of the energy distribution curve



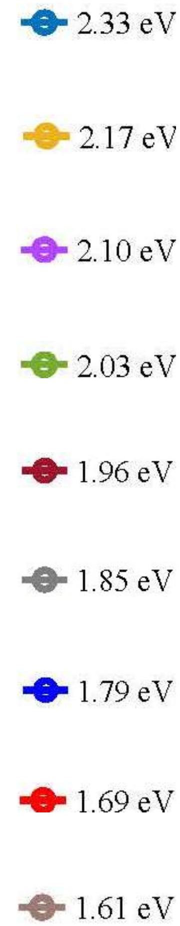
Cs_3Sb: Photoemission Electron Energy Spectra



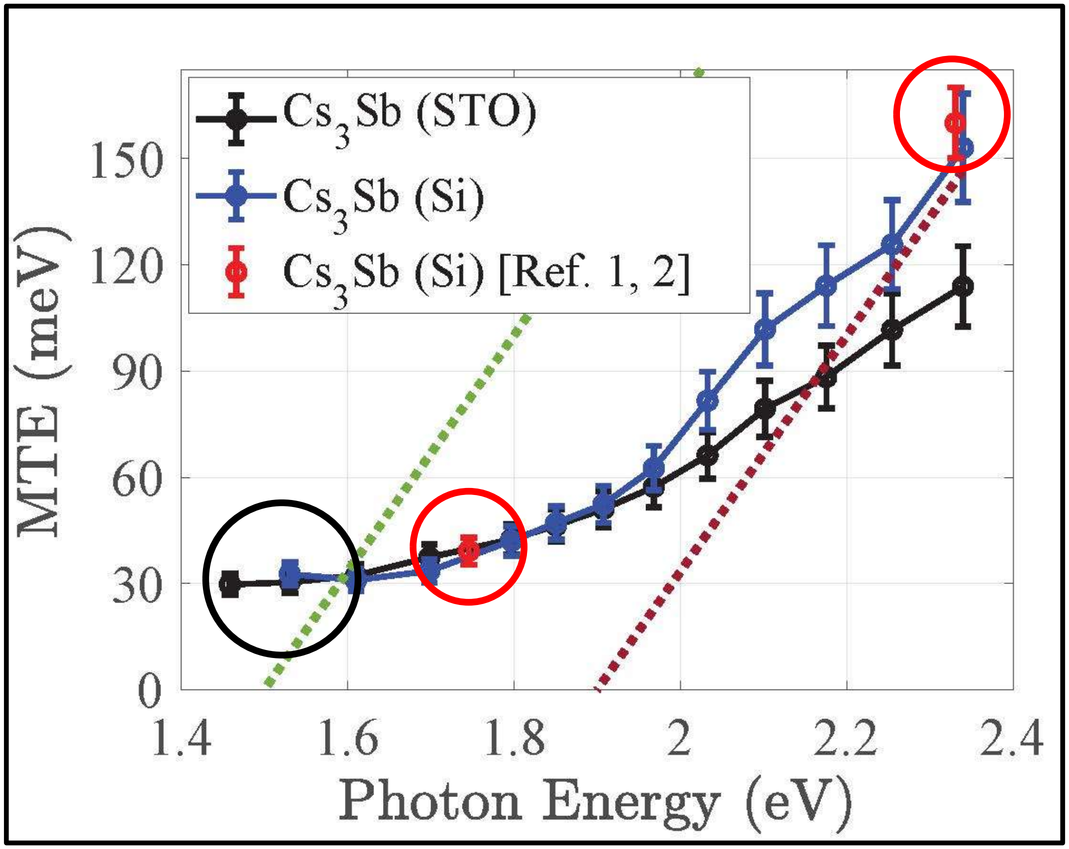
Substrate: Doped Si



Substrate: Nb Doped STO



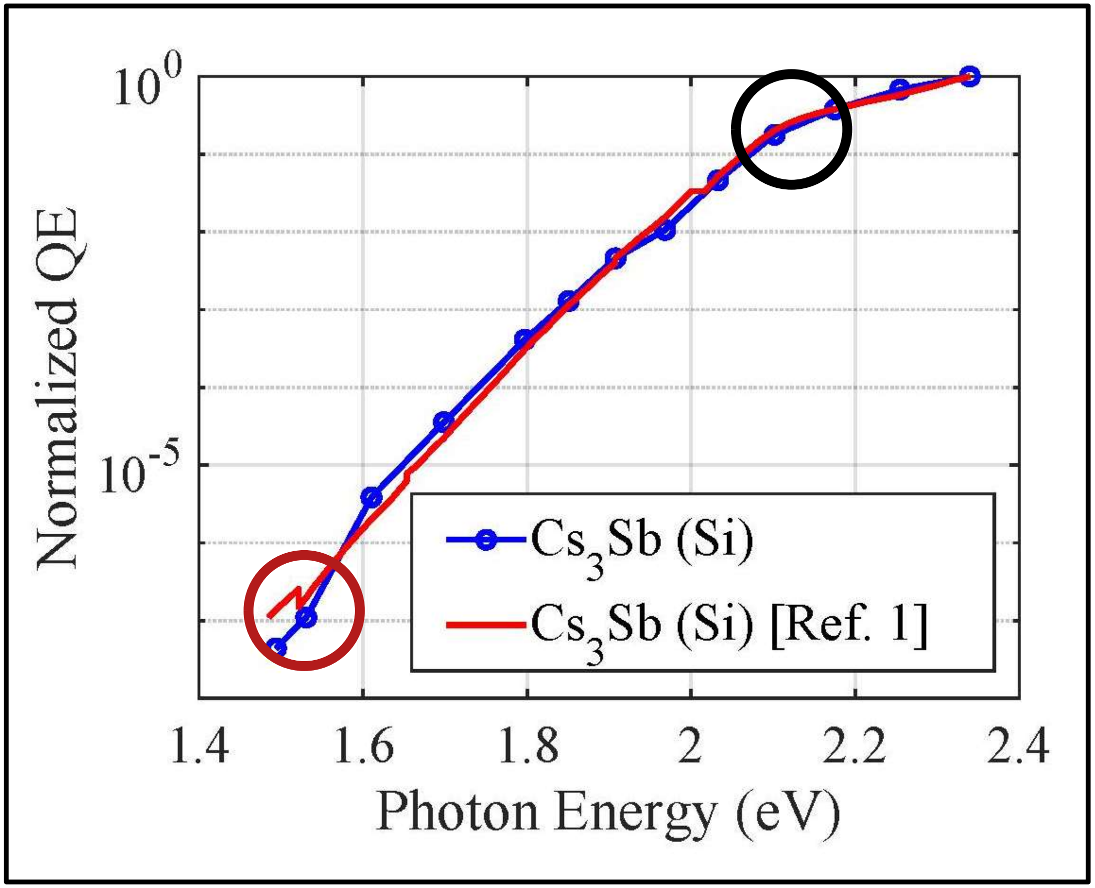
Cs_3Sb: Mean Transverse Energy



- At $\hbar\omega$ = 1.5 eV, MTE = 30 meV (~25 meV at 300 K)
- At $\hbar\omega$ = 1.8 eV, MTE = 40 meV and at $\hbar\omega$ = 2.3 eV, MTE = 150 meV (comparable to previously reported values)
- The dotted line is the plot for (excess energy)/3 considering **Φ = 1.5 eV (green)** and **Φ = 1.9 eV (brown)**
- MTE doesn't scale as $1/3^{rd}$ of excess energy (Scattering before emission)

1) *Physical Review Special Topics-Accelerators and Beams* 18.11 (2015): 113401.
2) *Applied Physics Letters* 99.15 (2011).

Cs_3Sb: Quantum Efficiency



- QE at $\hbar\omega$ =1.5 eV is 7 orders of magnitude lower when compared with that at $\hbar\omega$ = 2.3 eV
- A knee-like feature is also observed in the QE spectral response at $\hbar\omega$ = 2.1 eV
- Unstable $D0_3$ cubic structure

1) *Applied Physics Letters* 120.19 (2022): 194102.

Nangoi, J. K., et al. *arXiv preprint arXiv:2205.14322* (2022)

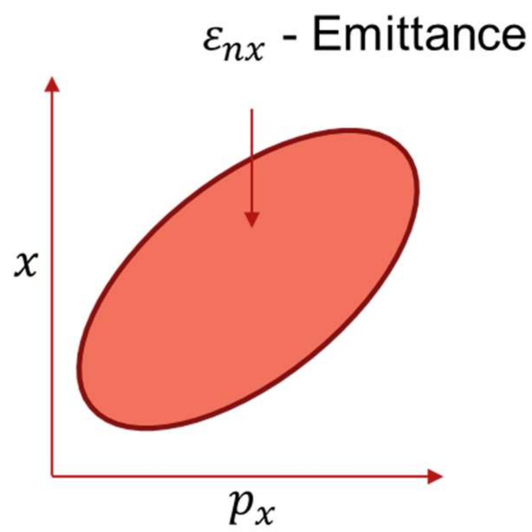
Cs_3Sb: Conclusion

These photocathodes to be used in SLAC-LCLS-II-HE

Parameter	Threshold	Operational
$\hbar\omega$	1.5 ± 0.1 eV	1.8 eV
MTE	~30 meV	~40 meV
QE (at Φ)	10^{-7}	10^{-4}
	Comparable to Metal Photocathodes	Better than Metal Photocathodes

1) *Physical Review Special Topics-Accelerators and Beams* 18.11 (2015): 113401.
2) *Applied Physics Letters* 99.15 (2011).

Need for Small Emission Area Photocathodes



Emittance

$\sqrt{\text{MTE}}$ σ_x

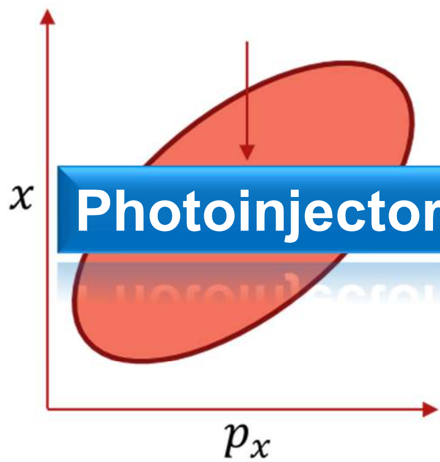
$$\varepsilon_{nx} = \frac{\sigma_x \sigma_{p_x}}{mc} = \sigma_x \sqrt{\frac{\text{MTE}}{mc^2}}$$

Reduce MTE

Reduce σ_x

Need for Small Emission Area Photocathodes

ε_{nx} - Emittance

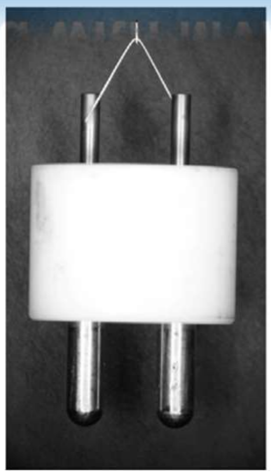


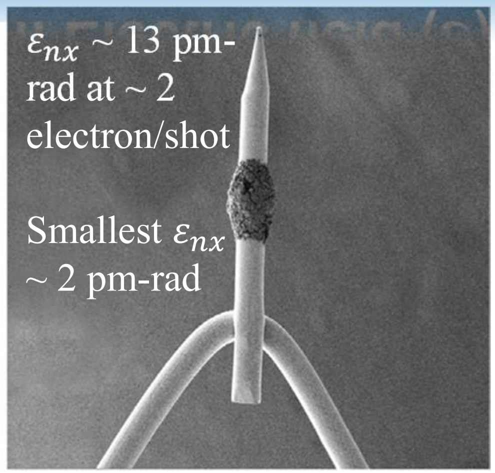
Reduce σ_x

Tip Emitters

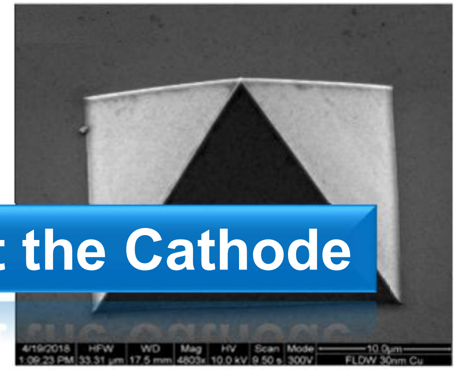
Photoinjector: Operated with MV/m Electric field ($\mathcal{E}$) at the Cathode

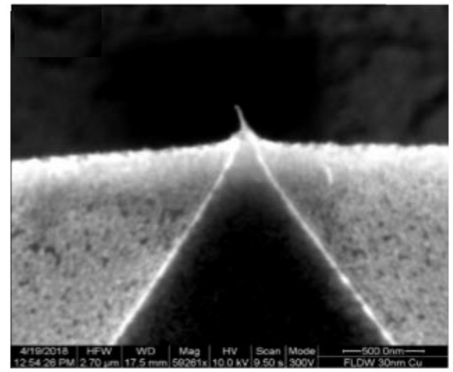
$$\varepsilon_{nx} = \frac{\sigma_x \sigma_{p_x}}{mc} = \sigma_x \sqrt{\frac{\text{MTE}}{mc^2}}$$





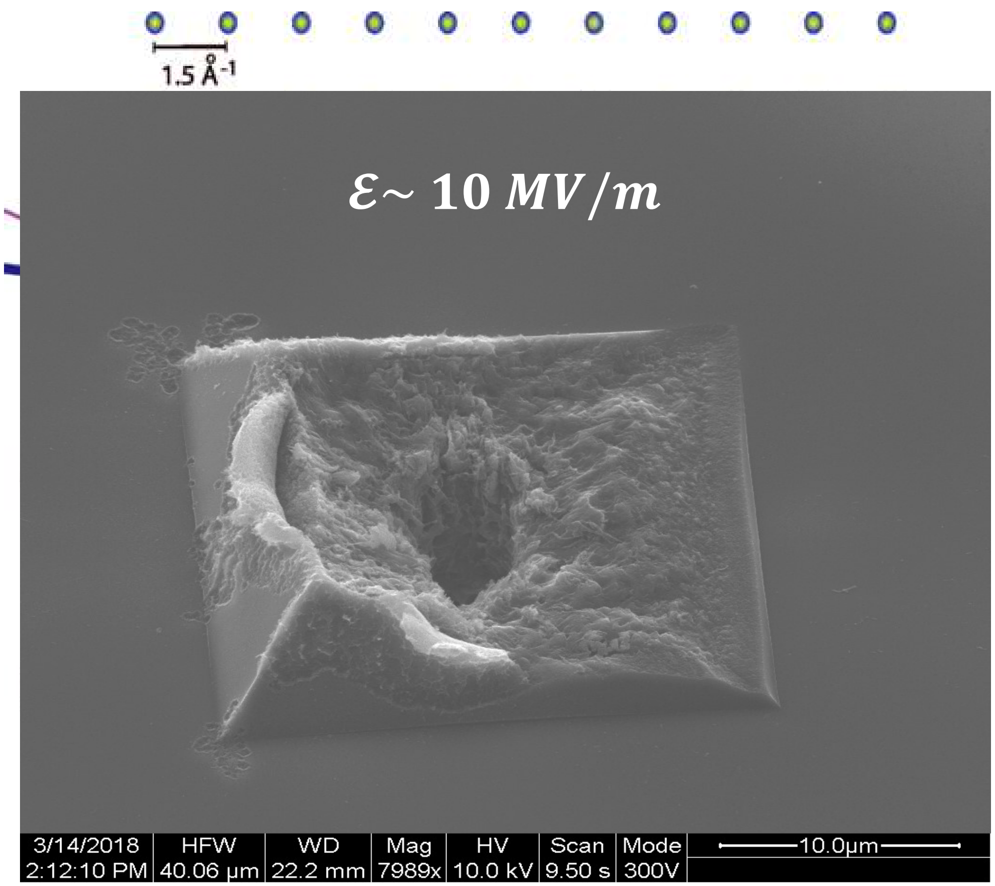
Ultramicroscopy 176 (2017): 63-73.





2018 IEEE Advanced Accelerator Concepts Workshop (AAC). IEEE, 2018.

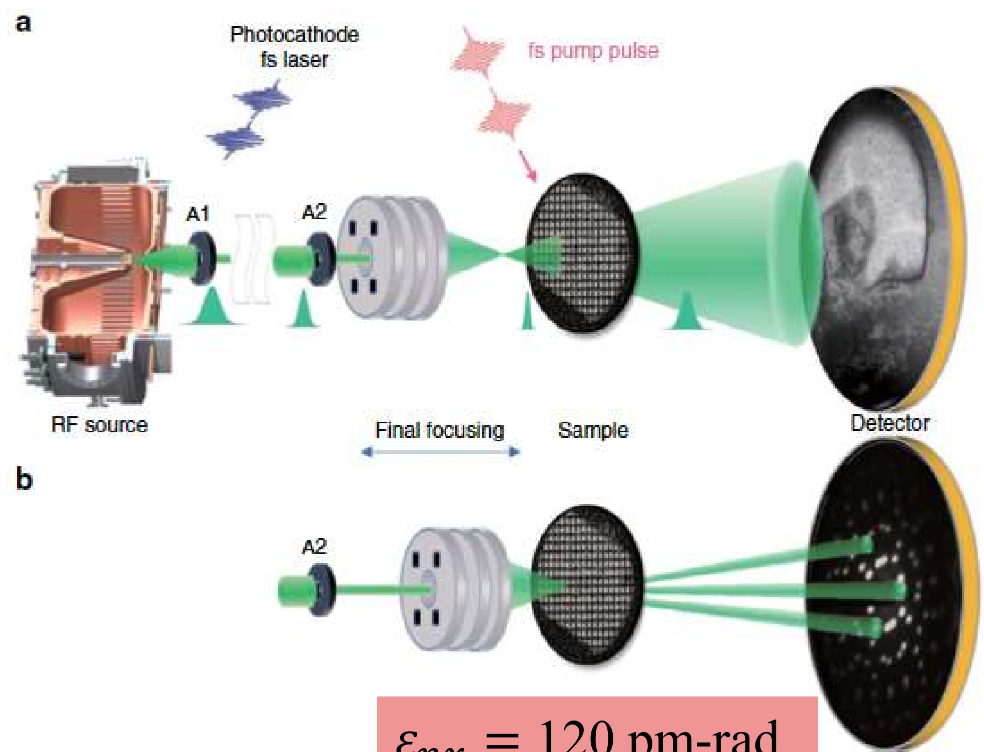
Need for Small Emission Area Photocathodes



Reviews of Modern Physics 94.4 (2022): 045004

Acknowledgement: Dr. Simakov and Dr. Kim

UED Beamlines with Collimating Apertures

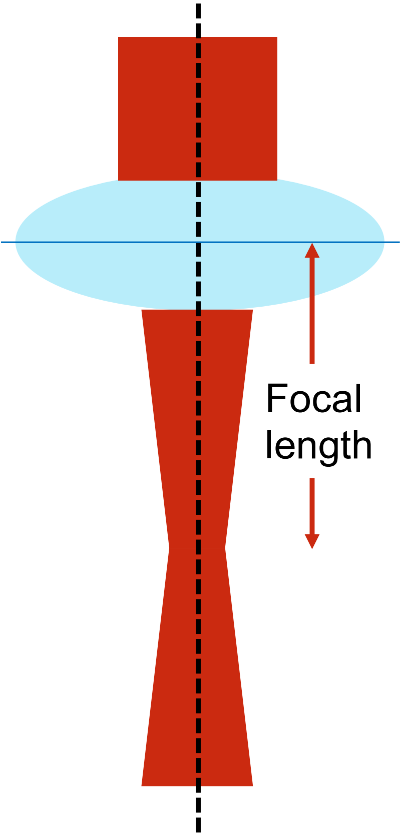


$\varepsilon_{nx} = 120$ pm-rad

Communications Physics 2.1 (2019): 54

Small Emission Area Photocathodes: Reducing σ_x

Conventional way of focusing light



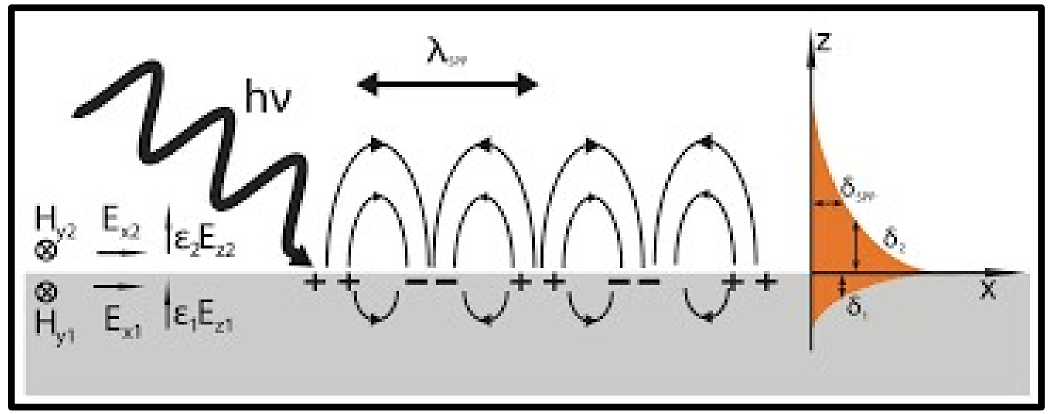
Limited by the Diffraction limit of light $\sim \frac{\lambda}{2}$

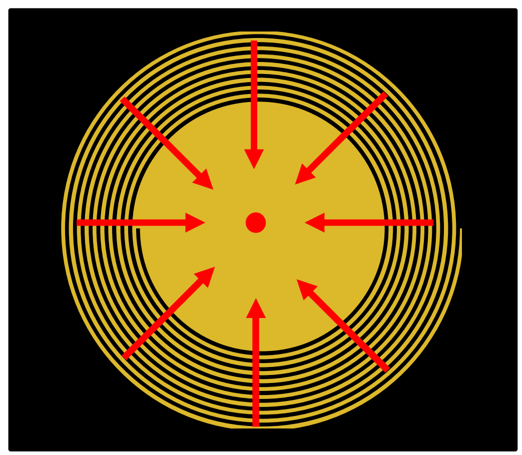
How to focus smaller than $\frac{\lambda}{2}$?

https://en.wikipedia.org

Structural Dynamics 9.2 (2022)

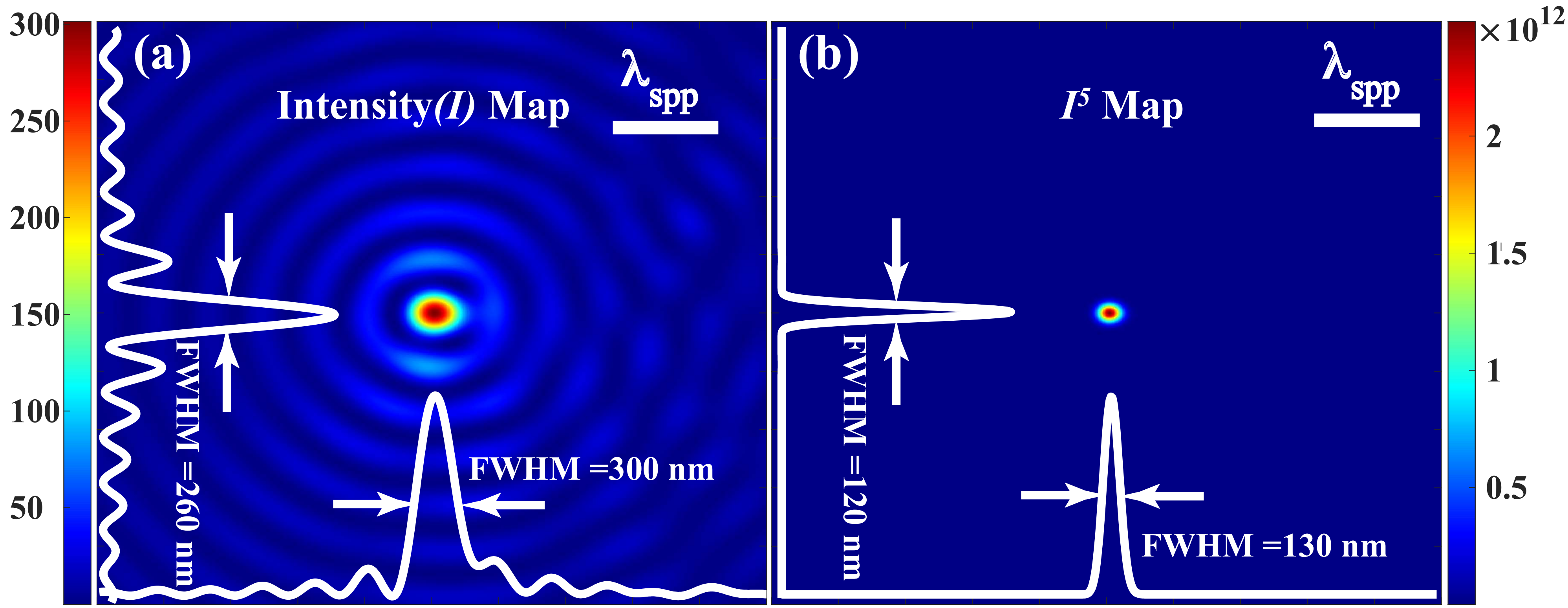
Surface Plasmon Polariton





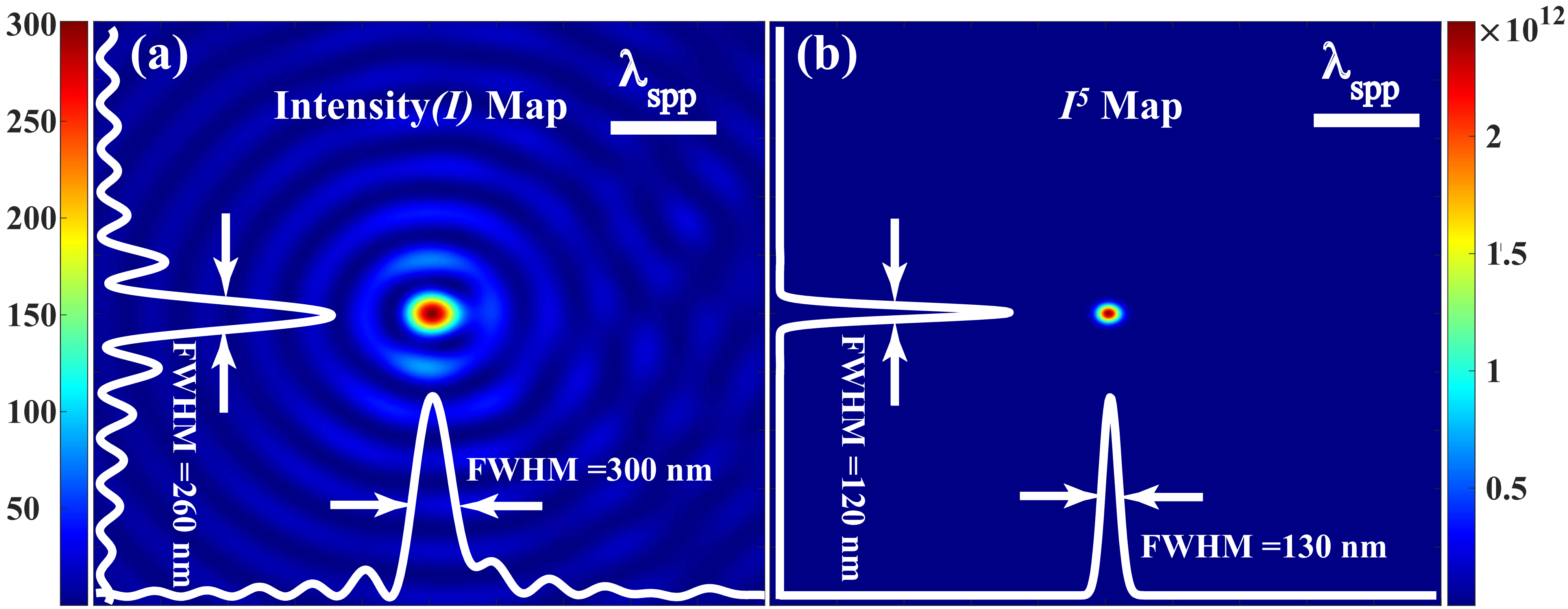
Achieve nanoscale electron emission area from **Plasmonic Gold Spiral**

Plasmonic Spiral Photocathode: FDTD Simulation



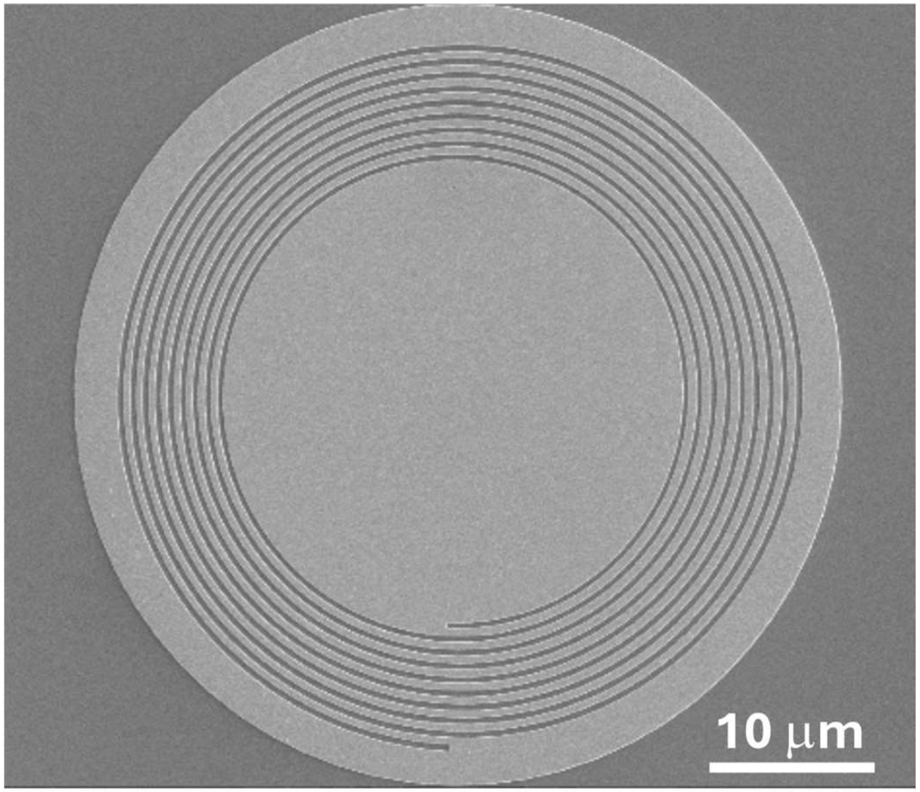
Source: Circularly Polarized Gaussian; $\hbar\omega$ = 1.55 eV (λ = 800 nm); Pulse Length = 150 fs; λ_{spp} = 783 nm

Plasmonic Spiral Photocathode: FDTD Simulation



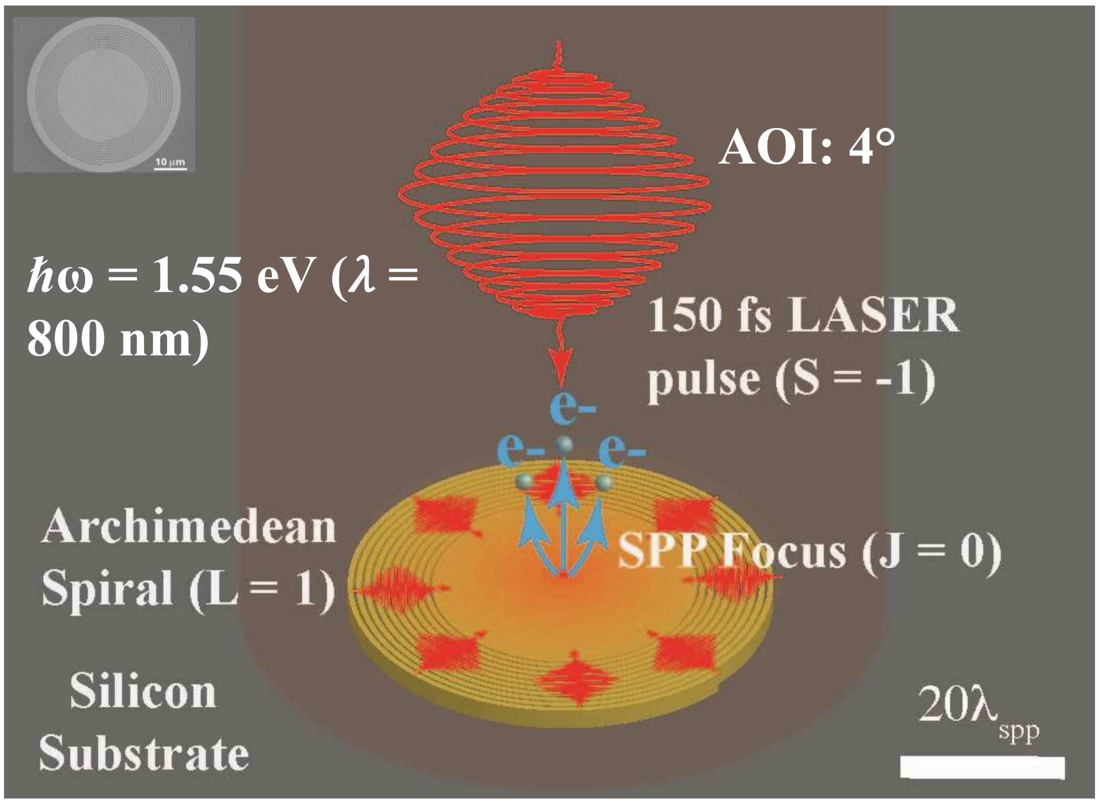
5th order Non-Linear Photoemission shrinks the electron source size ~120 nm

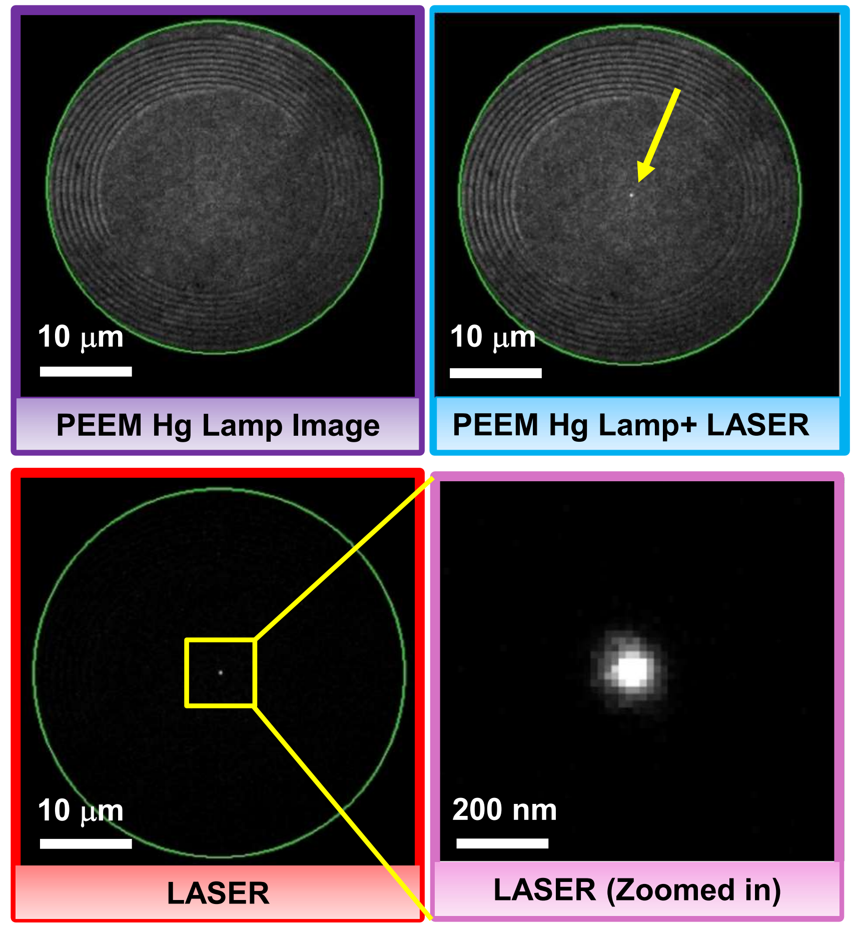
Plasmonic Spiral Photocathode: Experimental



Plasmonic Spiral Photocathode: Experimental

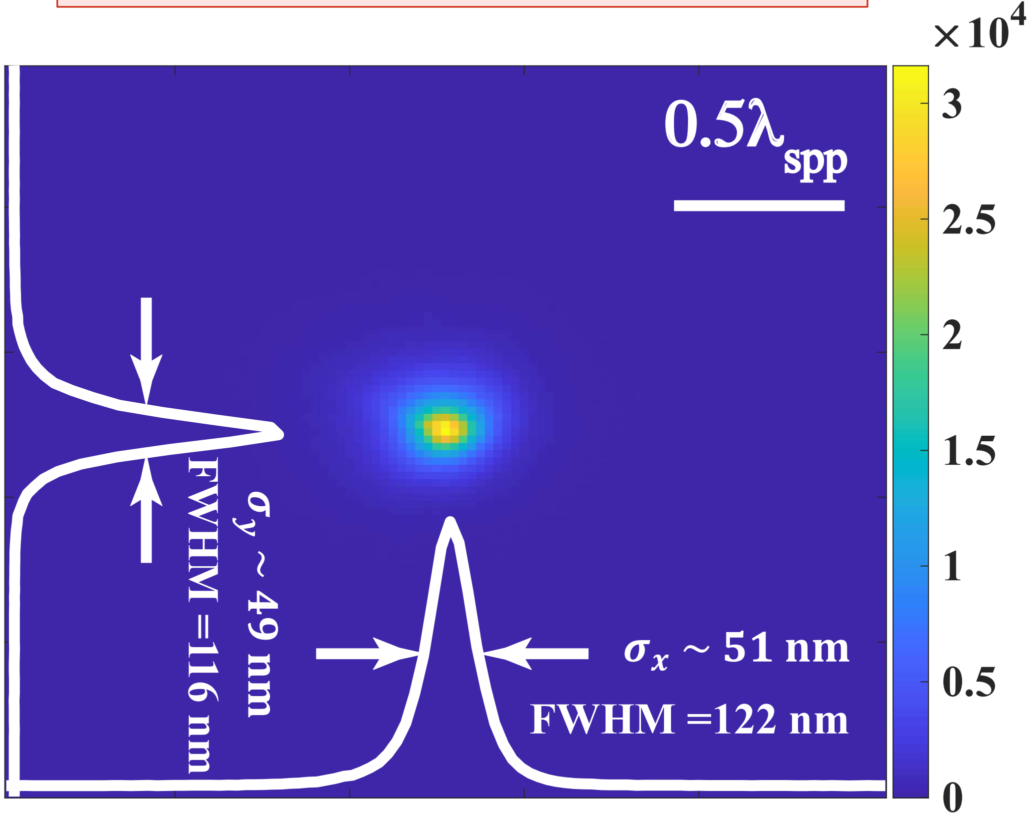
Schematic



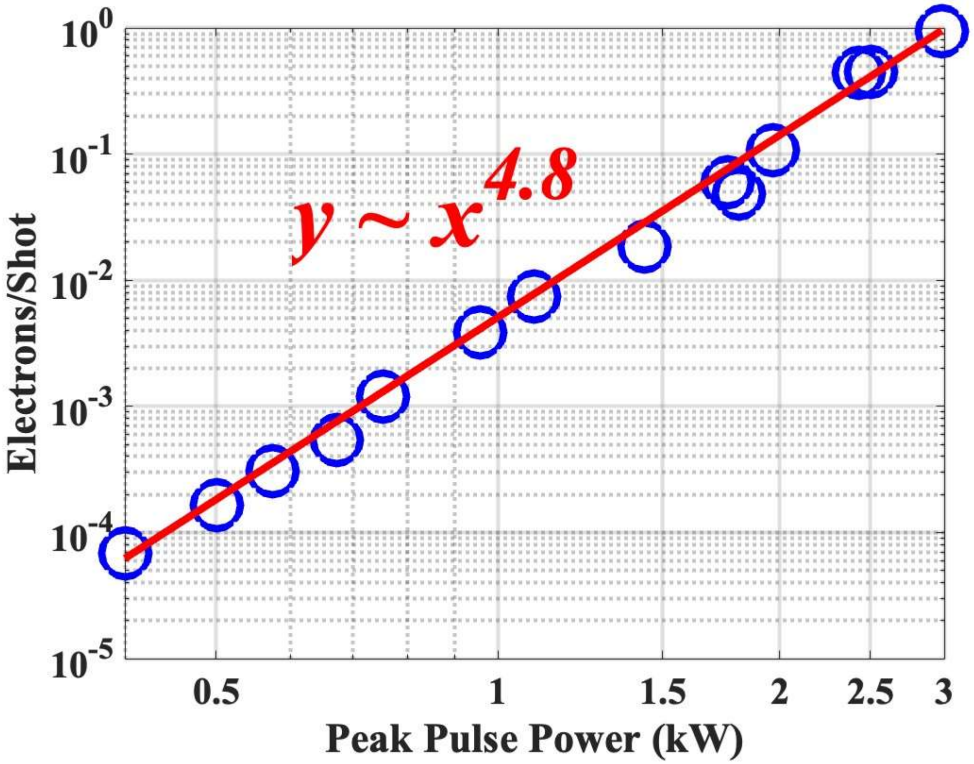


Plasmonic Spiral Photocathode: Experimental

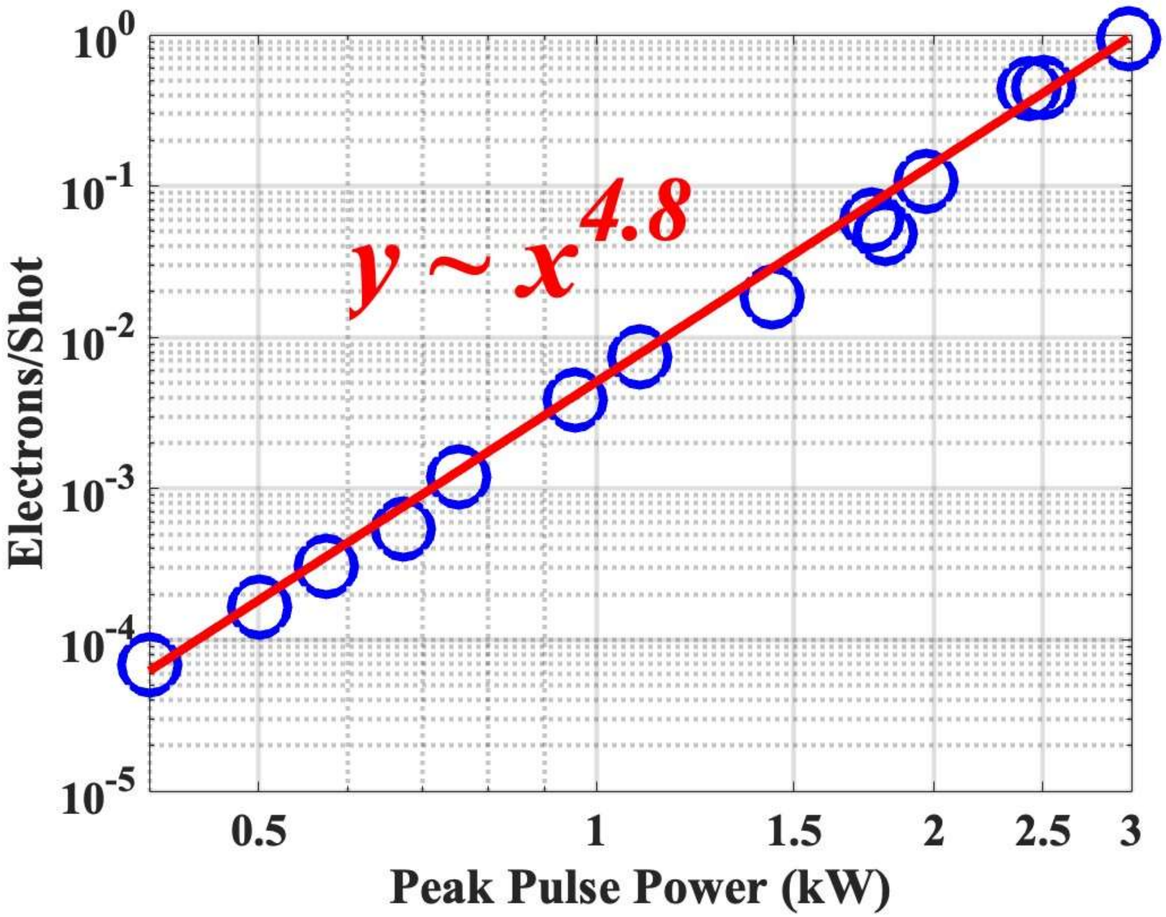
Peak LASER power = 1.8 kW



Order of Emission

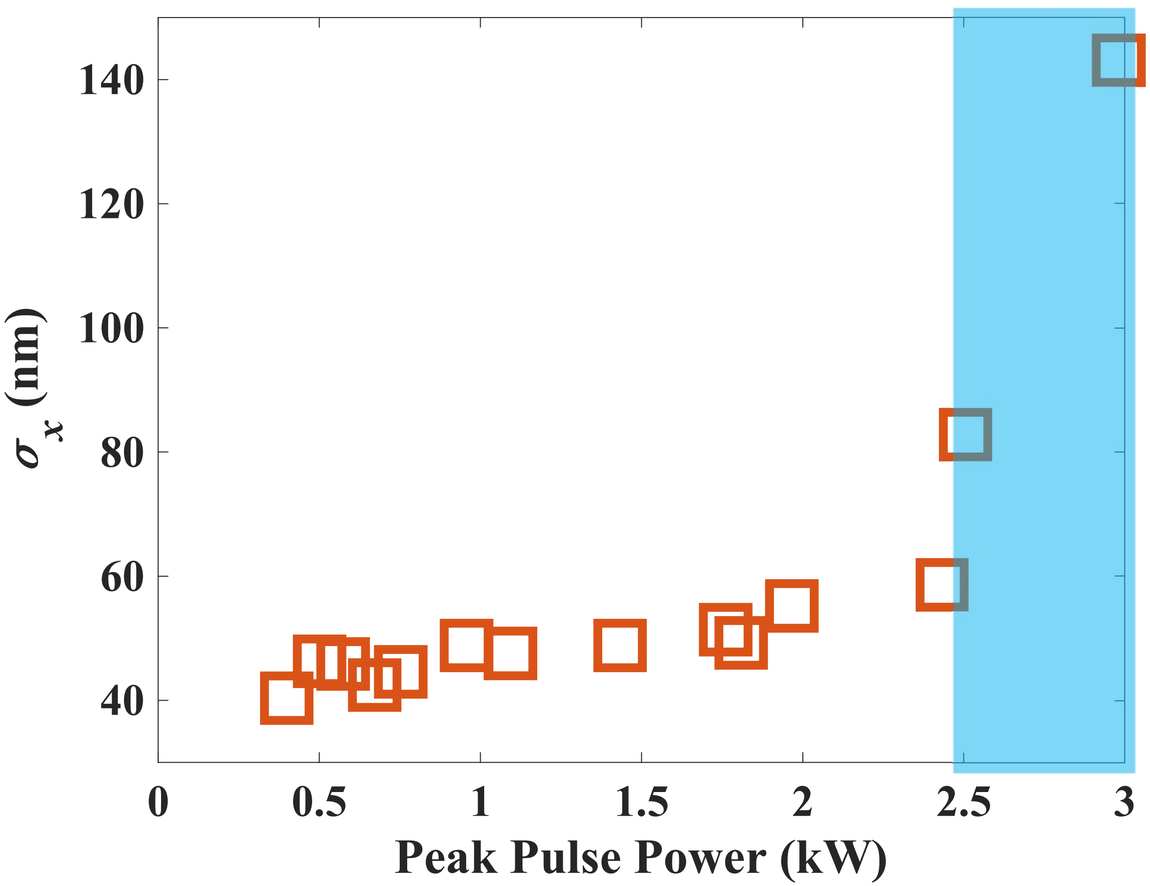


Spiral Photocathode: Order of Emission



~120 nm FWHM electron emission spot size makes sense as Order of Emission ~5th

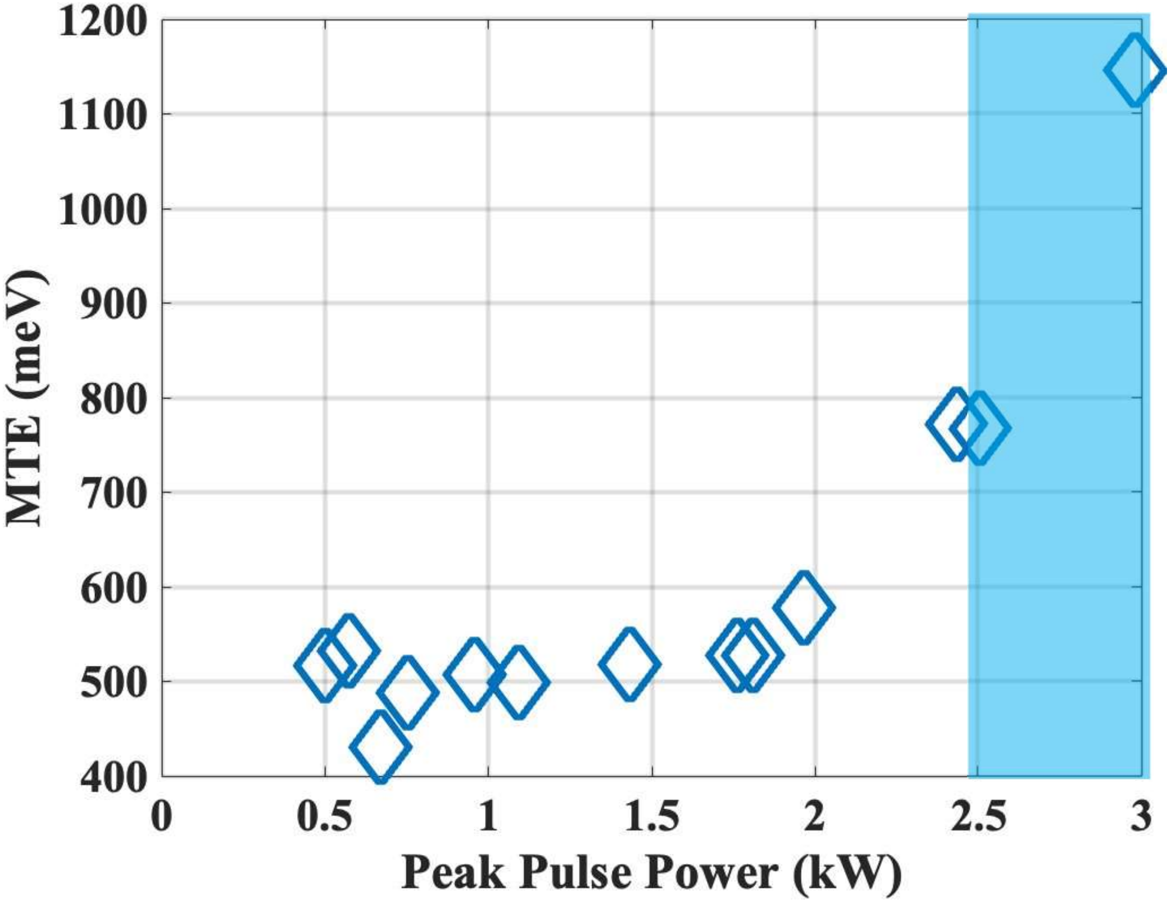
Spiral Photocathode: Spot Size



$\sigma_x \sim 50$ nm electron emission spot size over wide range of LASER power

Spot size increases
- $e^- - e^-$ interaction

Spiral Photocathode: MTE

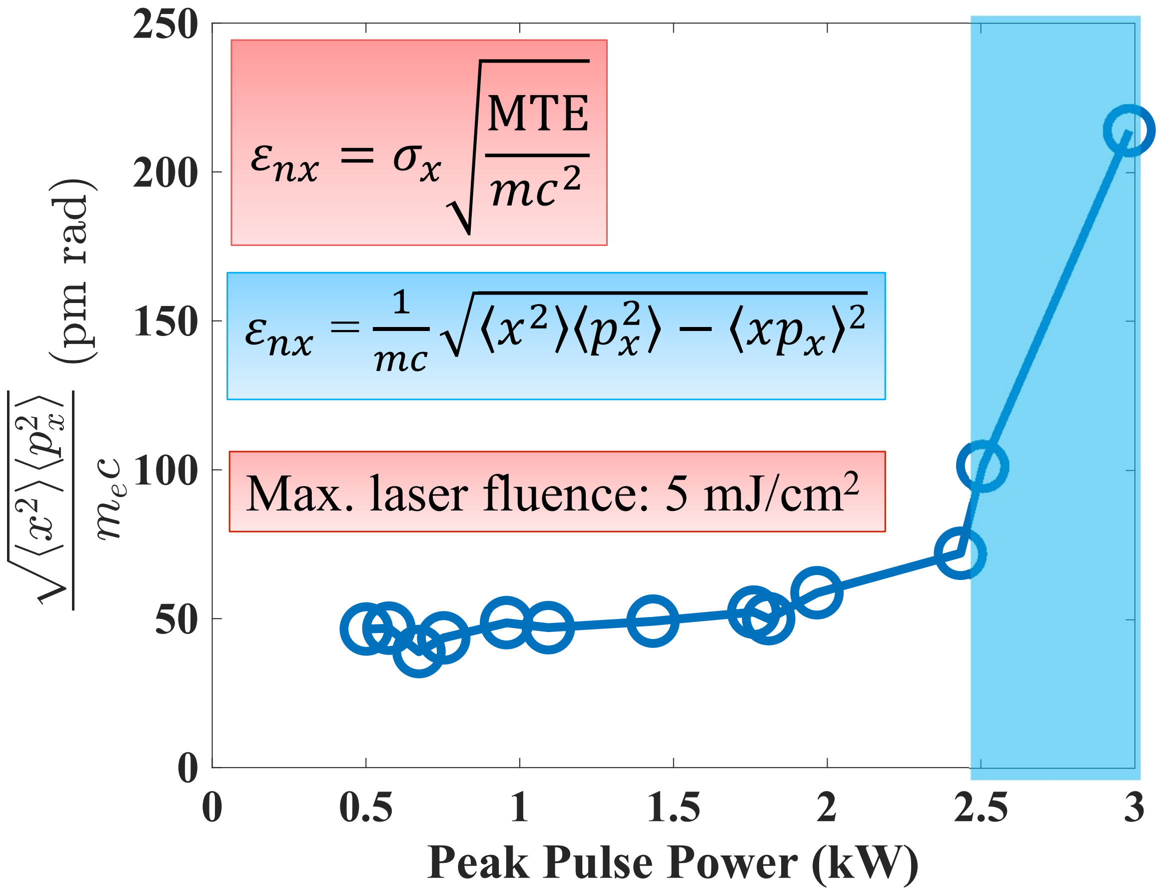


MTE ~ 500 meV over wide range of LASER power

MTE increases

- $e^- - e^-$ interaction

Spiral Photocathode: Emittance



Record $\boldsymbol{\varepsilon_n}$ ~40 pm rad achieved from a geometrically flat photocathode without the use of any pinholes

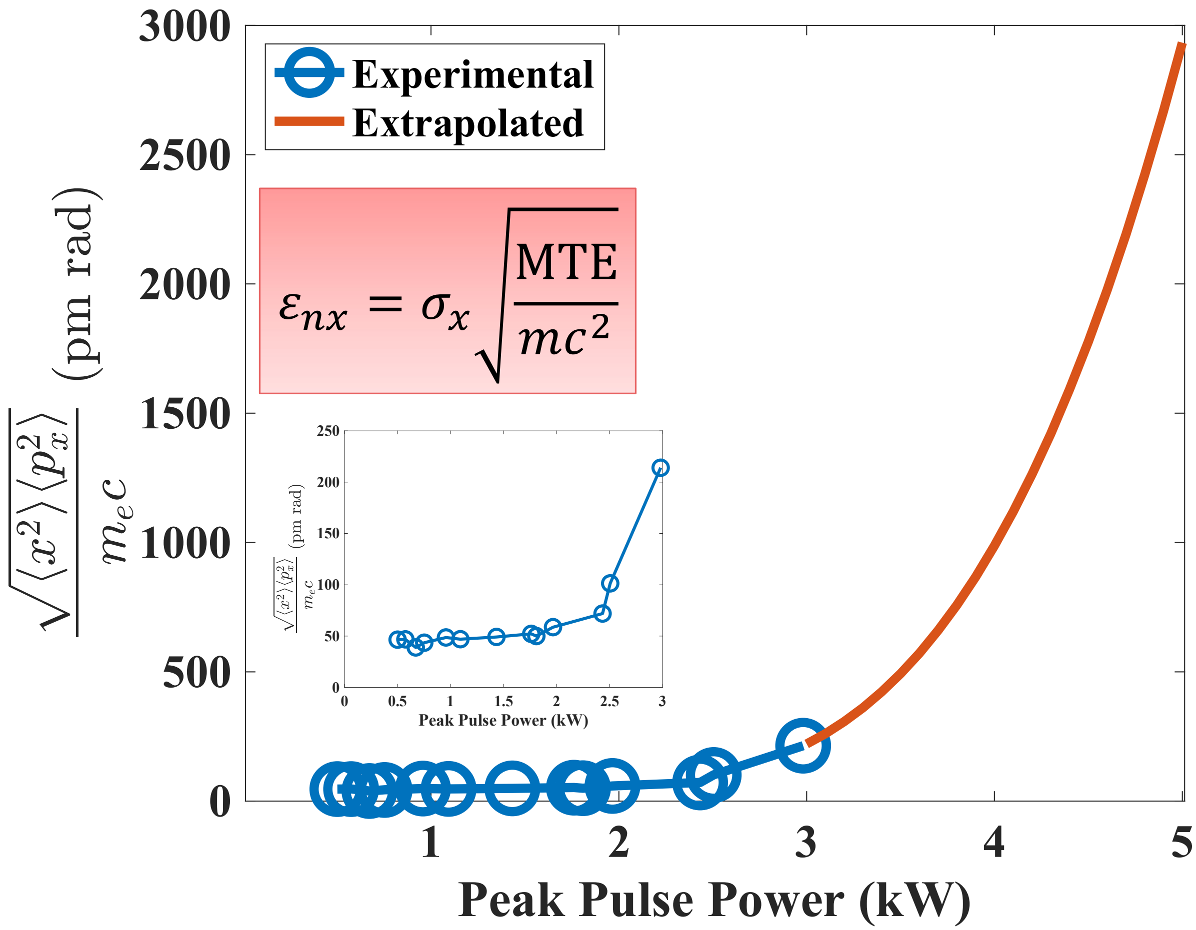
- 2 pm rad from ZrO/W emitter tip in an Electron Microscope [*Ultramicroscopy* 176 (2017): 63-73]
- 120 pm rad from flat cathode in a photoinjector after the pinhole [*HiRES UED Beamline*)]

ε_{nx} increases

- $e^- - e^-$ interaction

$e^- - e^-$ interaction could result in correlated $x - p_x$ so emittance could still be small

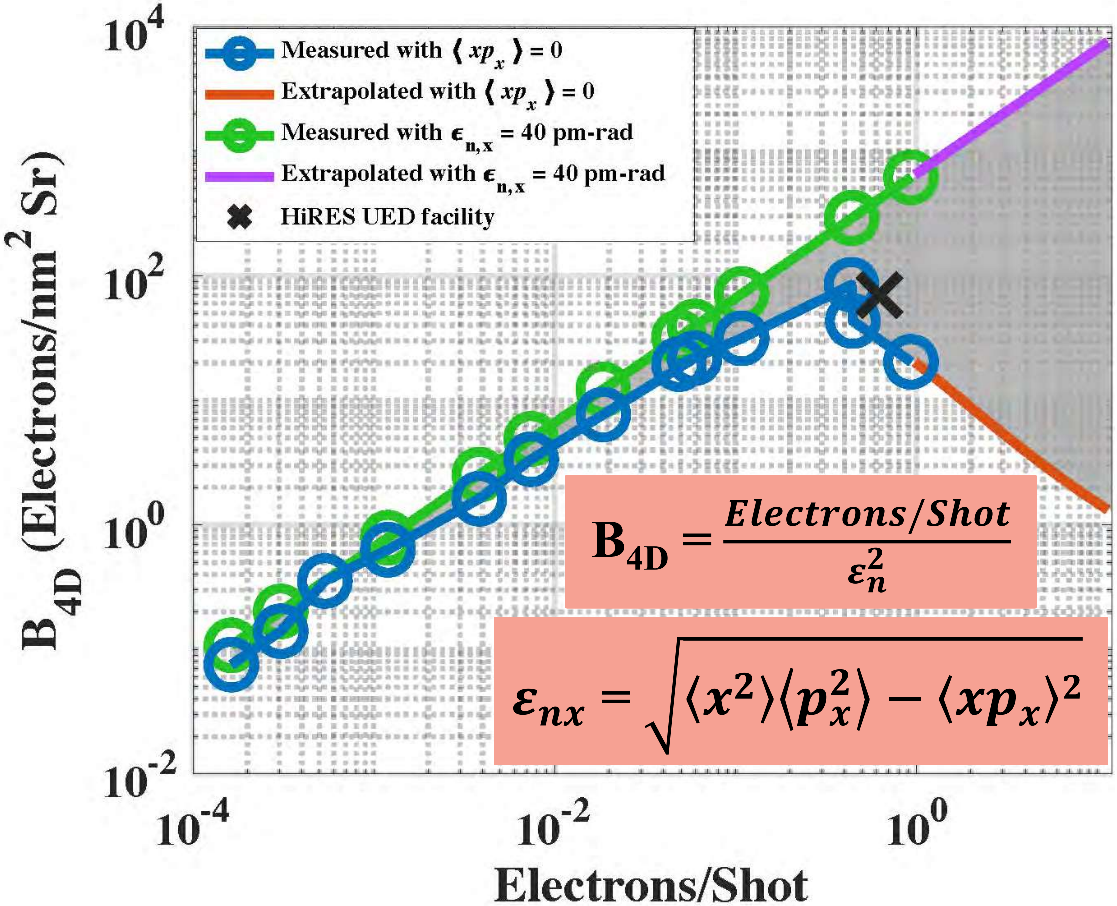
Spiral Photocathode: Emittance Extrapolated



It was not possible to reliably measure the σ_x and MTE beyond 3 kW due to increased Coulomb interactions.

Cubic fit to extrapolate the emittance (~10 electrons/shot)

Spiral Photocathode: 4D-Brightness



$$B_{4D} = \frac{Electrons/Shot}{\varepsilon_n^2}$$

$$\varepsilon_{nx} = \sqrt{\langle x^2\rangle\langle p_x^2\rangle - \langle xp_x\rangle^2}$$

Maximum 4-D Brightness achieved: ~85 electrons/nm^2 ($\langle xp_x\rangle = 0$)

Brightness decreases

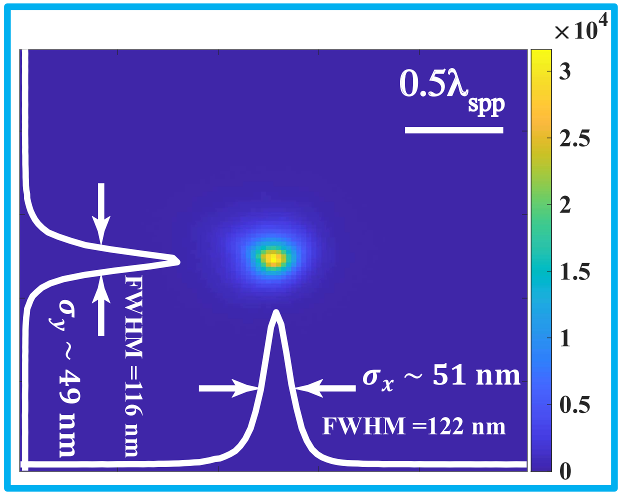
- $e^- - e^-$ interaction

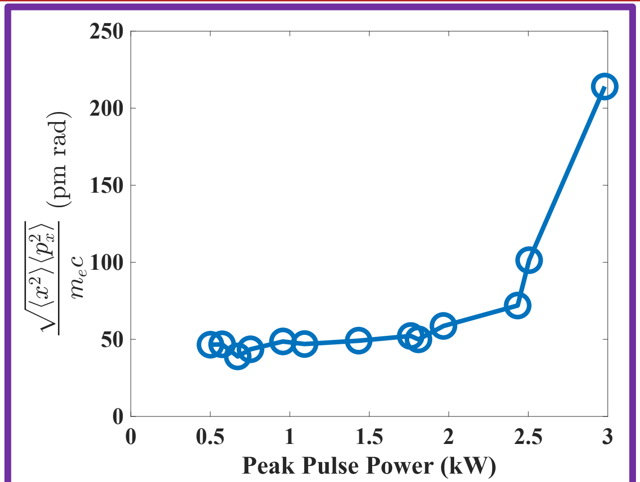
Maximum 4-D Brightness achieved: ~600 electrons/nm^2 ($\varepsilon_{nx} = 40$ pm-rad)

The gray area shows the region in which the brightness from spiral could lie depending on the nature of the correlations developed in x and p_x due to the Coulomb interactions

Spiral Photocathode: Conclusion

Record σ ~ 50 nm achieved from a flat metal photocathode

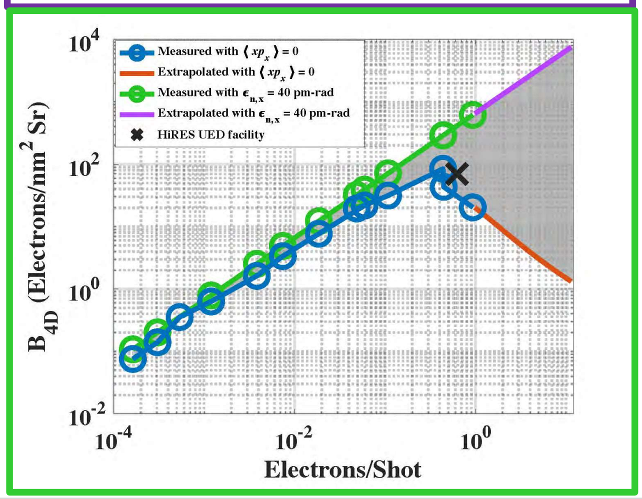




Record ε_n ~40 pm rad achieved from a flat metal photocathode

Max. B_{4D} = 85 electrons/nm^2 ($\langle xp_x\rangle = 0$)

- Electron source for UED/M
- Electron source for Dielectric Laser Accelerators
- Development of Compact UED
- Shaped Electron Beams for next generation accelerators



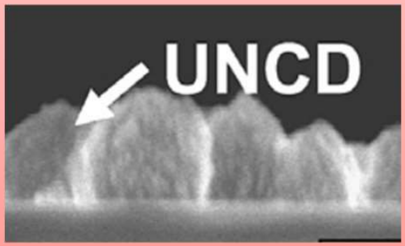
B_{4D} = 85 electrons/nm^2; ε_n <70 pm rad

Max. B_{4D} = 600 electrons/nm^2 (ε_{nx} = 40 pm-rad)

Conclusion

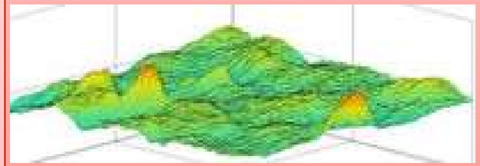
(N)UNCD Photocathode

- Vacuum Robustness
- Good for application which have poor vacuum conditions



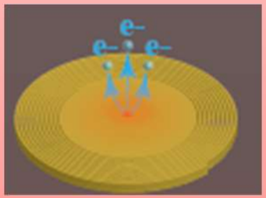
Cs_3Sb Photocathode

- Stringent vacuum requirements
- Can be used for applications that required high current



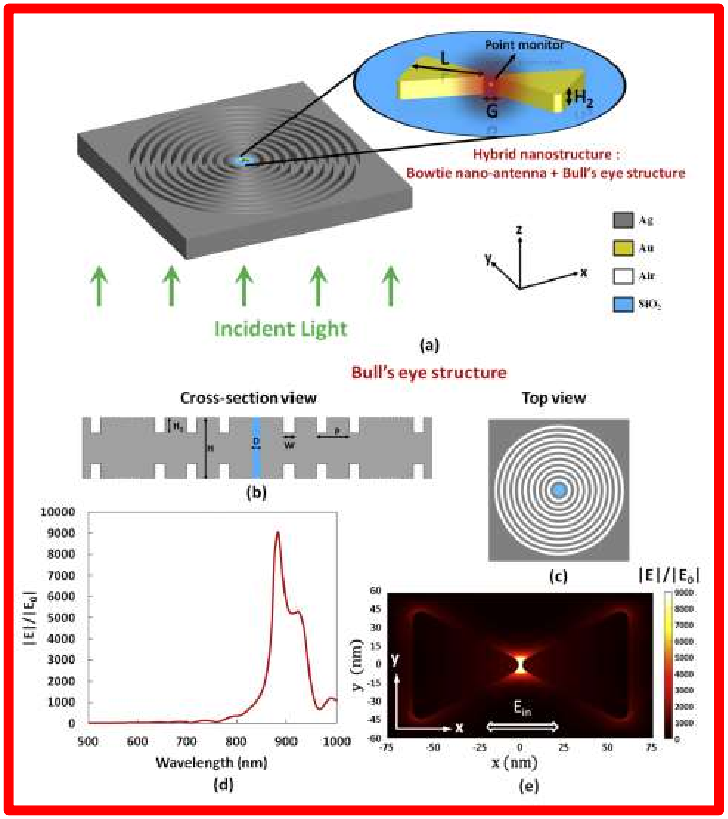
Plasmonic Spiral Photocathode

- Vacuum Robustness
- Limited Charge
- Stroboscopic UED/UEM
- Shaped Electron Beams

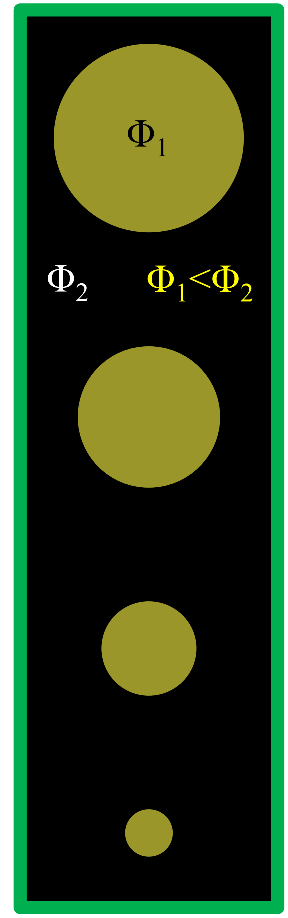


Future Work

- Photoemission from NEA - (N)UNCD
- Photoemission studies of epitaxial Cs_3Sb/CsSb and other alkali antimonide photocathodes such as K_2CsSb and Na_2KSb
- Study the performance of (N)UNCD, Cs_3Sb and other alkali antimonide photocathodes at cryogenic temperatures
- Integrate Spirals (small spot size) with alkali antimonides (small MTE)
- Photoemission from plasmonic bowtie structure or hybrid plasmonic structure (ε_{nx} ~ 10 pm-rad, B_{4D} ~ 10,000 electrons/(nm^2Sr)
- Work function engineered electron sources
- Test in Accelerator Environment



Osa Continuum 4.1 (2021): 193-211



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  - Dr. Dongsung Kim
  - Prof. Rehan Kapadia
  - Dr. Raghib Ahsan
  - Dr. Hyun Uk Chae
  - Prof. Jared Maxson
  - Dr. Chris Pierce
  - Dr. Danielle Filippetto

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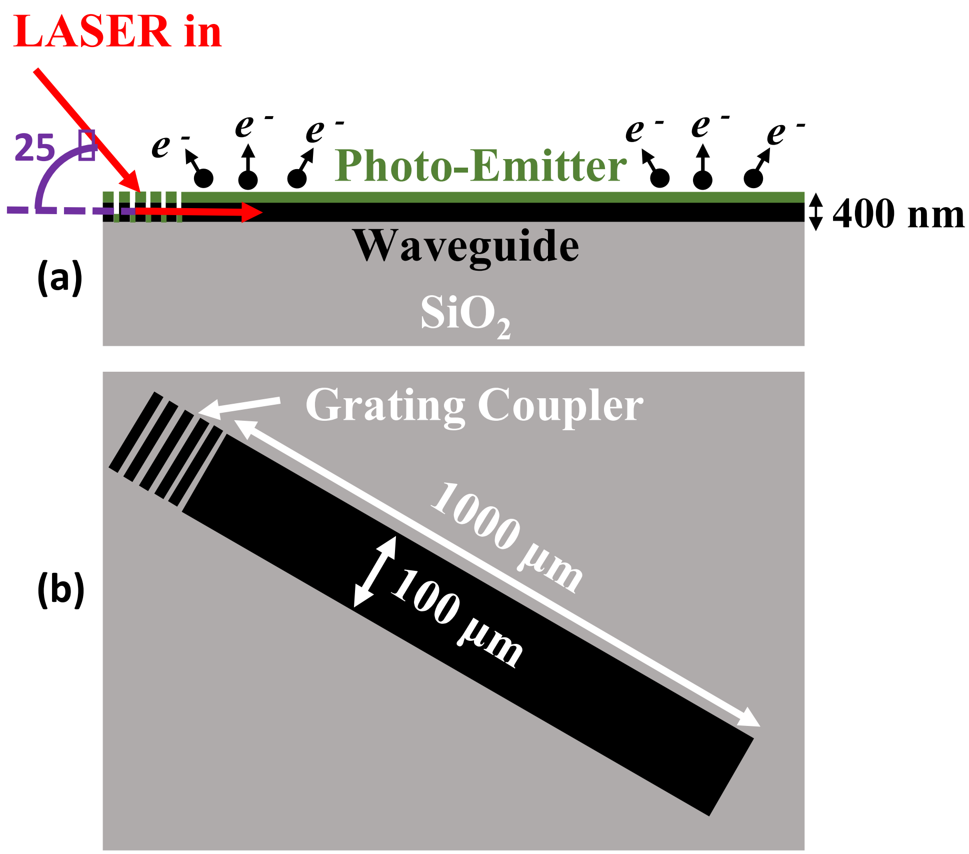
Thank You!

Questions? Comments?

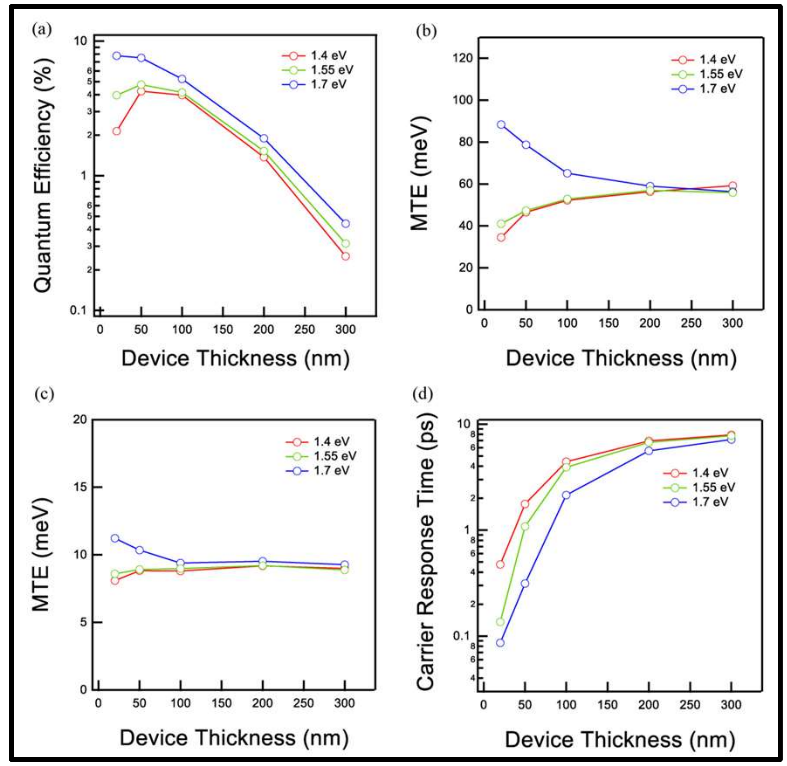
Back Up Slides

Photonics Integrated Cathodes

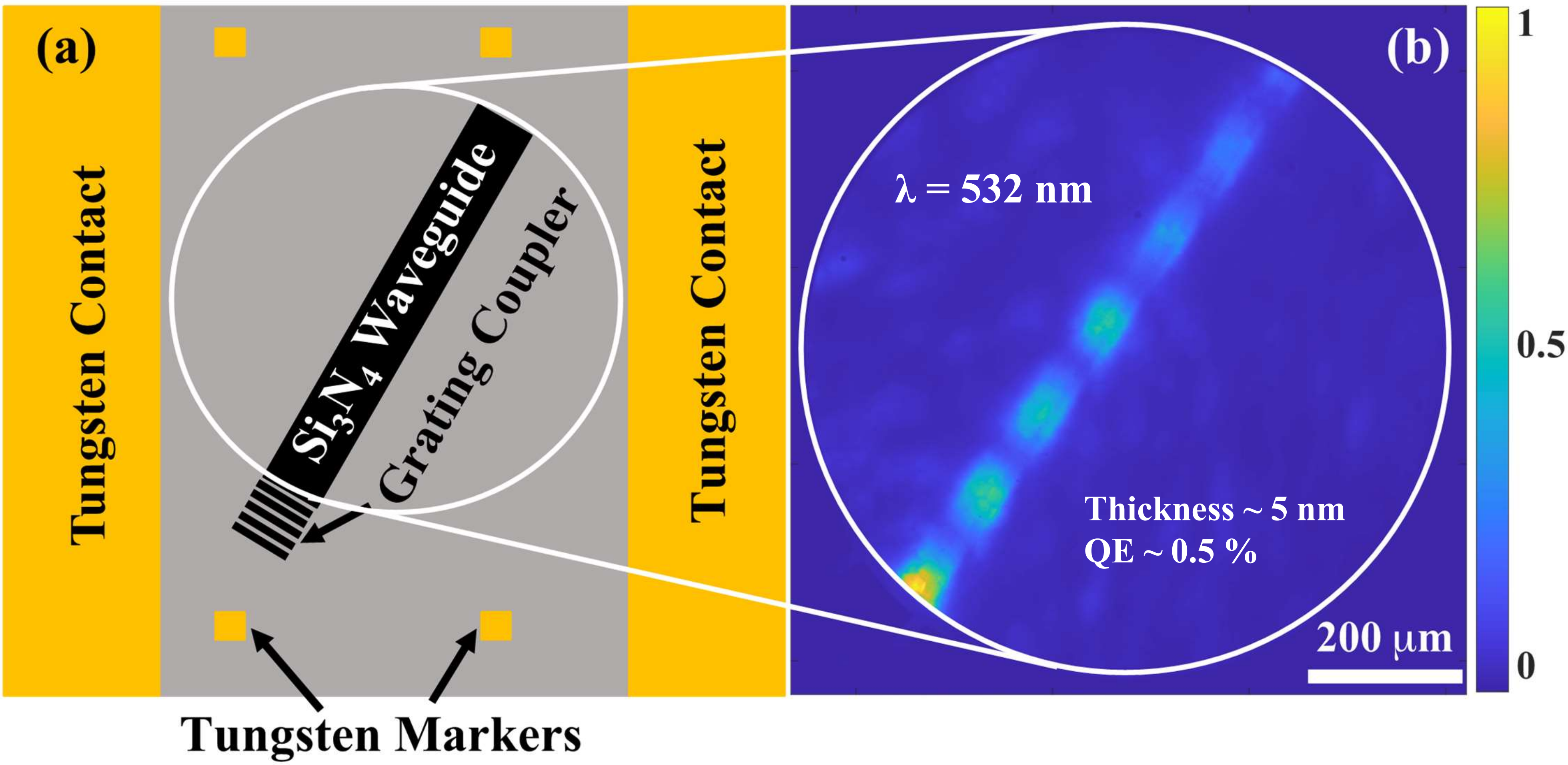
- ❑ **High quantum efficiency (QE)**
- ❑ **Low MTE**
- ❑ **Quick response time**



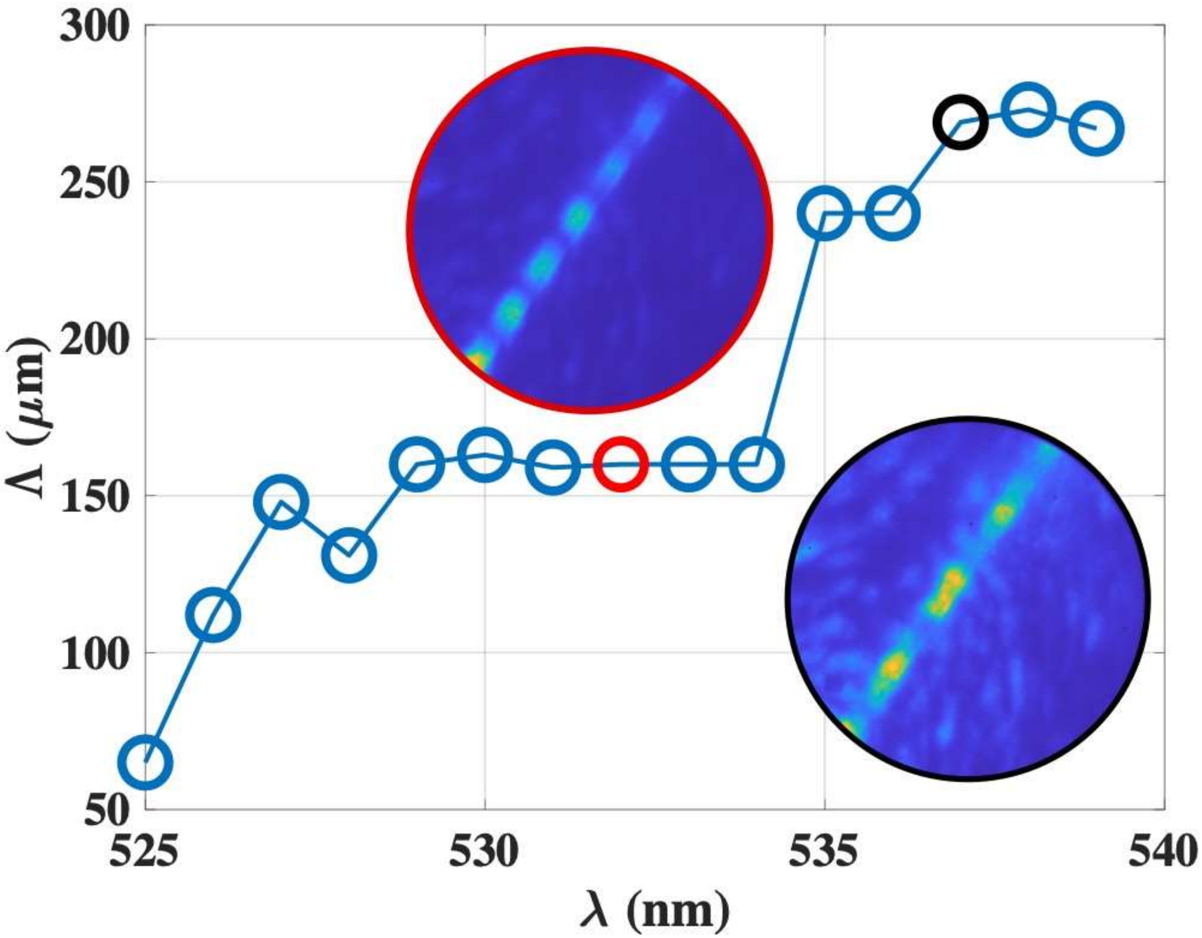
Blankemeier, L., et al., 2019.



Photonics Integrated Cathodes: Cs_3Sb

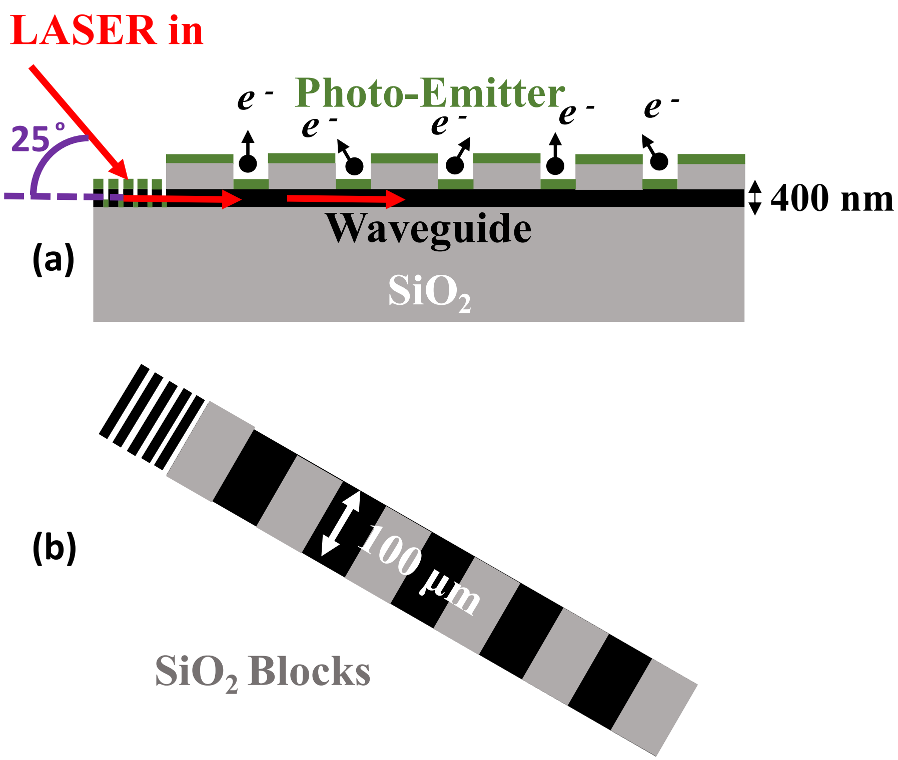


Photonics Integrated Cathodes: Cs_3Sb

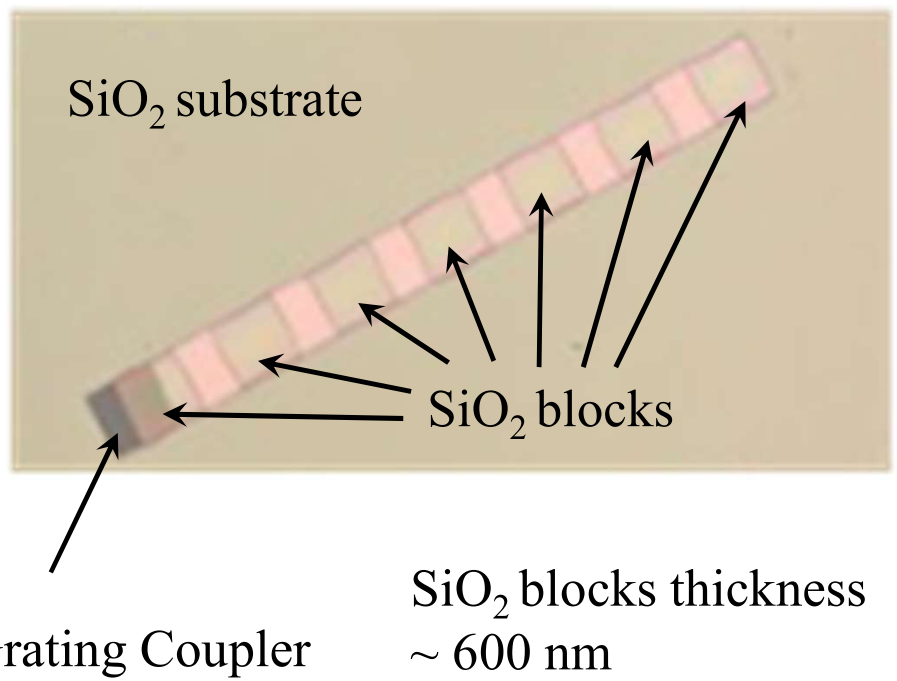


- Si_3N_4 waveguide with the cross section of the order of wavelength and high aspect ratios support fundamental as well as higher order modes at a single wavelength.
- Transverse patterns are formed due to interference between these co-propagating modes.

Photonics Integrated Cathodes: Oxide Pattern



Optical Microscope Image: SiO_2 blocks on top of Si_3N_4 waveguide

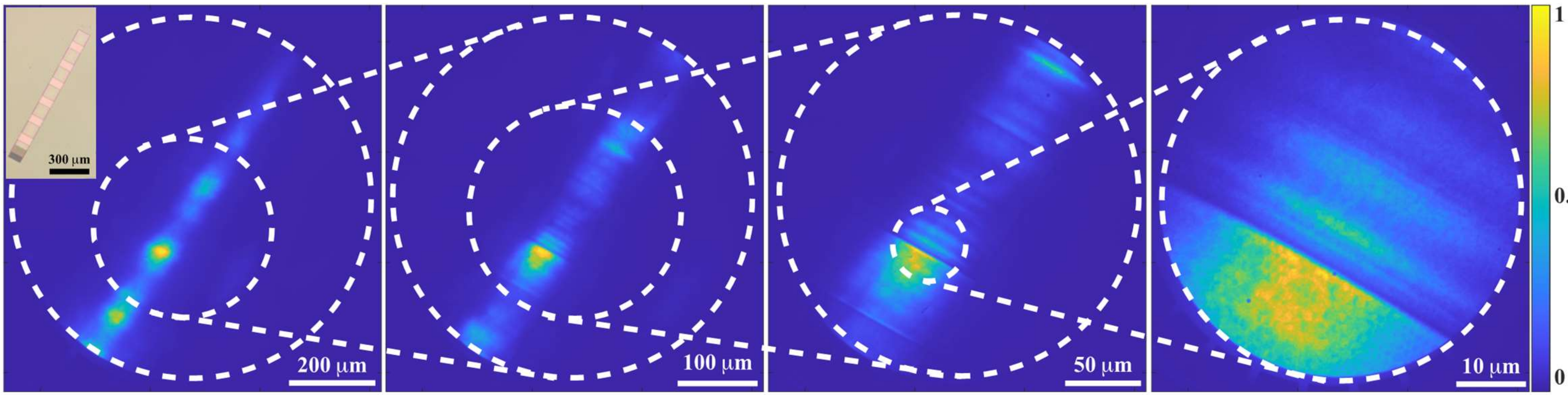


SiO_2 blocks thickness ~ 600 nm

Acknowledgement: Prof. Rehan Kapadia, Dr. Ragib Ahsan and Hyun Uk Chae

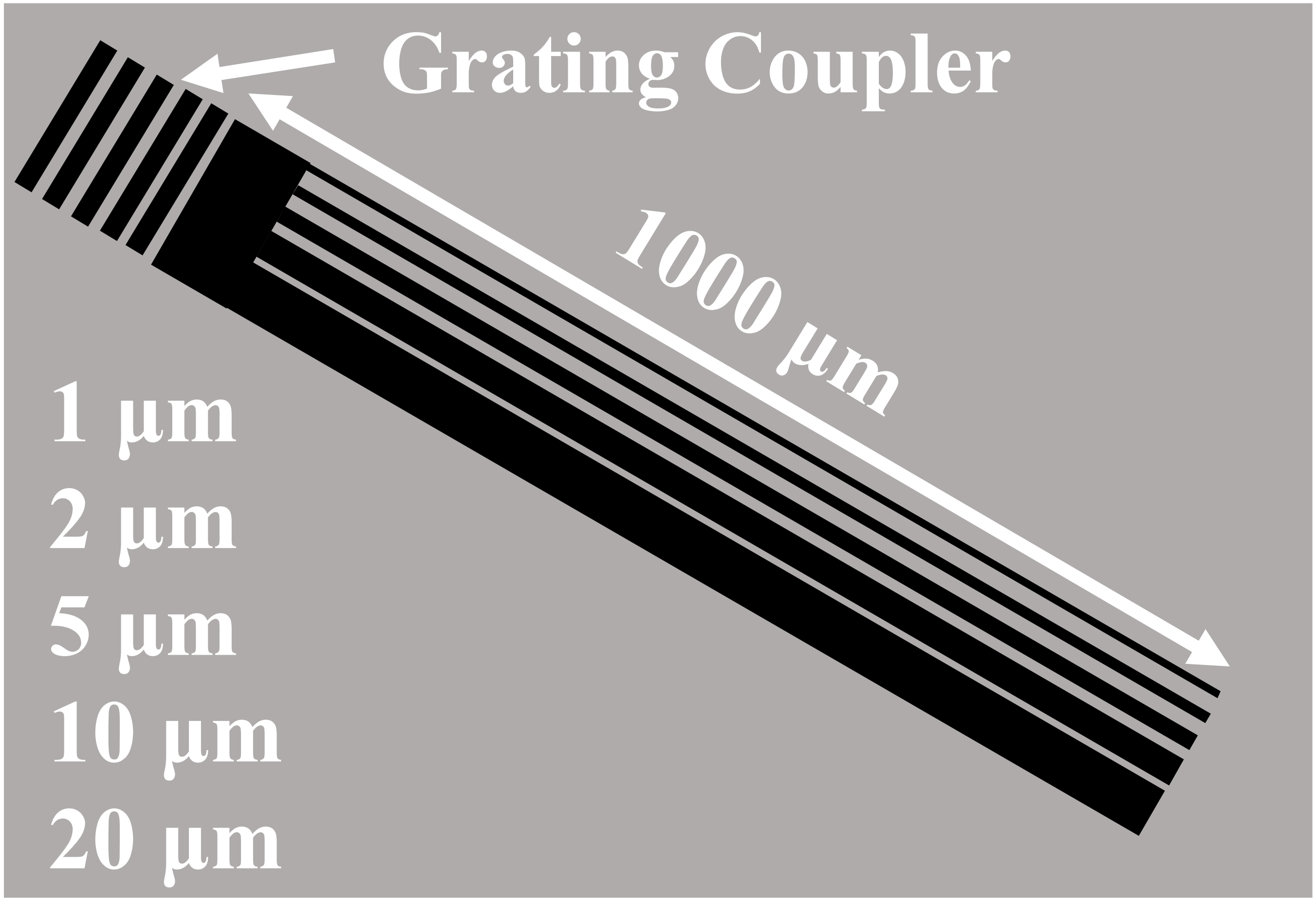
Photonics Integrated Cathodes: Oxide Pattern

$\mathcal{E} \sim 50\ kV/m$ | $\mathcal{E} \sim 500\ kV/m$ | $\mathcal{E} \sim 2000\ kV/m$ | $\mathcal{E} \sim 2000\ kV/m$



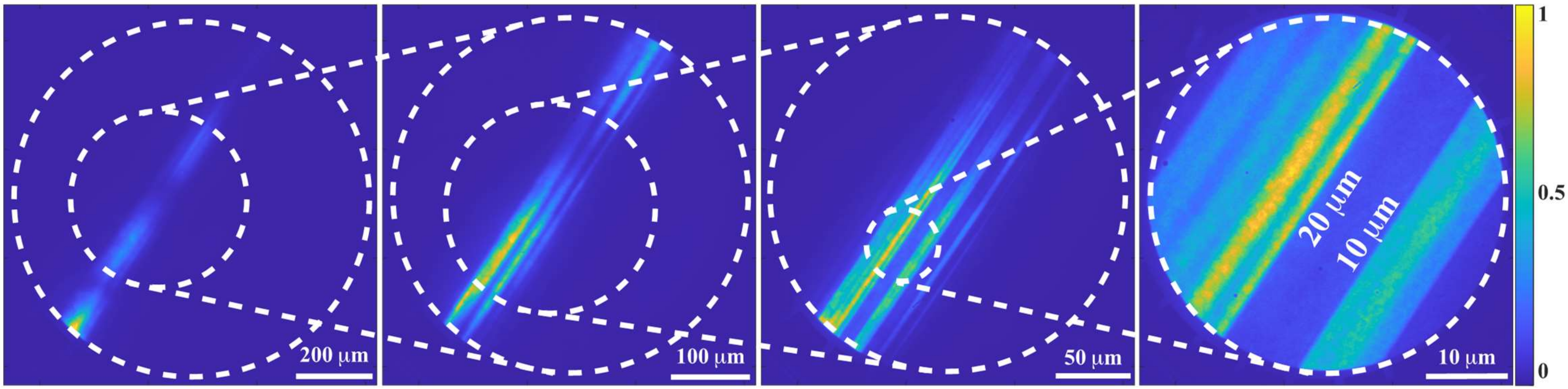
PEEM Image: SiO_2 blocks on top of Si_3N_4 waveguide; λ = 522 nm; Film thickness ~ 5 nm; QE ~ 0.5 %

Photonics Integrated Cathodes: Multiple Waveguides



Photonics Integrated Cathodes: Cs_3Sb

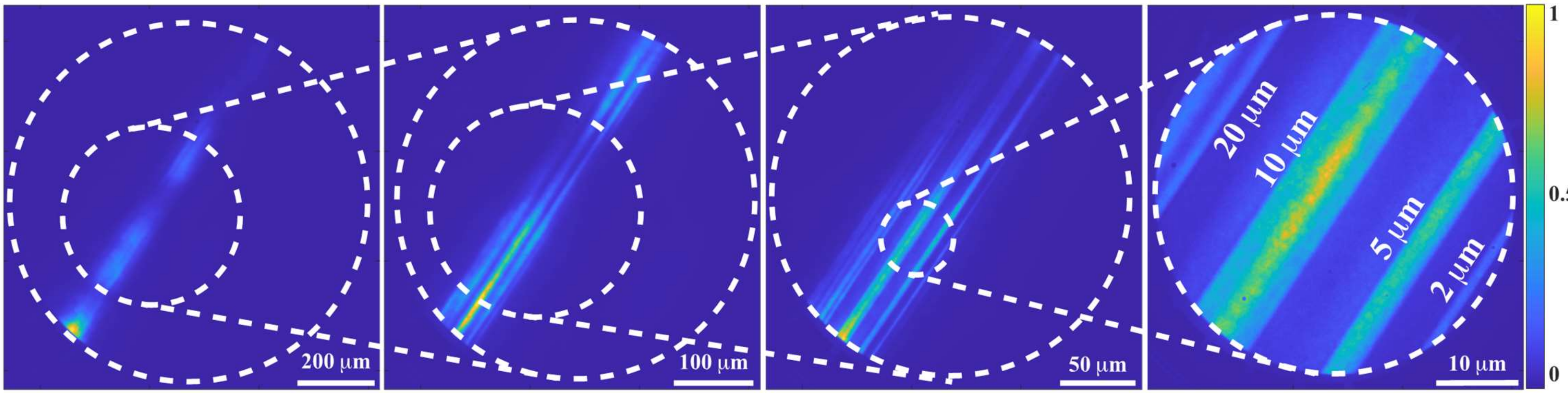
$\mathcal{E} \sim 50\ kV/m$ | $\mathcal{E} \sim 500\ kV/m$ | $\mathcal{E} \sim 2000\ kV/m$ | $\mathcal{E} \sim 2000\ kV/m$



PEEM Image: Multiple Si_3N_4 waveguide; $\lambda = 522$ nm; Film thickness ~ 5 nm; QE ~ 0.5 %

Photonics Integrated Cathodes: Cs_3Sb

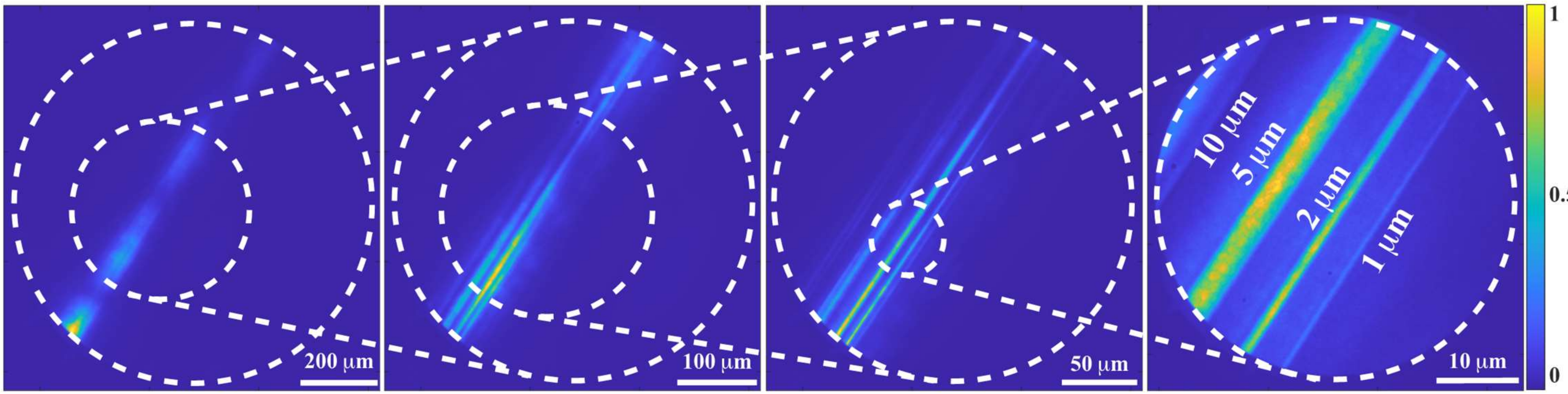
$\mathcal{E} \sim 50\ kV/m$	$\mathcal{E} \sim 500\ kV/m$	$\mathcal{E} \sim 2000\ kV/m$	$\mathcal{E} \sim 2000\ kV/m$



PEEM Image: Multiple Si_3N_4 waveguide; λ = 522 nm; Film thickness ~ 5 nm; QE ~ 0.5 %

Photonics Integrated Cathodes: Cs_3Sb

$\mathcal{E} \sim 50\ kV/m$	$\mathcal{E} \sim 500\ kV/m$	$\mathcal{E} \sim 2000\ kV/m$	$\mathcal{E} \sim 2000\ kV/m$



PEEM Image: Multiple Si_3N_4 waveguide; λ = 522 nm; Film thickness ~ 5 nm; QE ~ 0.5 %

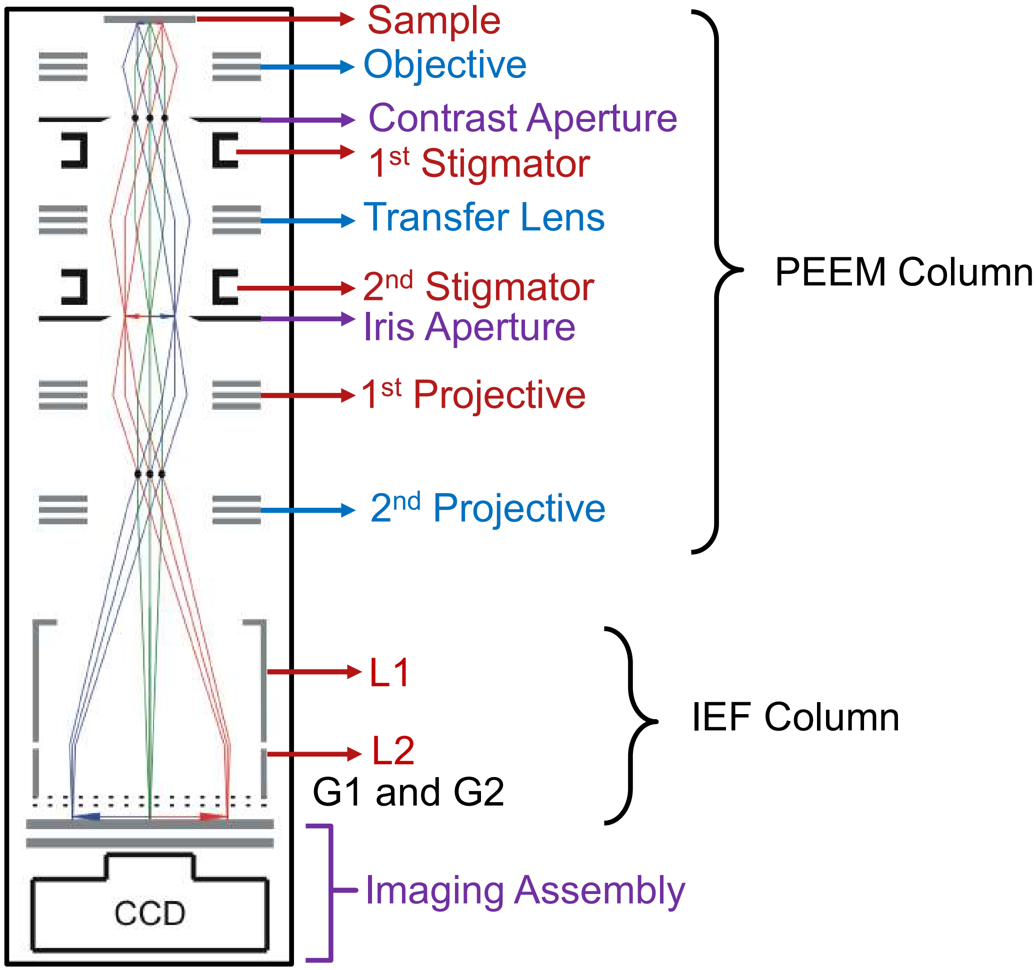
MTE

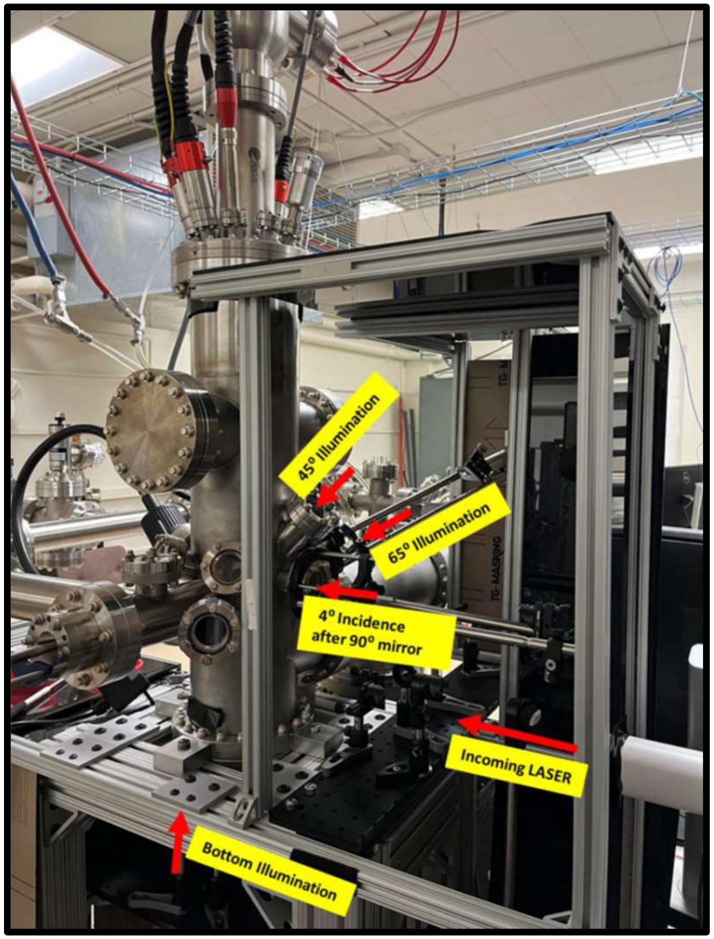
- $TE = \frac{1}{2}\left(mv_x^2 + mv_y^2\right) = \frac{\hbar^2}{2m}(k_x^2 + k_y^2)$

- $MTE_x = \frac{\hbar^2}{2m}\frac{\int k_x^2 e^{-\frac{1}{2}\left(\frac{k_x}{\sigma_x}\right)^2} dk_x}{\int e^{-\frac{1}{2}\left(\frac{k_x}{\sigma_x}\right)^2} dk_x}$, $\int_{-\infty}^{\infty} x^2 e^{-ax^2} = \frac{1}{2}\sqrt{\frac{\pi}{a^3}}$, $\int_{-\infty}^{\infty} e^{-ax^2} = \sqrt{\frac{\pi}{a}}$

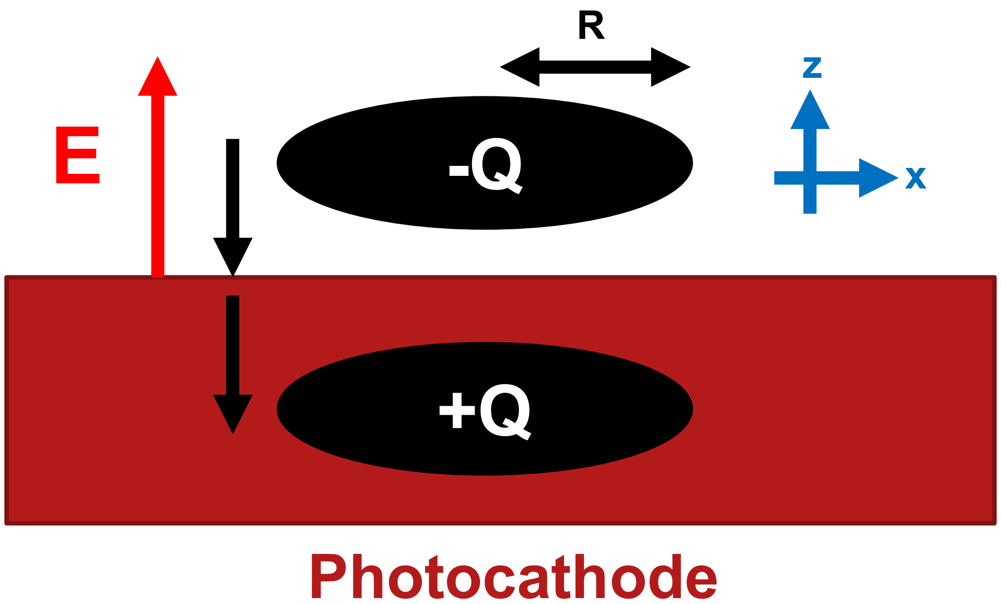
- $MTE_x = \frac{\hbar^2\sigma_x^2}{2m}$, $MTE_y = \frac{\hbar^2\sigma_y^2}{2m}$
- $MTE = MTE_x + MTE_y = \frac{\hbar^2(\sigma_x^2+\sigma_y^2)}{2m} = \frac{\hbar^2\sigma^2}{2m}$

Brief Description of PEEM





Maximum Extracted Charge



Electric Field due to Uniformly Charged Disk:

$$E_{disc} = \frac{\sigma}{2\varepsilon_0}\left(1 - \frac{z}{\sqrt{z^2 + R^2}}\right)$$

For *R* >> *z*,

$$E_{disc} = \frac{\sigma}{2\varepsilon_0}$$

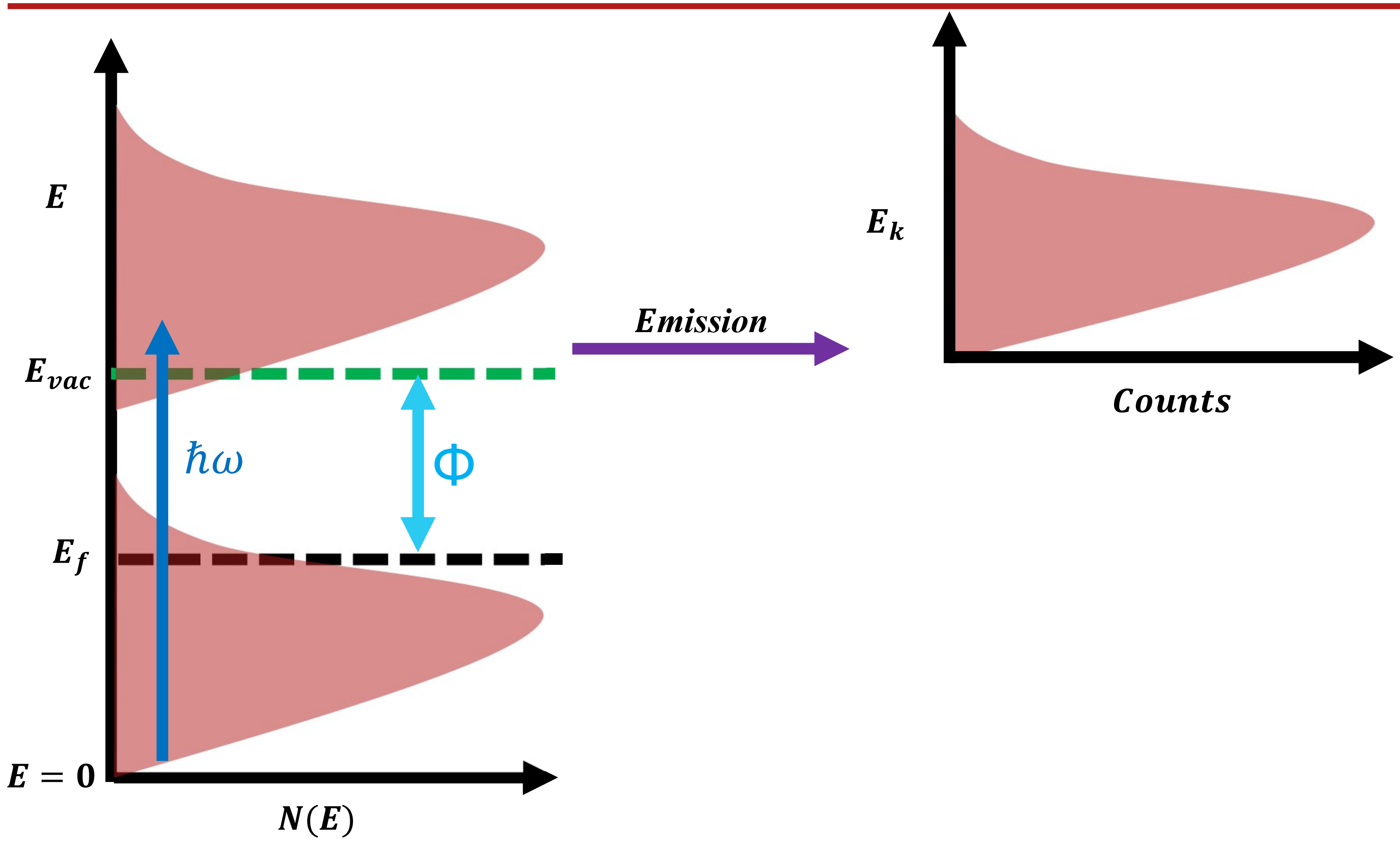
Now the emission ceases once the applied electric field is equal to the electric field due to the emitted electron bunch and hence, we have,

$$E = \frac{\sigma}{\varepsilon_0}$$

$$E = \frac{Q_{max}}{A\varepsilon_0}$$

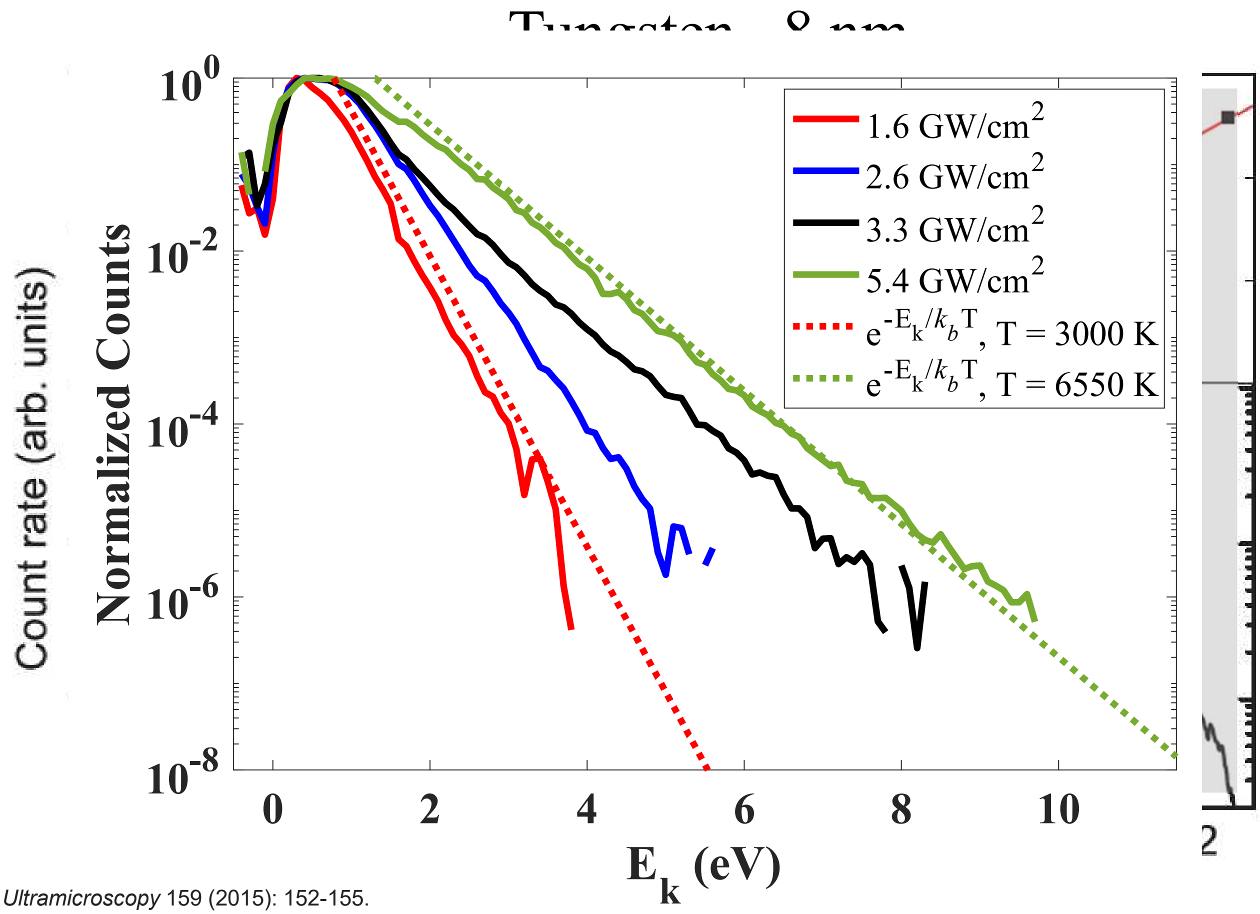
$$Q_{max} = \varepsilon_0 AE$$

Energy Spectra



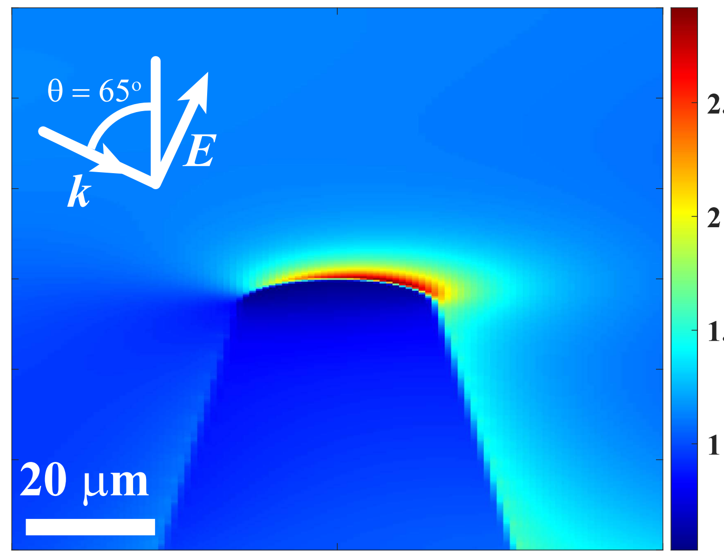
GB

(N)UNCD Pyramid Tip Cathode: Energy Spectra



$$\gamma = \sqrt{\frac{\varphi}{2U_p}}$$

$$U_p = \frac{e^2\alpha^2E^2}{4m\omega^2}$$

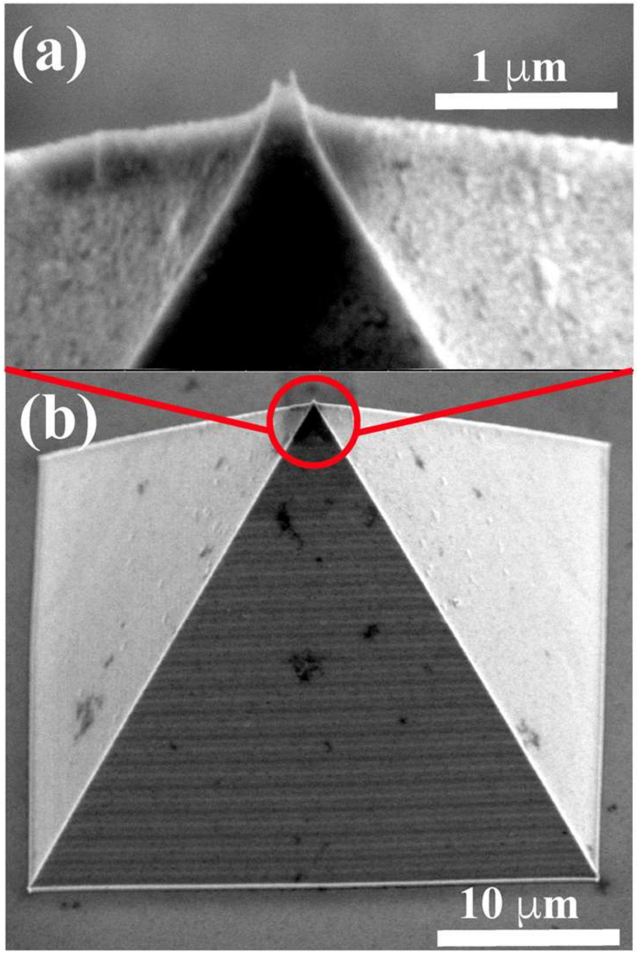


$U_p \sim 0.3\ \mu eV.$

$\gamma \sim 3900$

Ultramicroscopy 159 (2015): 152-155.
New Journal of Physics 18.10 (2016): 103010.
ACS nano 16.9 (2022): 14479-14489.

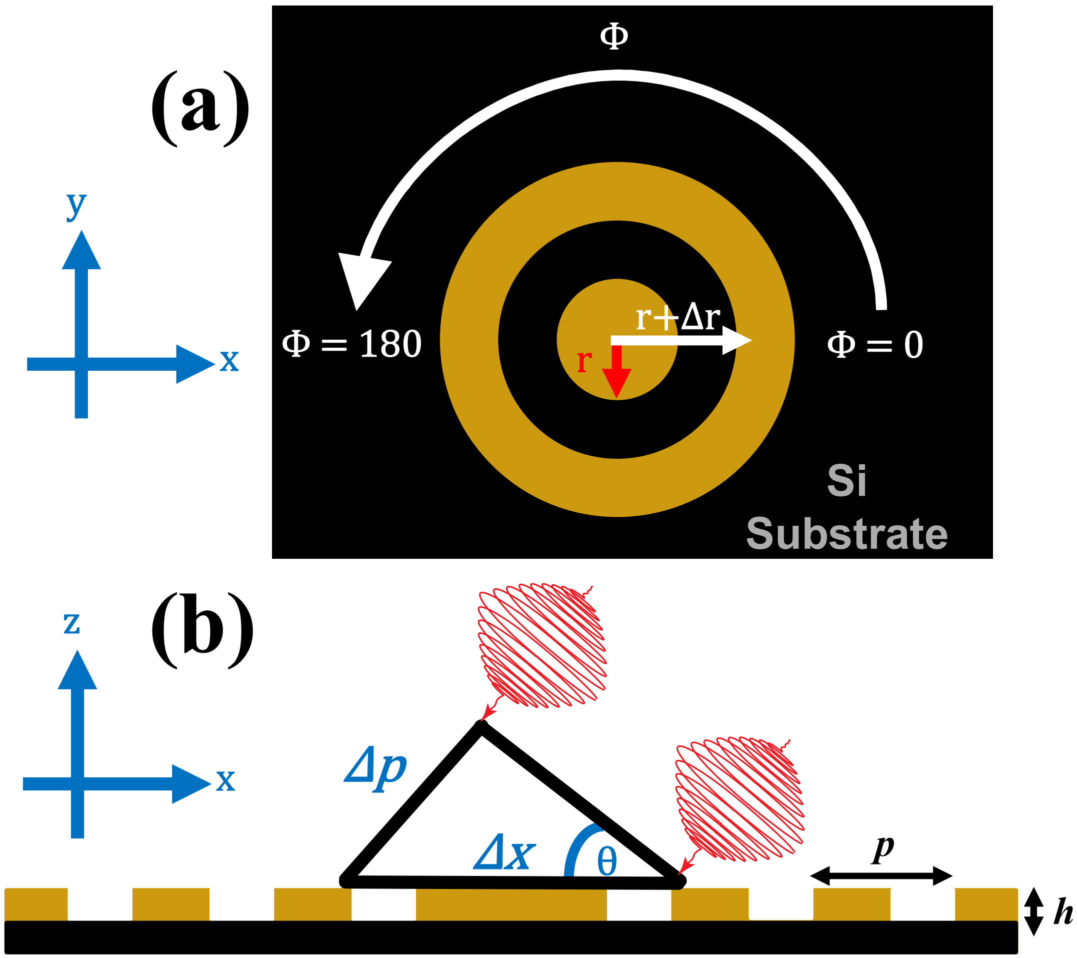
(N)UNCD Pyramid Tip Cathode: SEM After



(a) Structural change in the tip at the apex of (N)UNCD PTC after irradiation with femtosecond laser with the pulse length of 150 fs and central wavelength of 800 nm

(b) (N)UNCD PTC showing laser-induced periodic surface structures (LIPSS) on the pyramid face exposed to the incident laser. The LIPSS were oriented perpendicular to the direction of the electric field of the incident laser with a spatial period of the order of 800 nm.

Spiral Compensation



$$\frac{\Delta p}{c} = \frac{\Delta r}{v_{sp}}$$

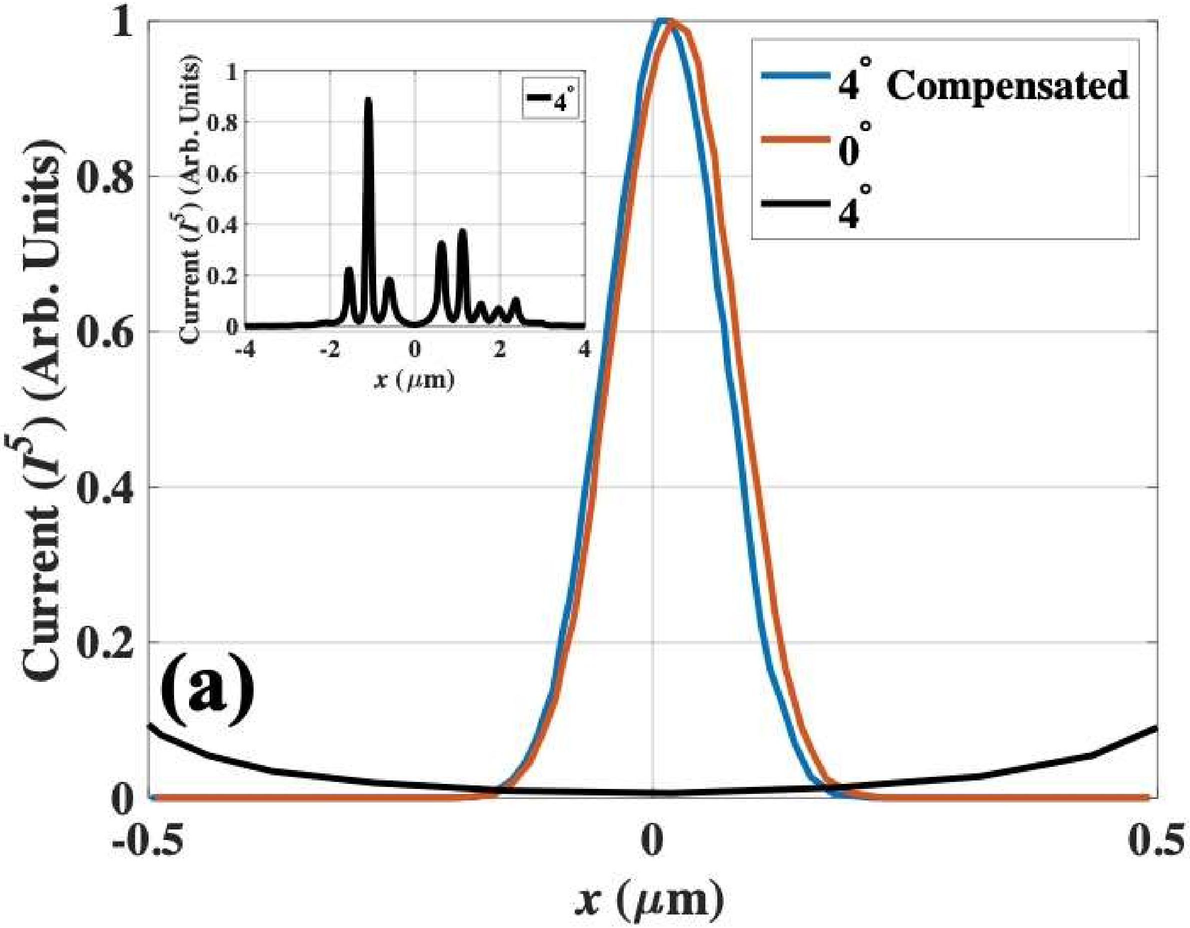
$$\Delta r = \frac{(\Delta p)(v_{sp})}{c}$$

$$\Delta r = \frac{(\Delta p)(\lambda_{sp})}{\lambda} = \frac{(\Delta x sin(\theta))(\lambda_{sp})}{\lambda}$$

$$x' = r\cos(\phi) + r\cos(\phi)sin(\theta)\left(\frac{\lambda_{sp}}{\lambda}\right)\cos(\phi)$$

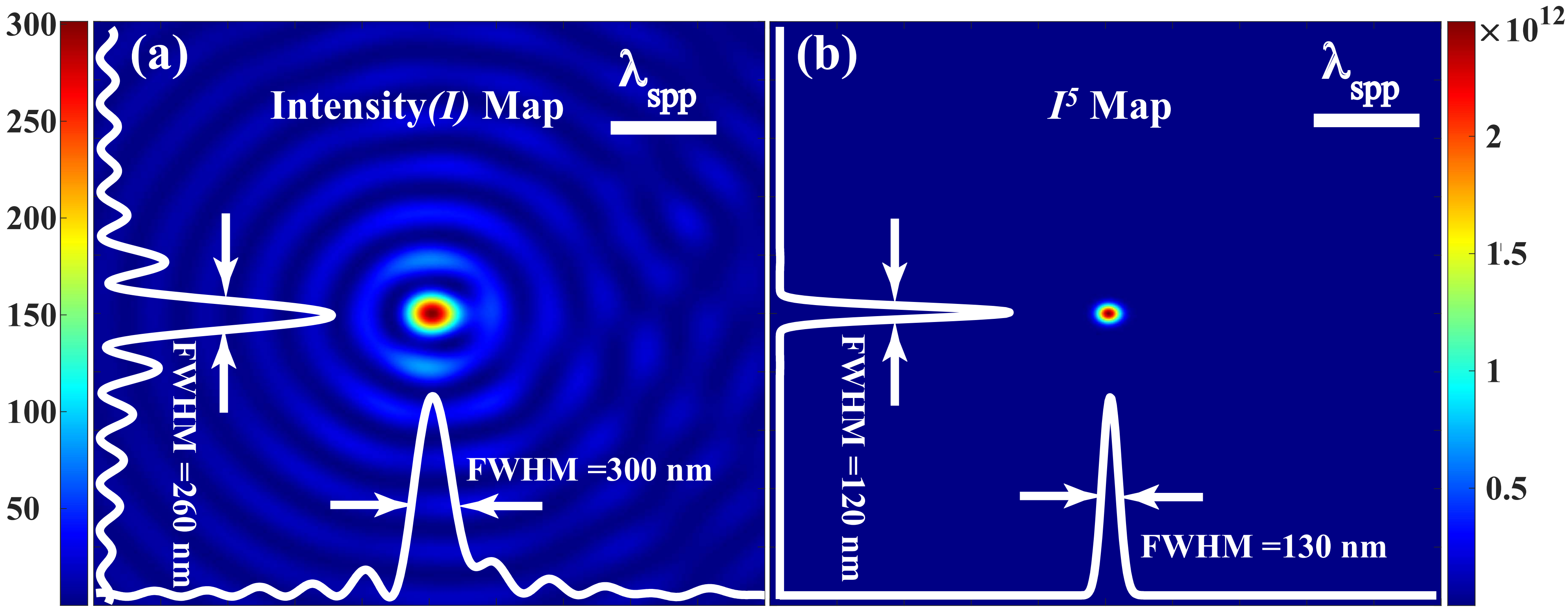
$$y' = r\sin(\phi) + r\cos(\phi)sin(\theta)\left(\frac{\lambda_{sp}}{\lambda}\right)sin(\phi)$$

Plasmonic Spiral: Tilt Compensation



FWHM ~ 120 nm
5th order electron emission

Plasmonic Spiral Photocathode: FDTD Simulation

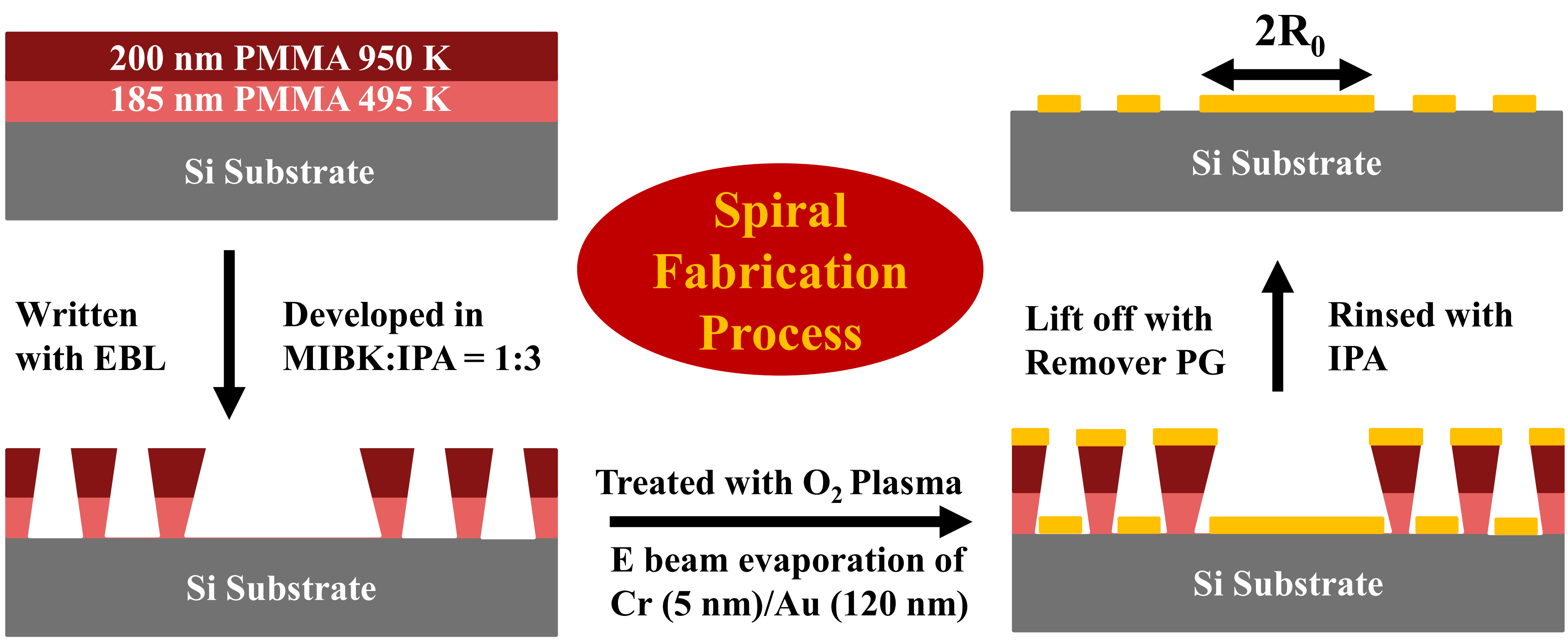


Fowler Dubridge:
$J_n \propto I^n$

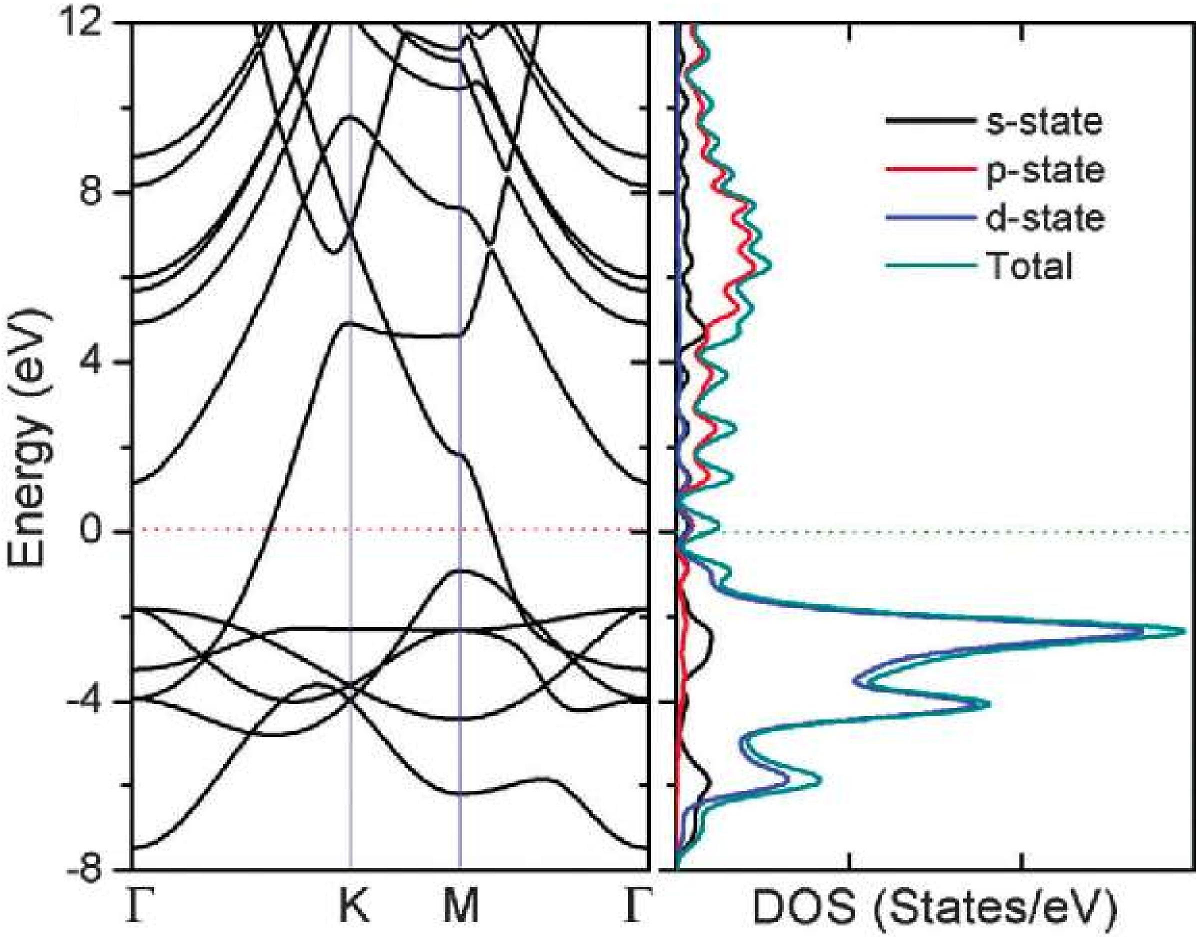
Φ_{Au} ~5.4 eV; $\hbar\omega$ = 1.55 eV
n = 4 (5) , $J_4 \propto I^4$ (I^5)

Non-Linear Photoemission:
electron source size ~140 (120) nm

New Fabrication Technique

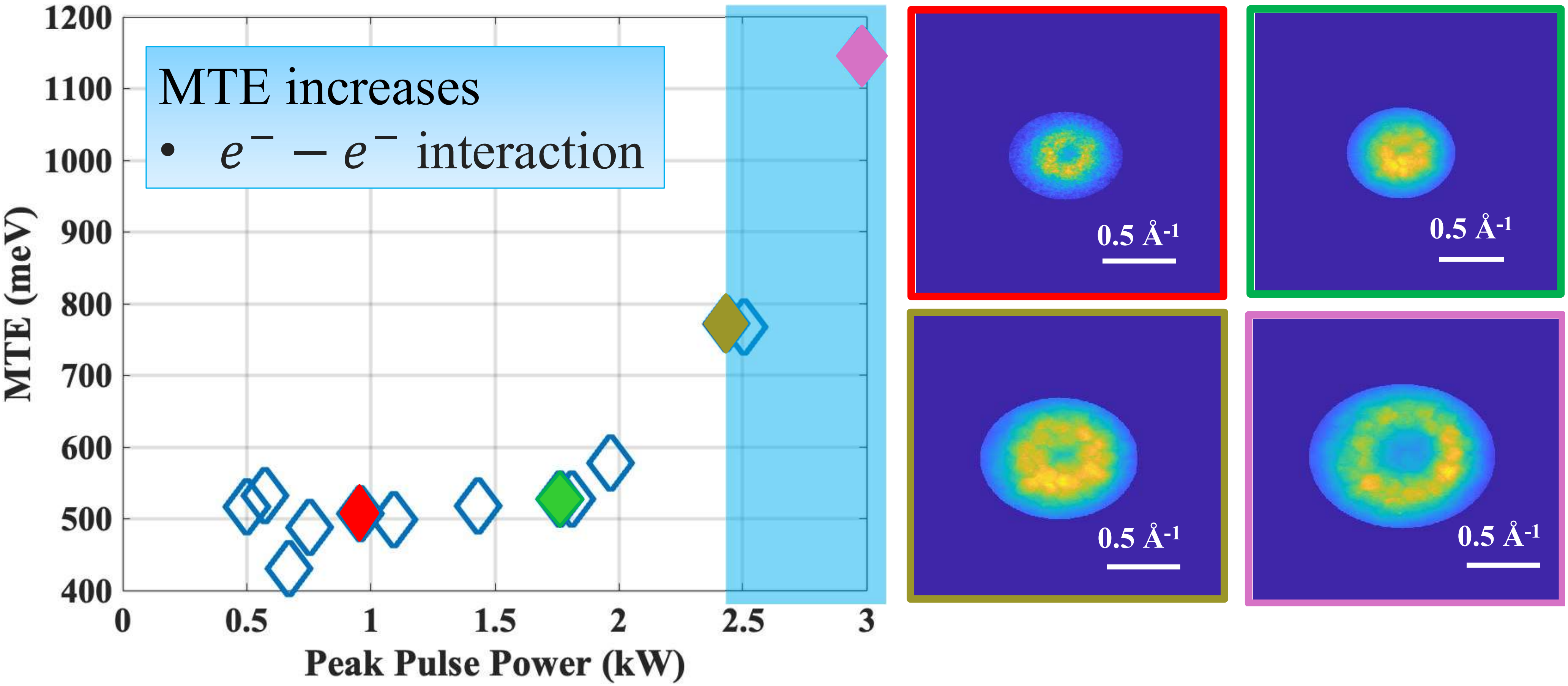


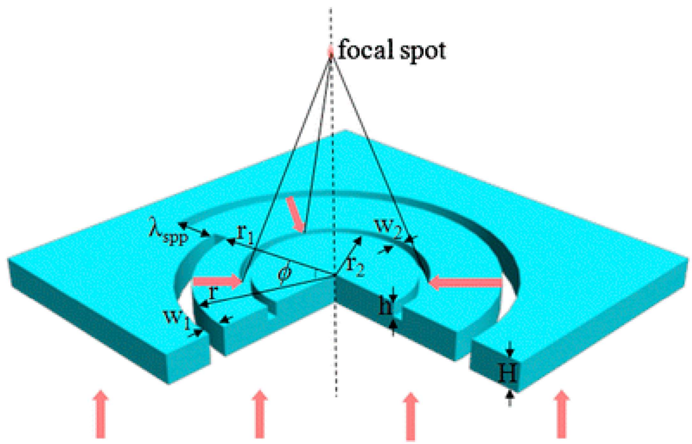
Density of States: Gold

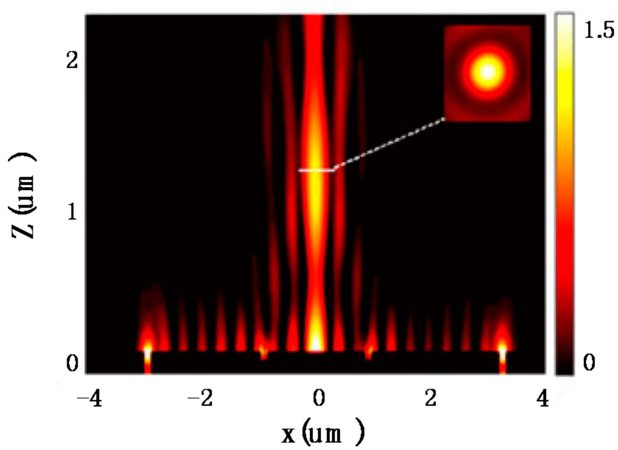


Physical Chemistry Chemical Physics 17.39 (2015): 26036-26042

Spiral Photocathode: MTE







Nanomaterials 7.11 (2017): 405.

Epitaxial Transfer of GaAs