The Center for BRIGHTBEAMS
A National Science Foundation Science & Technology Center

Novel Plasmonic and Photonics Integrated Photocathodes

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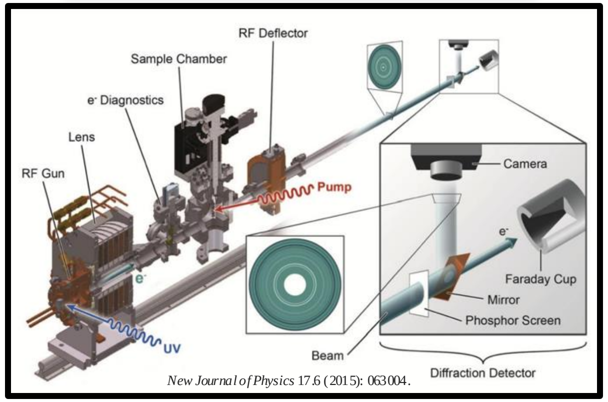
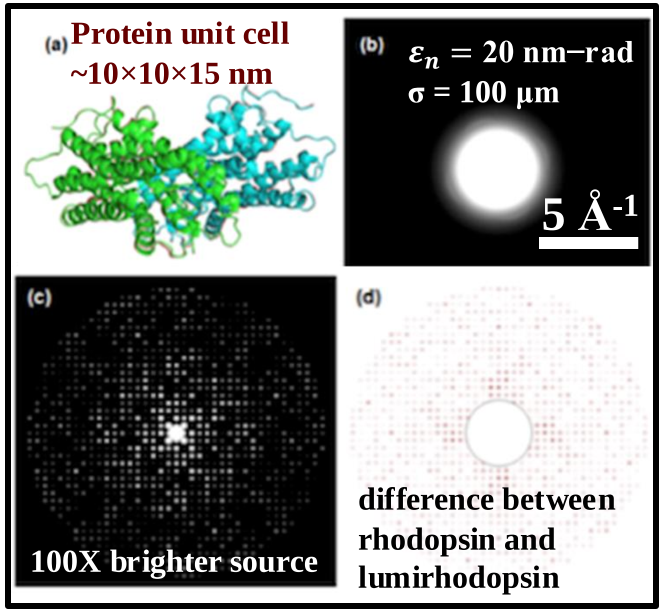
Arizona State University

Introduction

Ultrafast Electron Diffraction (UED)

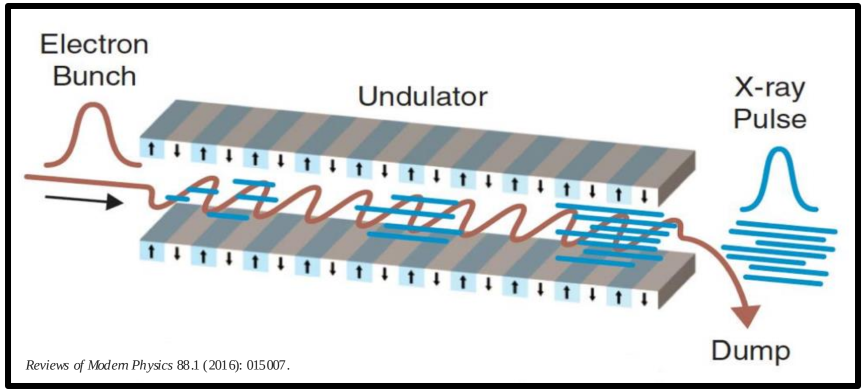


New Journal of Physics 17.6 (2015): 063004.

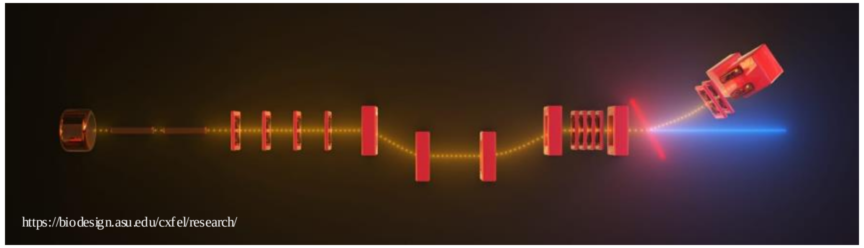


https://www.classe.cornell.edu/

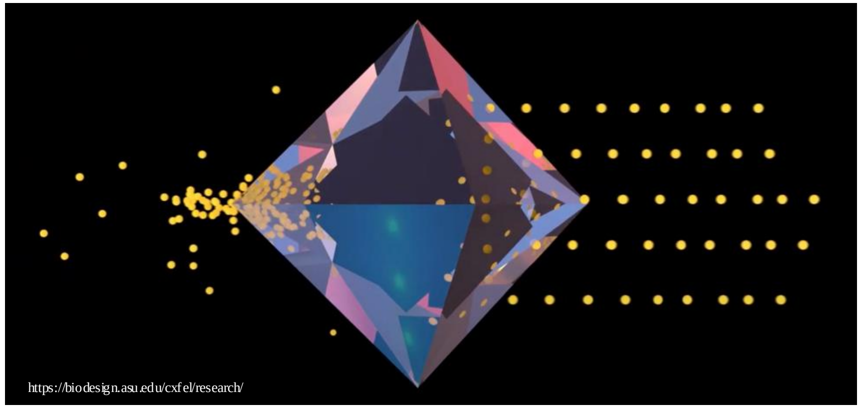
XFEL/C-XFEL



Reviews of Modern Physics 88.1 (2016): 015007.

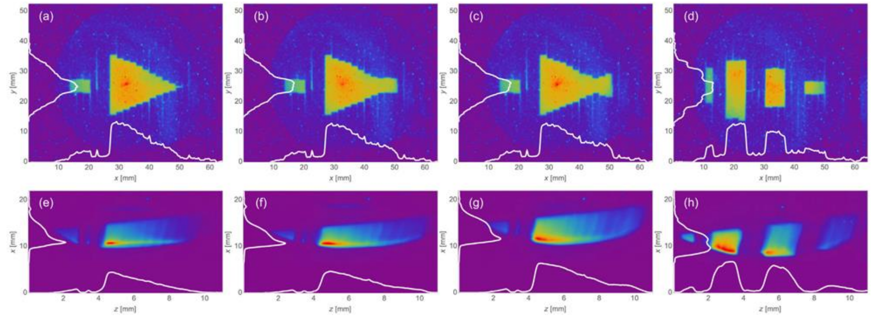


https://biodesign.asu.edu/cxfel/research/



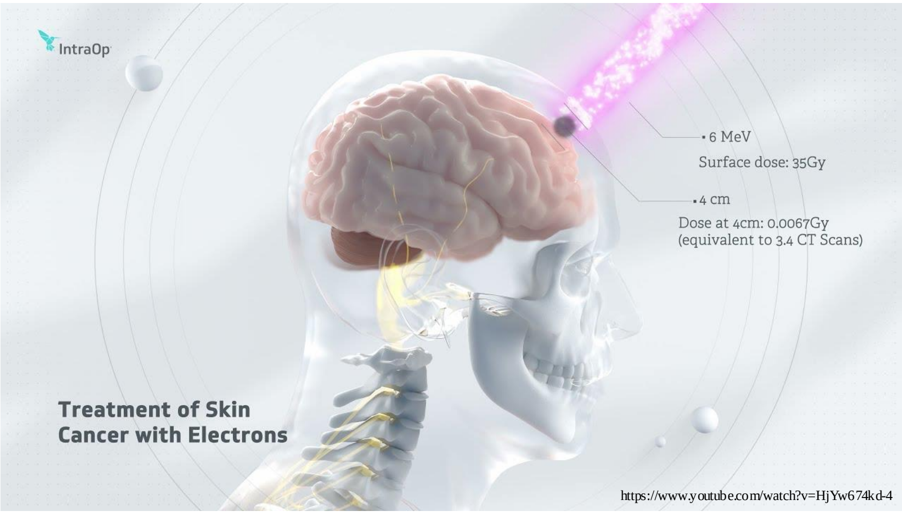
https://biodesign.asu.edu/cxfel/research/

Wakefield Accelerators



PhysRevAccelBeams.26.022801

Medical Physics: Shaped Electron beam for Treating tumors



https://www.youtube.com/watch?v=HjYw674kd-4

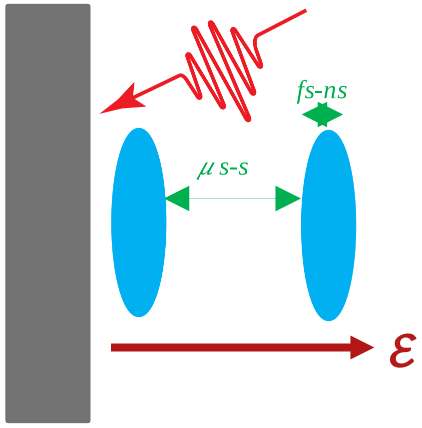
Photocathode Brightness

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

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

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

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

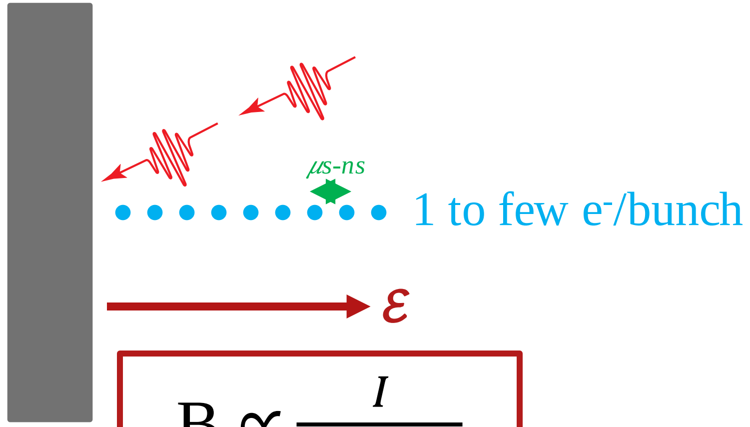


$$\mathrm{B} \propto \frac{I}{\sigma_x^2 \mathrm{MTE}}$$

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

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

- Pulsed Electron Beam
  - Stroboscopic UED/M

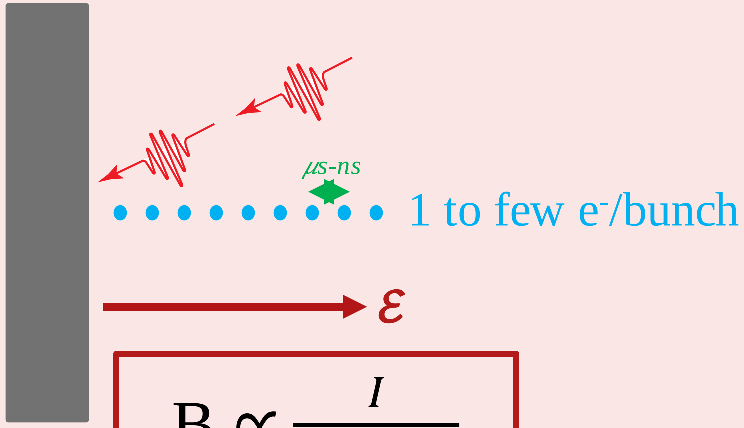


$$\mathrm{B} \propto \frac{I}{\sigma_x^2 \mathrm{MTE}}$$

Few μm limited by the diffraction limit of light

Story So Far….

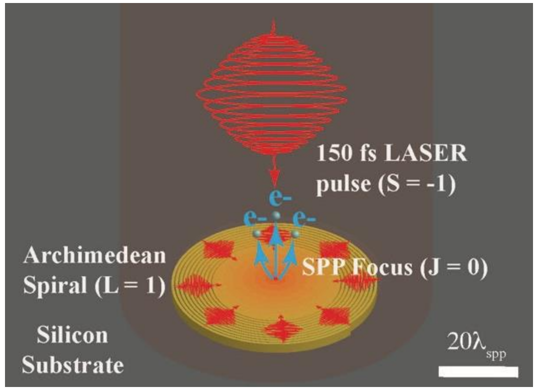
- Pulsed Electron Beam
  - ➢ Stroboscopic UED/M



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

Few μm limited by the diffraction limit of light

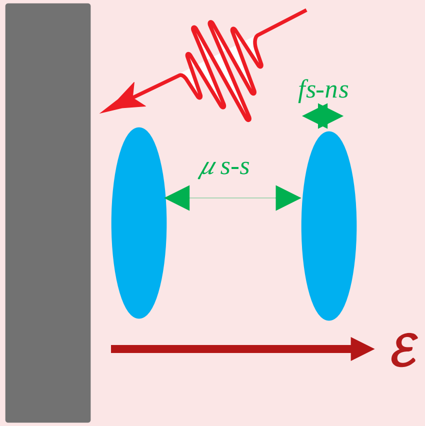
Can we go below diffraction limited laser spot?



Plasmonics

Photonics-Integrated Photocathodes

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



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

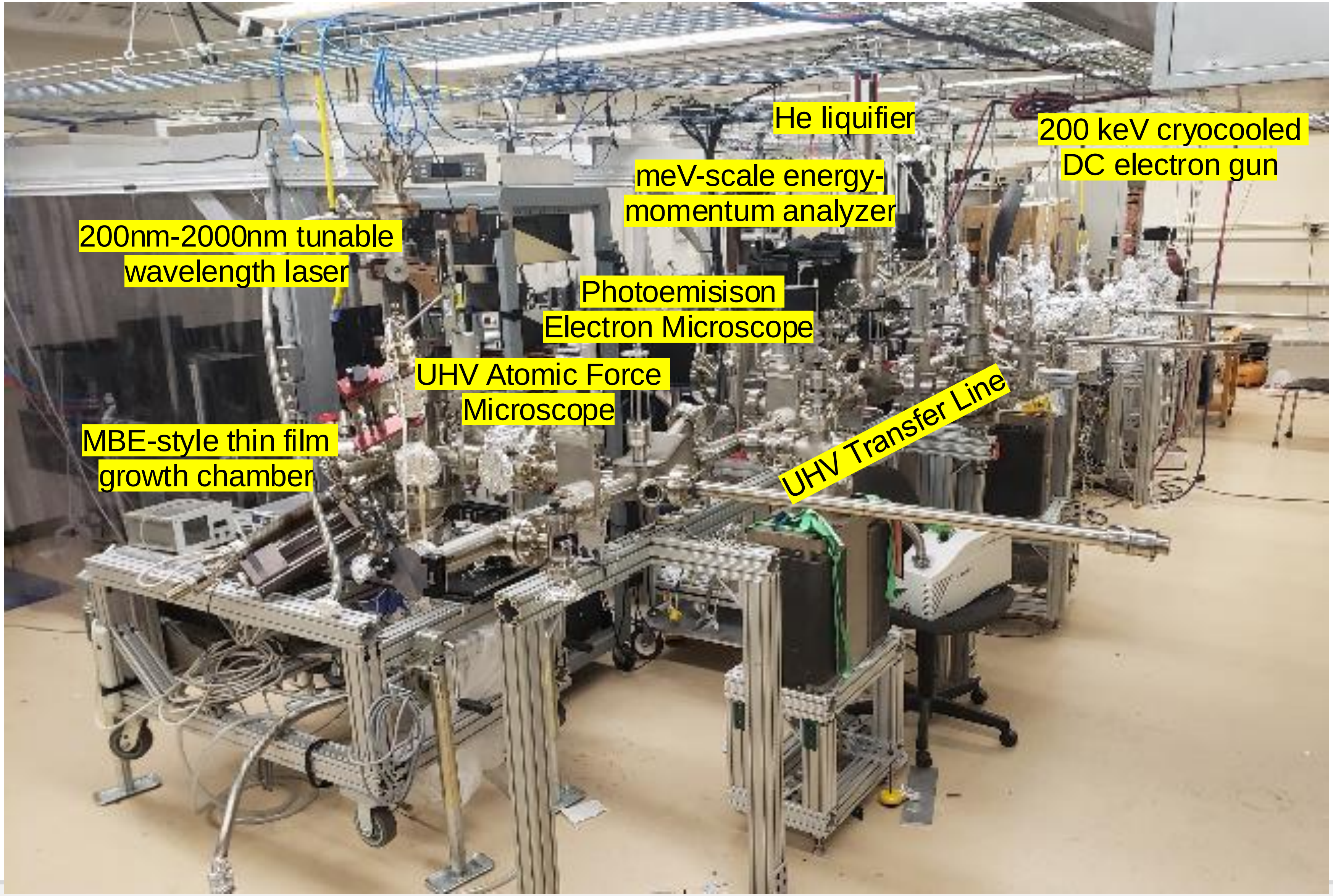
$$I \propto \sigma_x^2 \mathcal{E}$$

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

For large charge density applications/shaped electron beam applications

Can we create transversely shaped electron beam at the cathode?

Photoemission and Bright Beams Lab

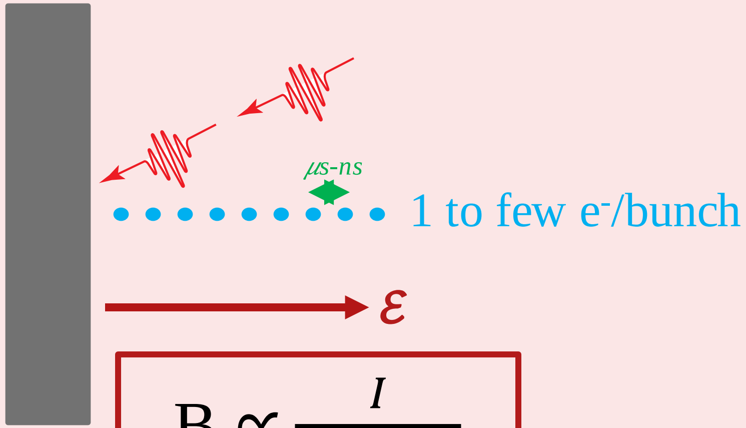


- UHV thin film growth
- Atomic scale surface characterization
- Fundamental photoemission physics
- Electron Beam Physics
- Ultrafast Electron Diffraction (soon)

Visit Poster for More Details!!!

Small Emission Area Plasmonic Photocathodes

- Pulsed Electron Beam
  - ➢Stroboscopic UED/M

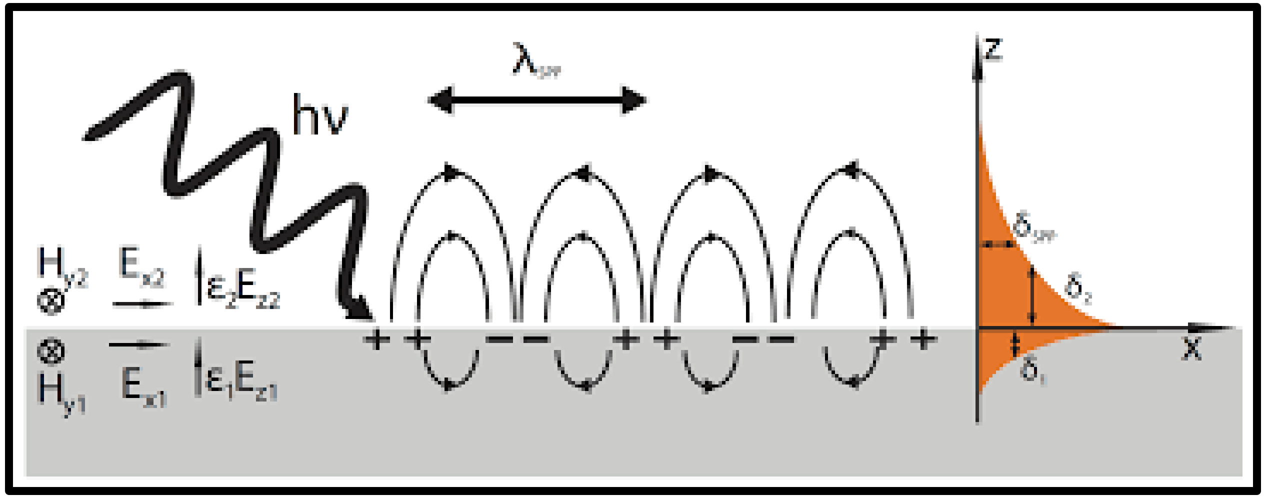


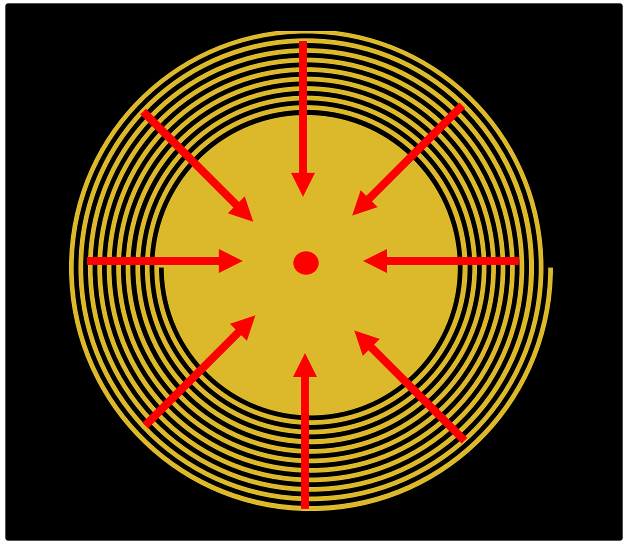
$$\boxed{B \propto \frac{I}{\sigma_x^2 \mathrm{MTE}}}$$

Few μm limited by the diffraction limit of light

Can we go below diffraction limited laser spot?

Surface Plasmon Polariton

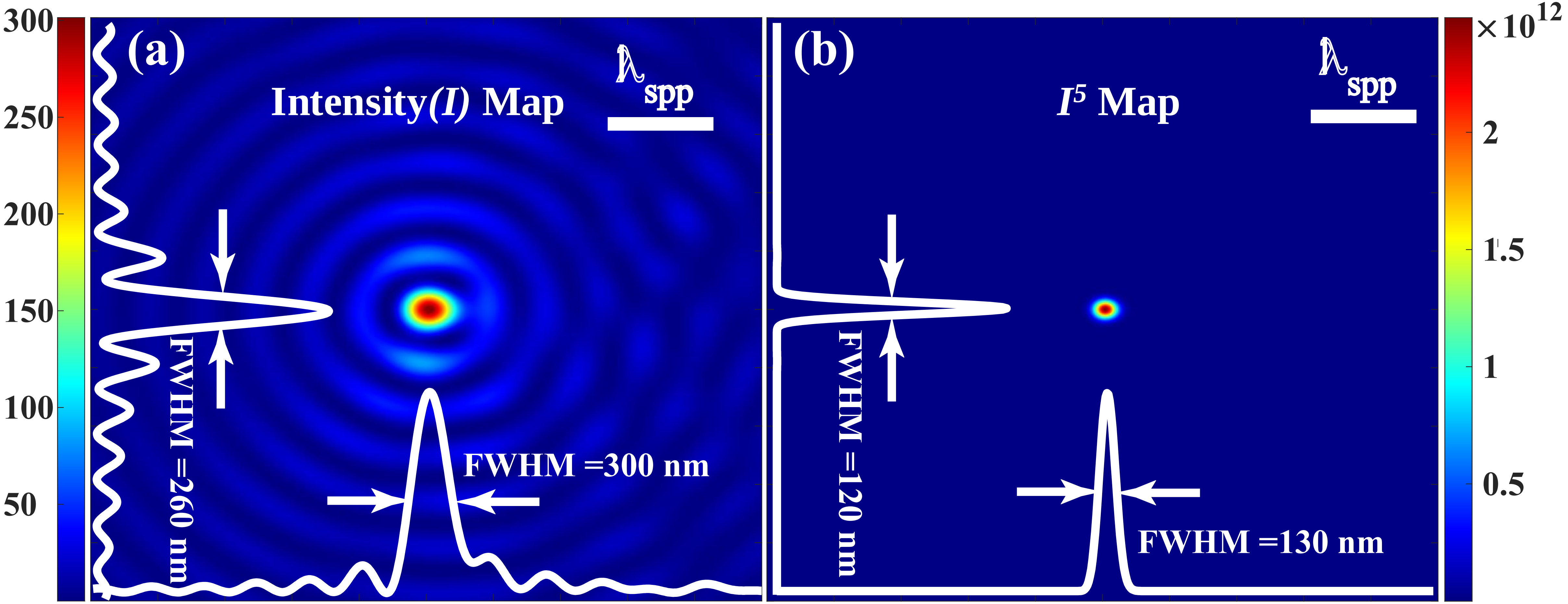




Achieve nanoscale electron emission area from **Plasmonic Gold Spiral**

https://en.wikipedia.org

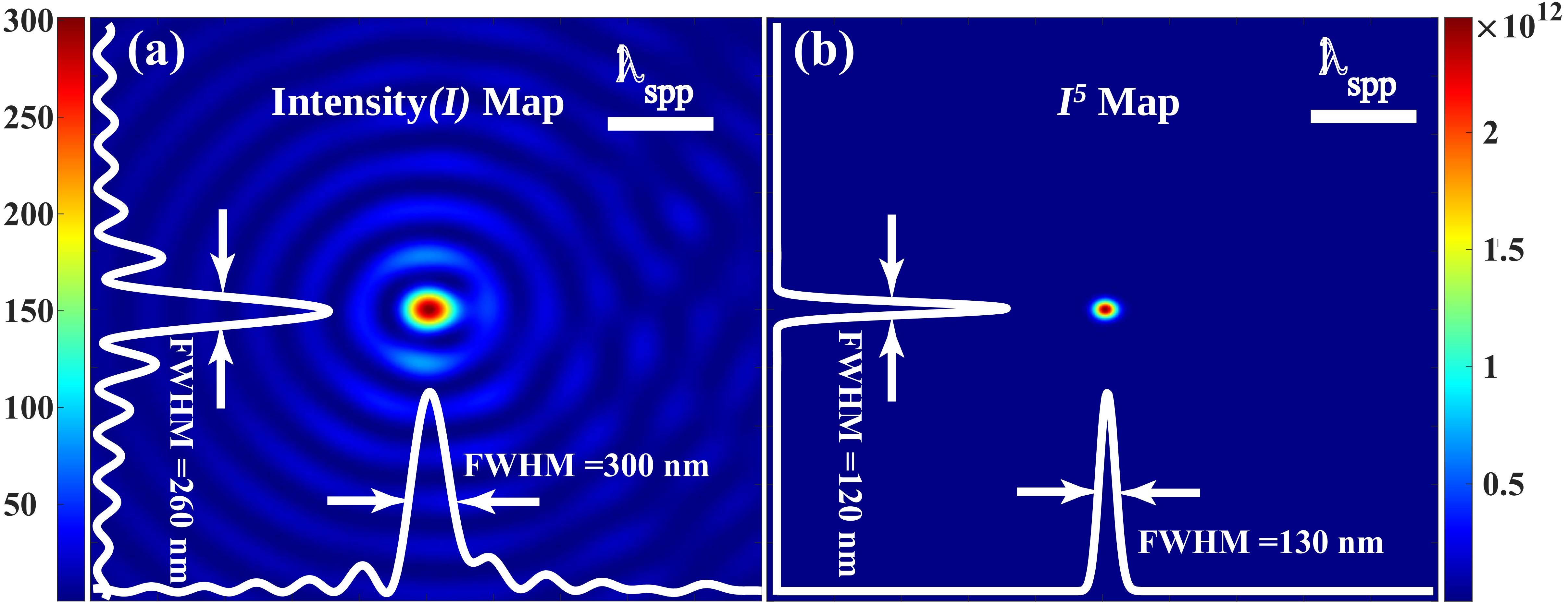
Plasmonic Spiral Photocathode: FDTD Simulation



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

Kachwala, Rizi, …, **Maxson, Karkare,** under review PRL, arXiv:2406.08678v1 [physics.acc-ph] 12 Jun 2024

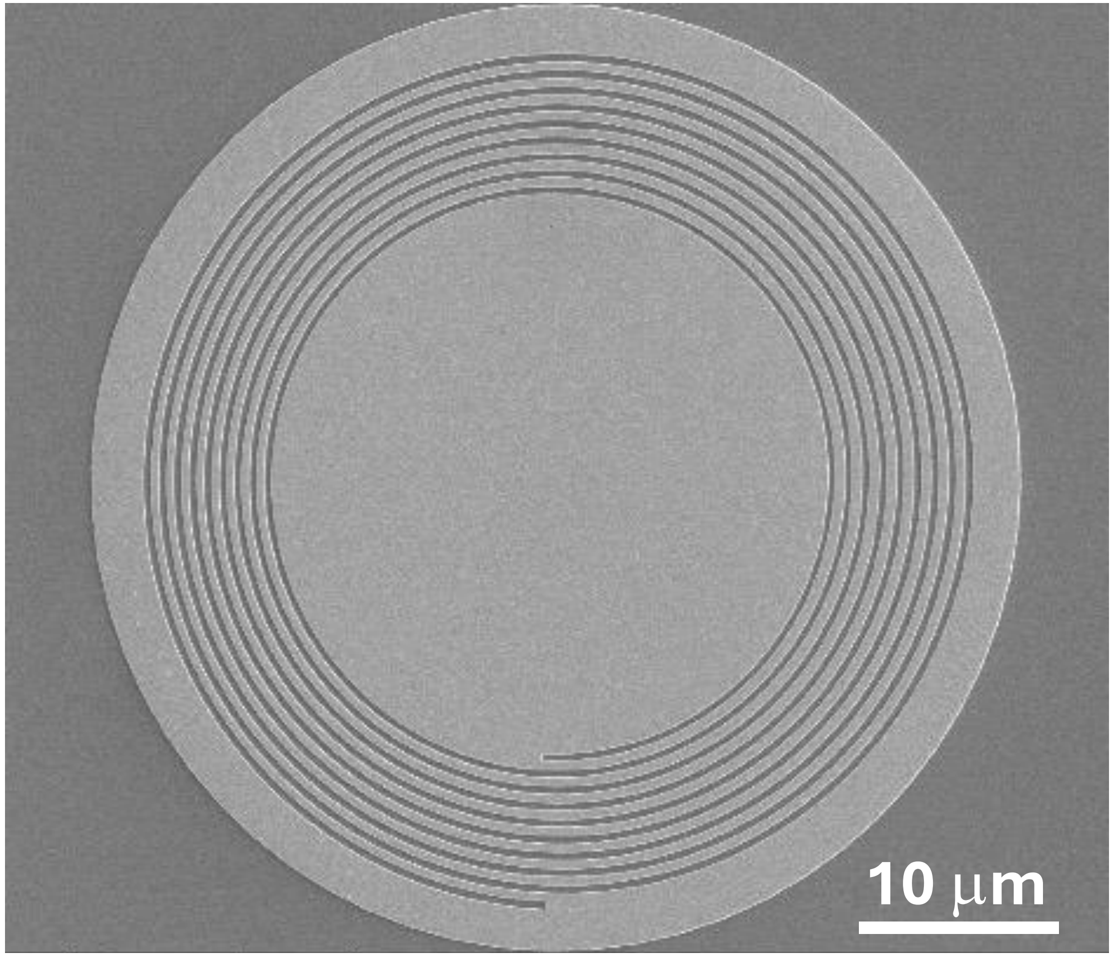
Plasmonic Spiral Photocathode: FDTD Simulation



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

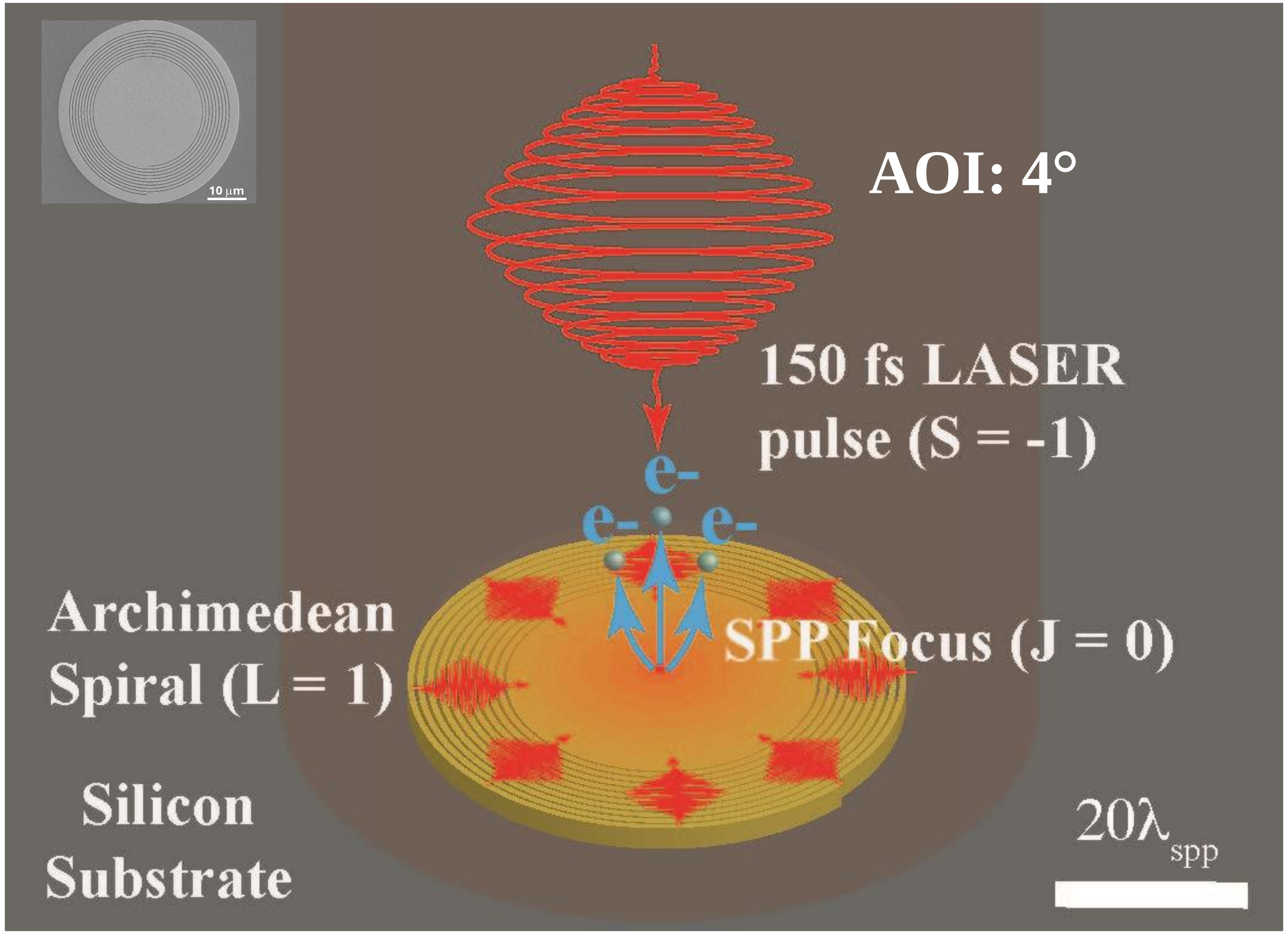
Kachwala, Rizi, …, **Maxson, Karkare,** under review PRL, arXiv:2406.08678v1 [physics.acc-ph] 12 Jun 2024

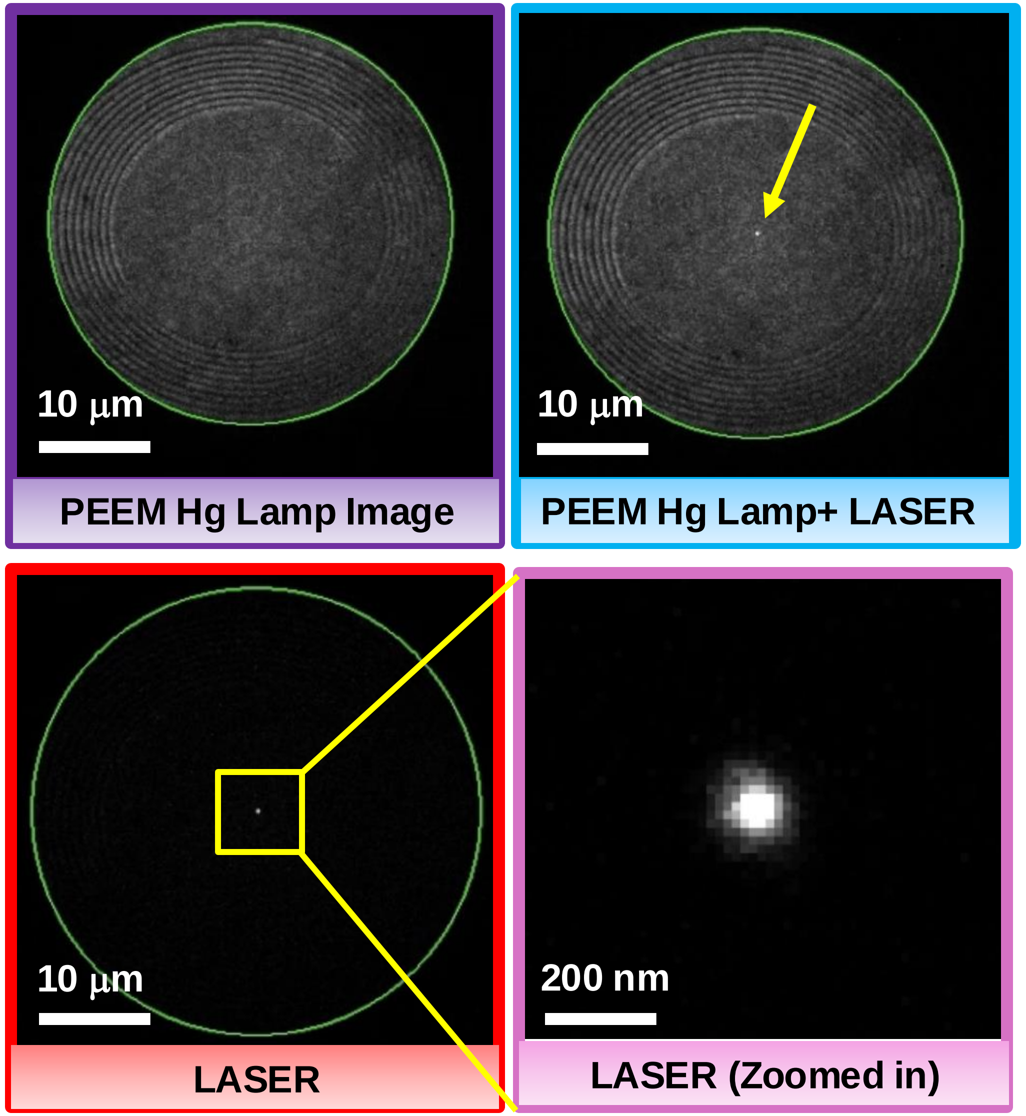
Plasmonic Spiral Photocathode: Experimental



Plasmonic Spiral Photocathode: Experimental

Schematic

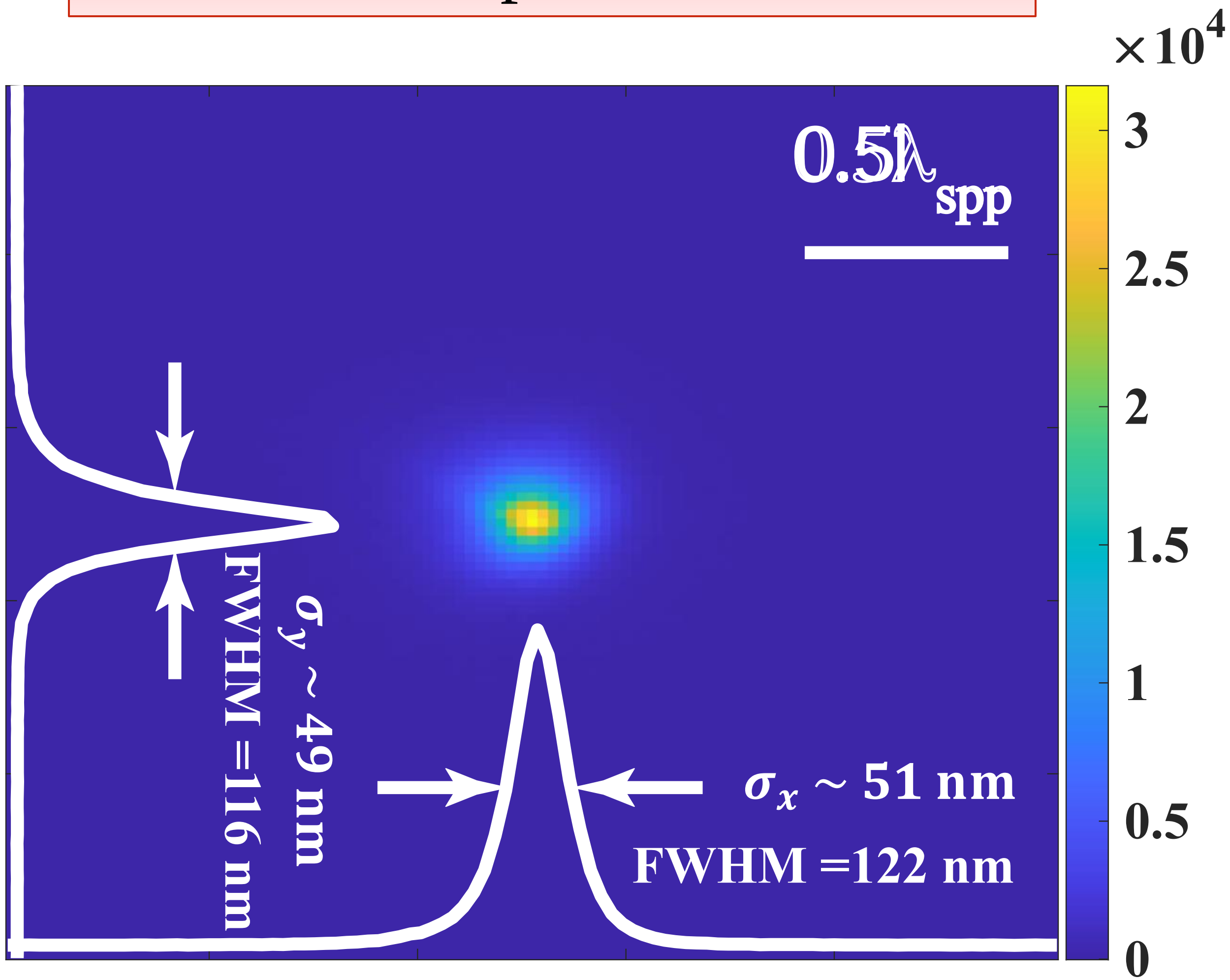




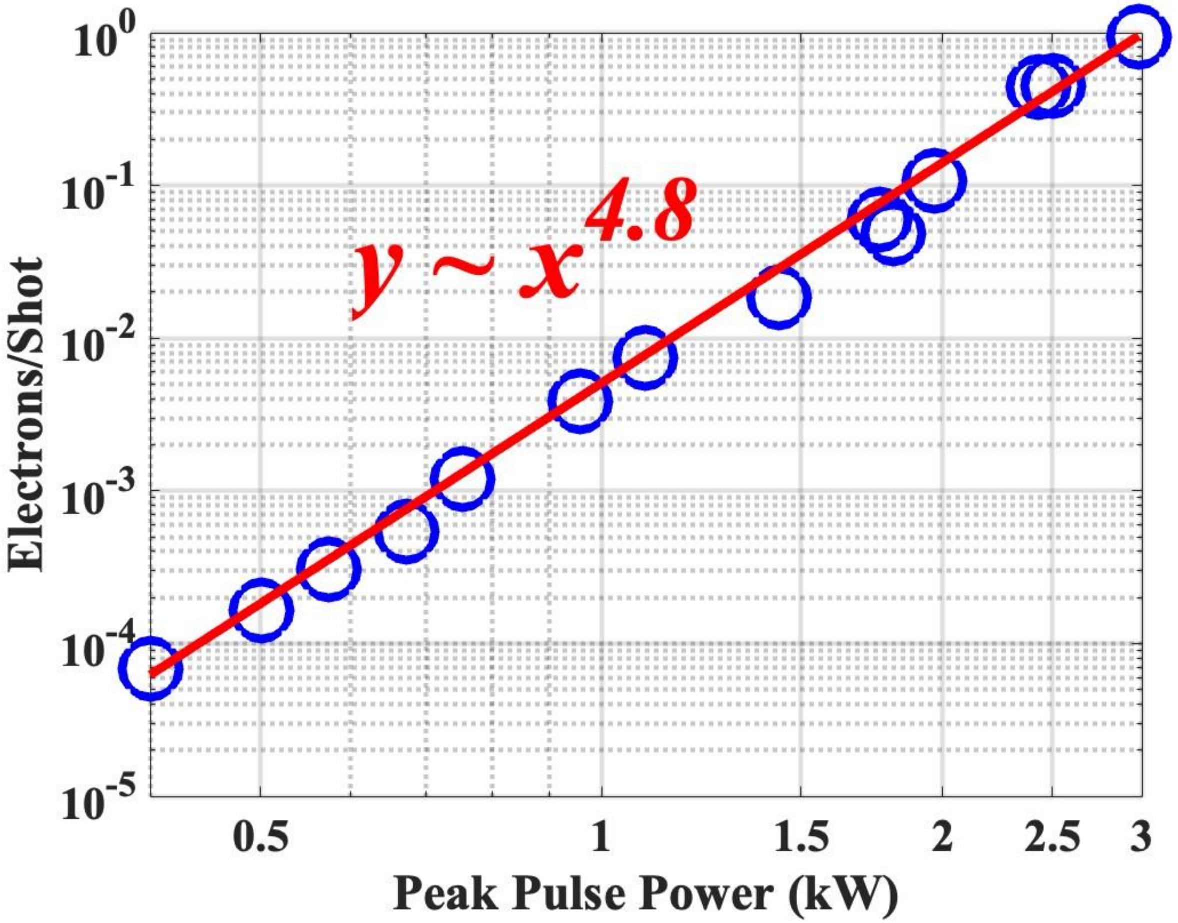
Kachwala, Rizi, …, Maxson, Karkare, under review PRL, arXiv:2406.08678v1 [physics.acc-ph] 12 Jun 2024

Plasmonic Spiral Photocathode: Experimental

Peak LASER power = 1.8 kW

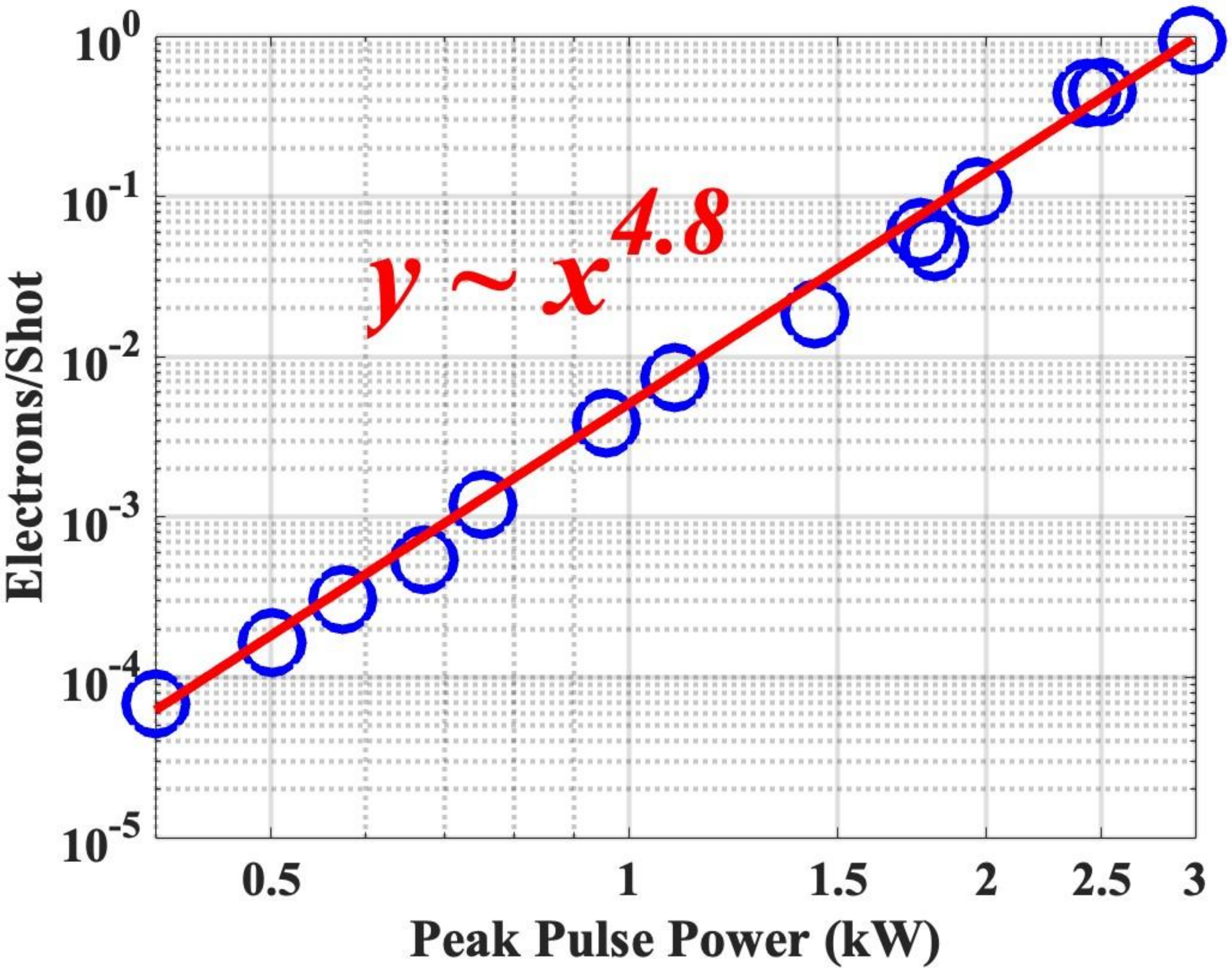


Order of Emission



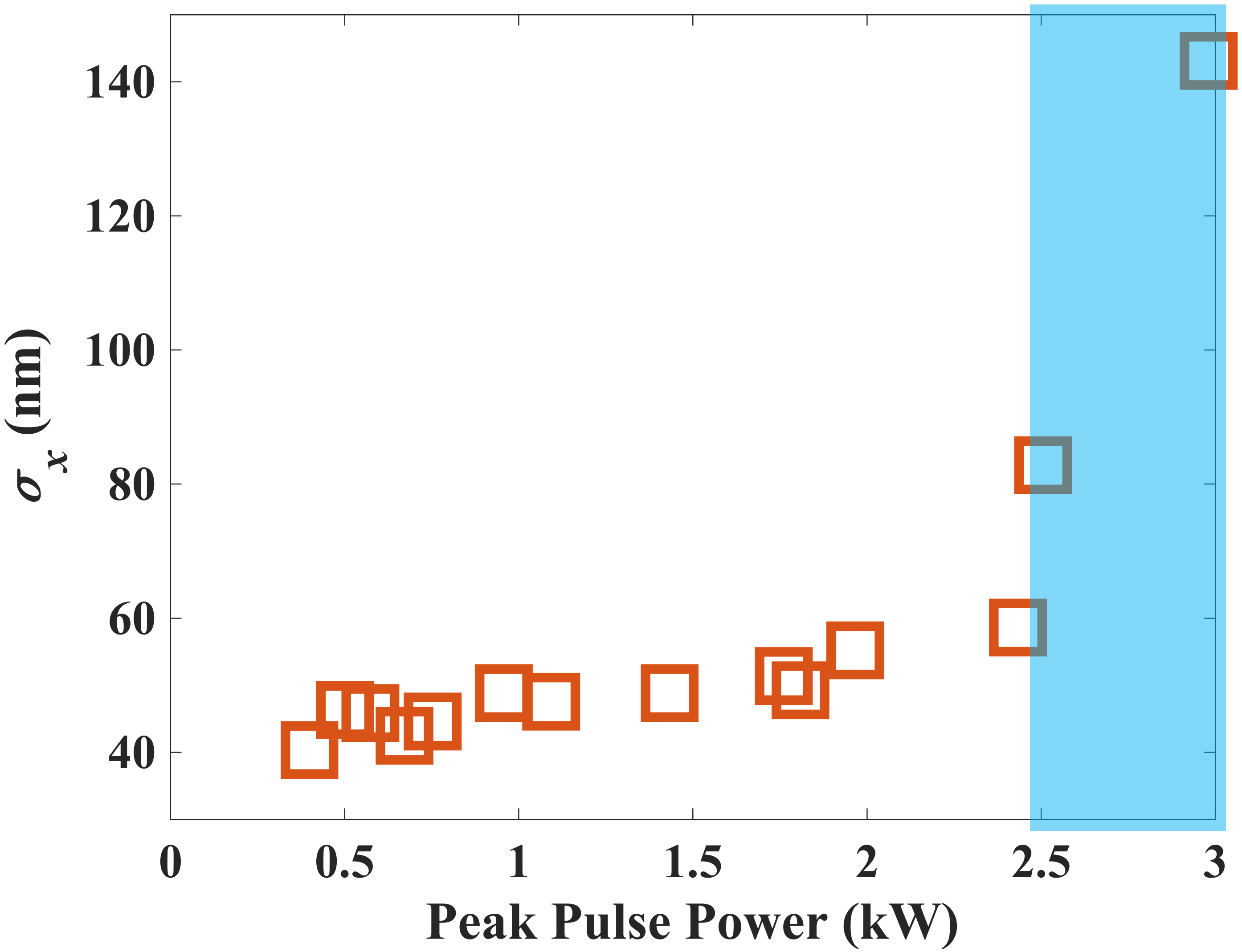
Kachwala, Rizi, …, **Maxson, Karkare,** under review PRL, arXiv:2406.08678v1 [physics.acc-ph] 12 Jun 2024

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

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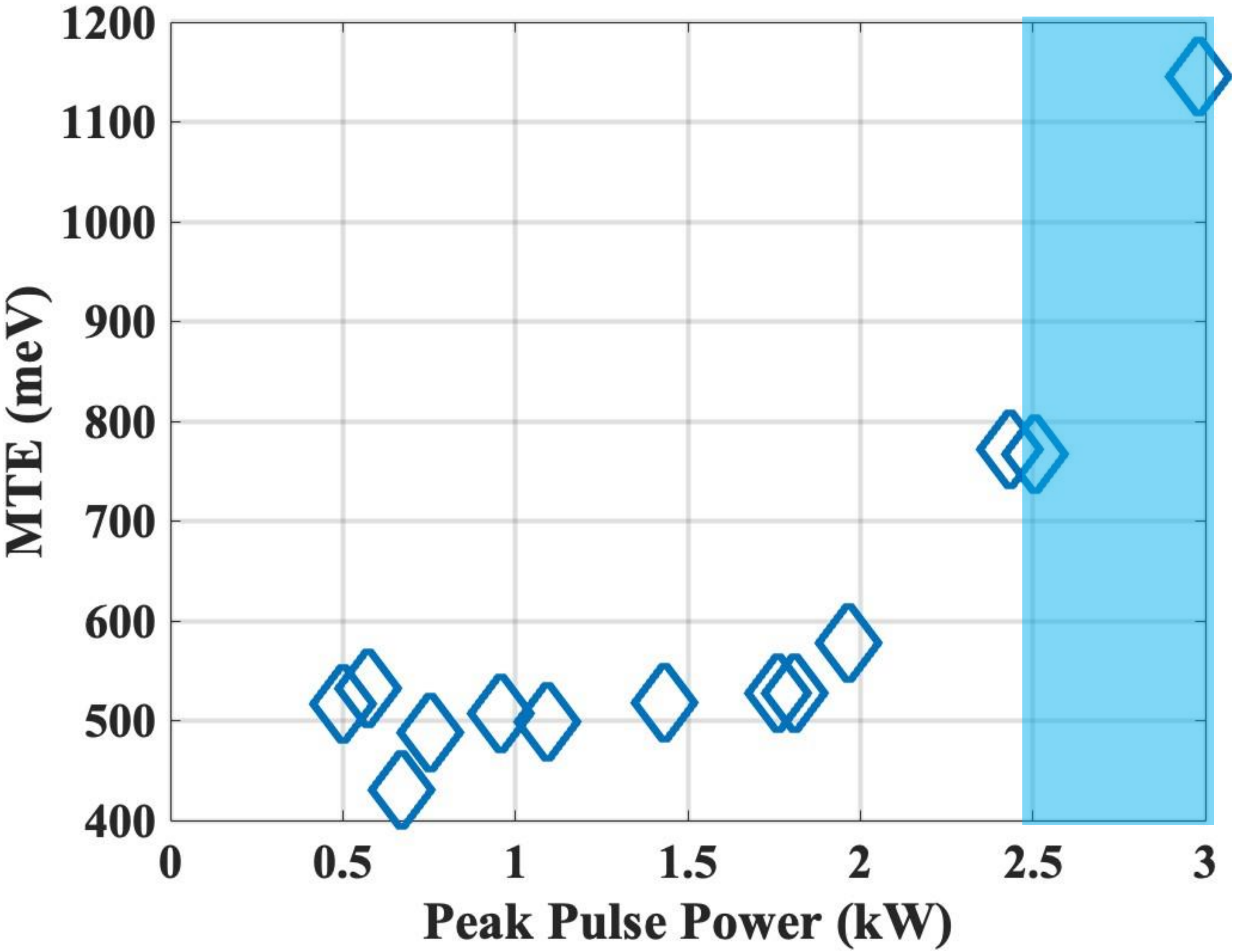
Spiral Photocathode: MTE



MTE ~ 500 meV over wide range of LASER power

MTE increases

- $e^{-} - e^{-}$ interaction

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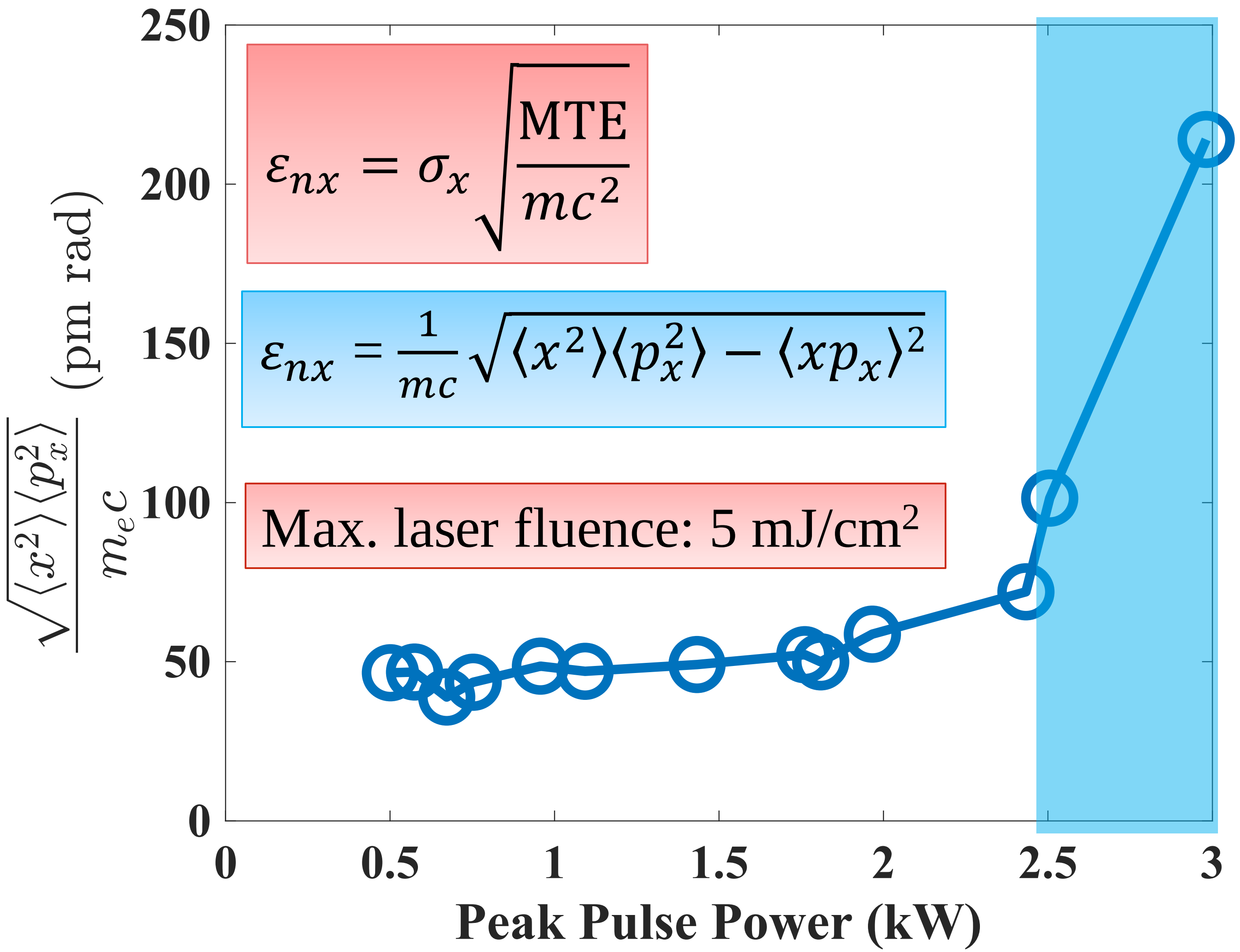
Spiral Photocathode: Emittance



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

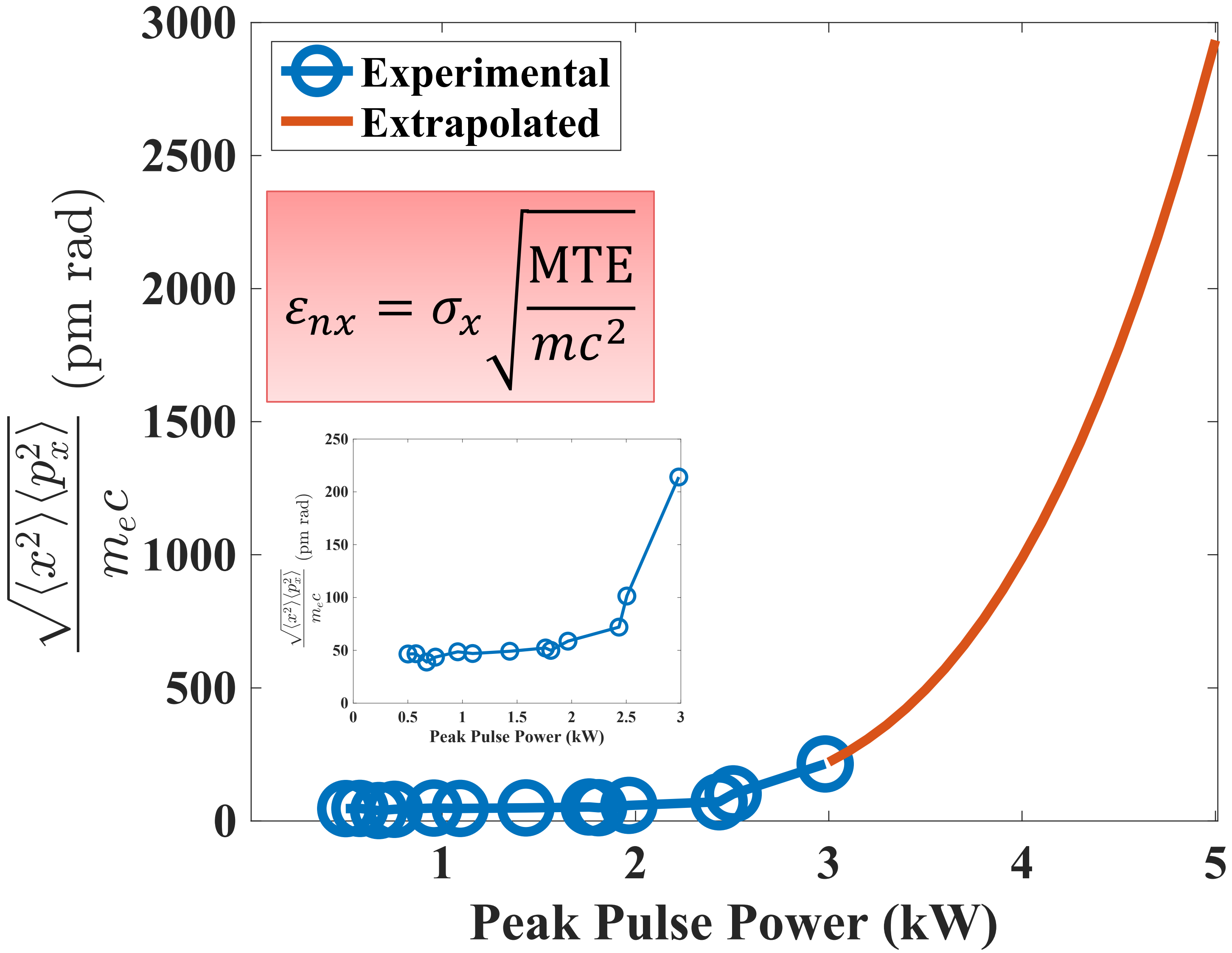
- 2 pm rad from ZrO/W emitter tip in an Electron Microscope [*Ultramicroscopy* 176 (2017): 63-73]
- 120 pm rad from flat cathode in a photoinjector after the pinhole [*HiRES UED Beamline*)]

ε_{nx} increases
- $e^- - e^-$ interaction

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

Kachwala, Rizi, …, Maxson, Karkare, under review PRL, arXiv:2406.08678v1 [physics.acc-ph] 12 Jun 2024

Spiral Photocathode: Emittance Extrapolated



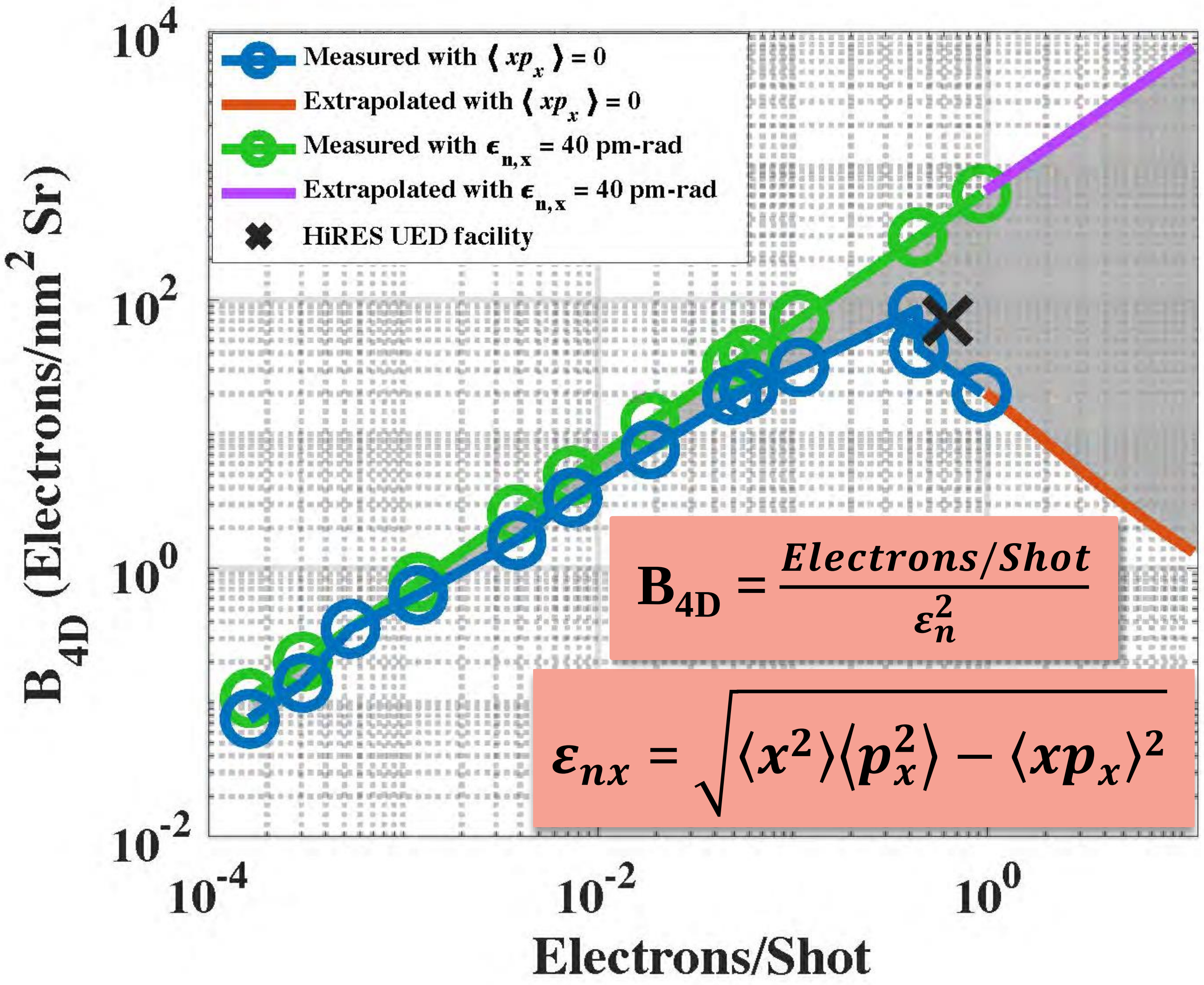
$$\varepsilon_{nx} = \sigma_x \sqrt{\frac{\text{MTE}}{mc^2}}$$

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)

Kachwala, Rizi, …, Maxson, Karkare, under review PRL, arXiv:2406.08678v1 [physics.acc-ph] 12 Jun 2024

Spiral Photocathode: 4D-Brightness



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

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

Kachwala, Rizi, …, Maxson, Karkare, under review PRL, arXiv:2406.08678v1 [physics.acc-ph] 12 Jun 2024

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

Brightness decreases

- $e^- - e^-$ interaction

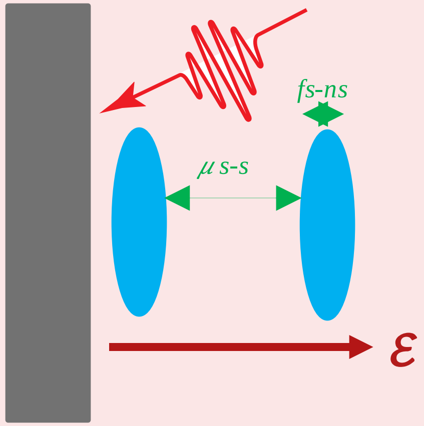
Maximum 4-D Brightness achieved:
~600 electrons/nm^2 ($\varepsilon_{nx} = 40$ pm-rad)

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

Shaped Electron Beam: Photonics Integrated Photocathodes

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

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



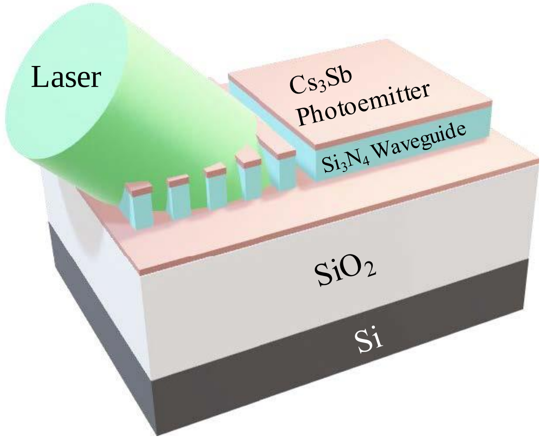
$$B \propto \frac{\varepsilon}{\mathrm{MTE}}$$

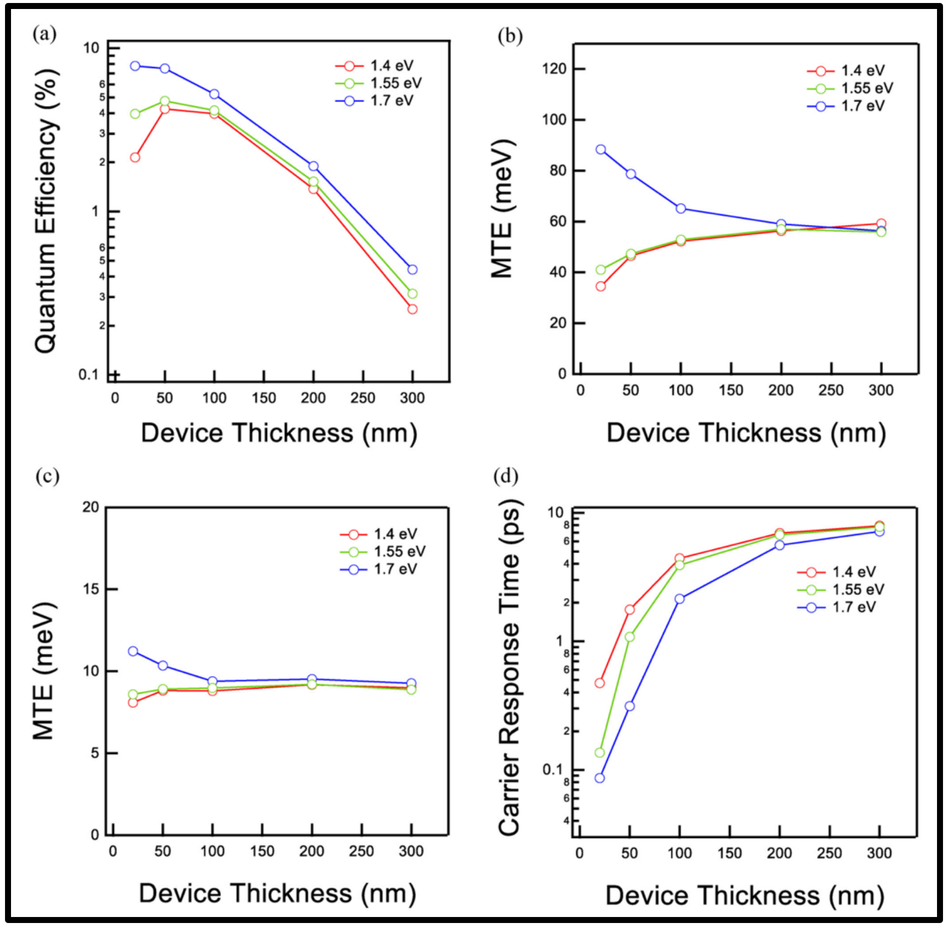
$$I \propto \sigma_x^2 \varepsilon$$

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

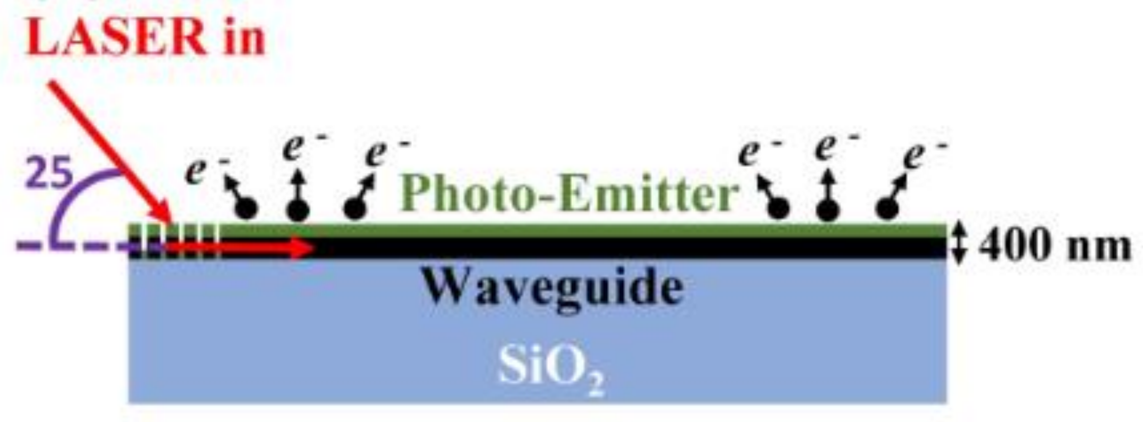
For large charge density applications/shaped electron beam applications

Can we create transversely shaped electron beam at the cathode?

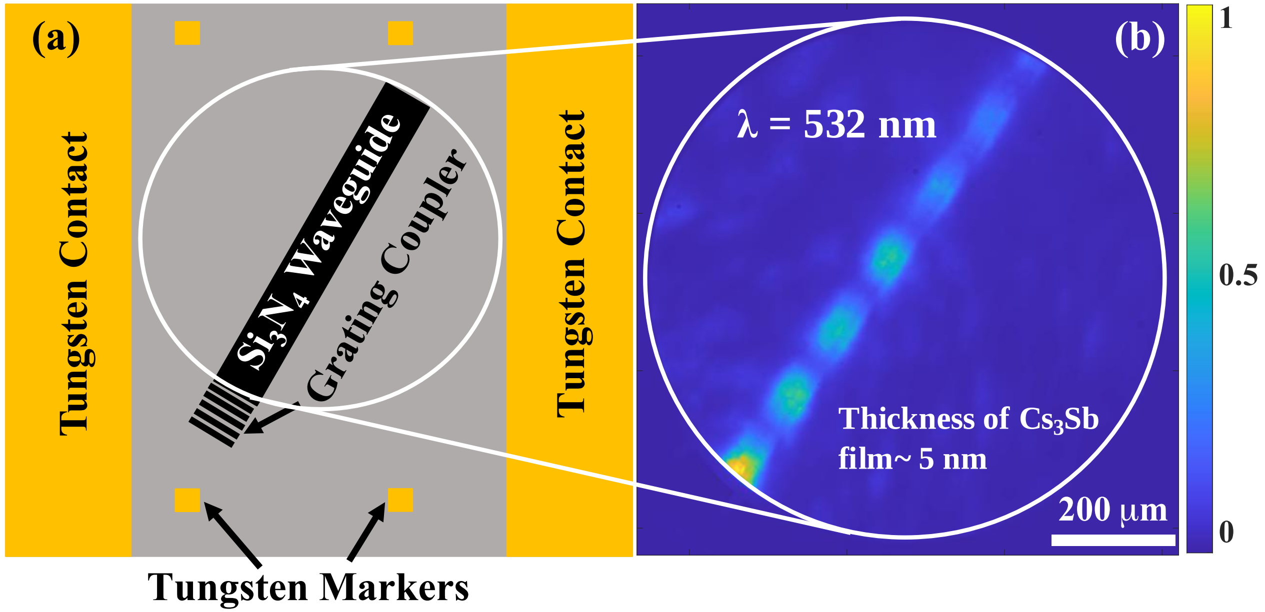




Photonics Integrated Cathodes – Beam Patterning



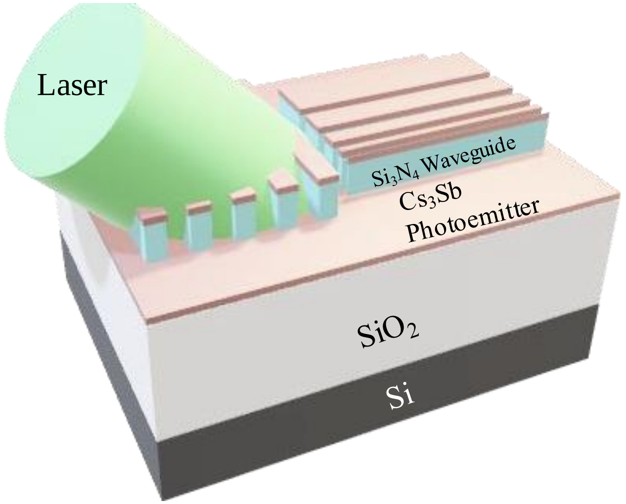
- Emission confined to waveguide
- Beating pattern due to interference of TE and TM modes
- Evanescent wave photoemission
  - a new photoemission mode

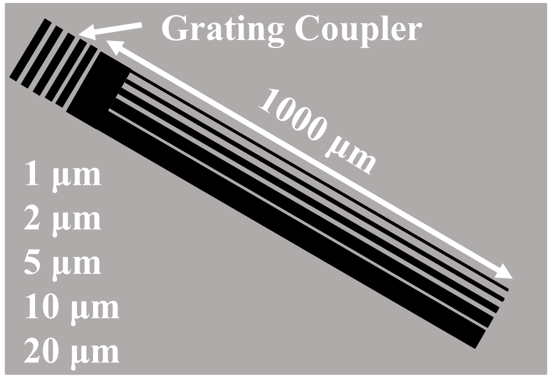


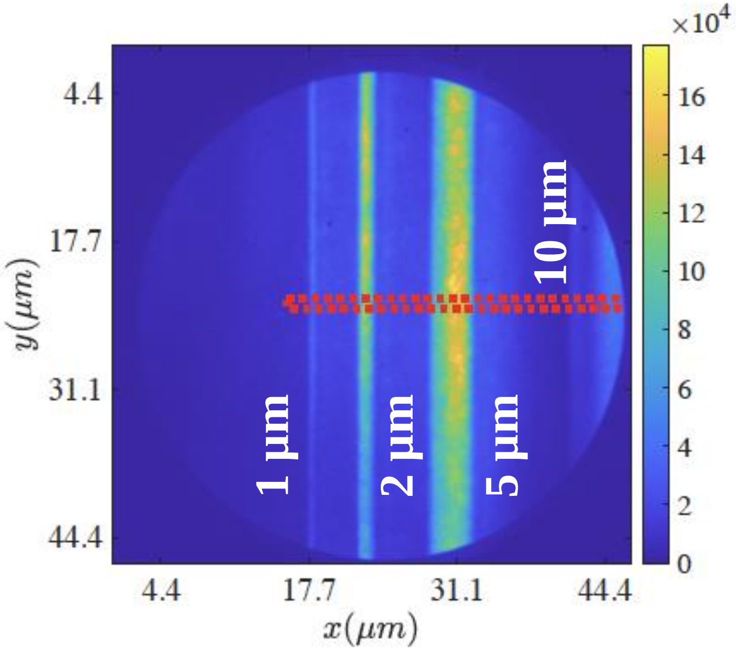
A novel way to generate arbitrary transverse beam shapes by shaping waveguide to μm scales

Photonics Integrated Cathodes – Beam Patterning

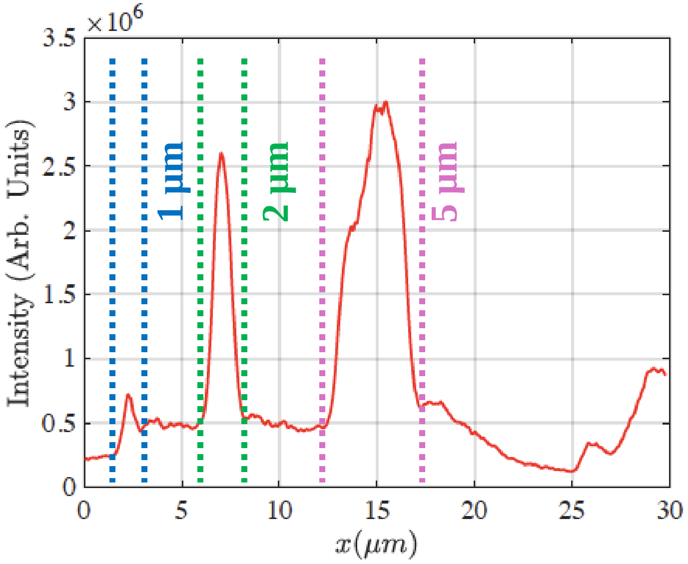
How small can we go?

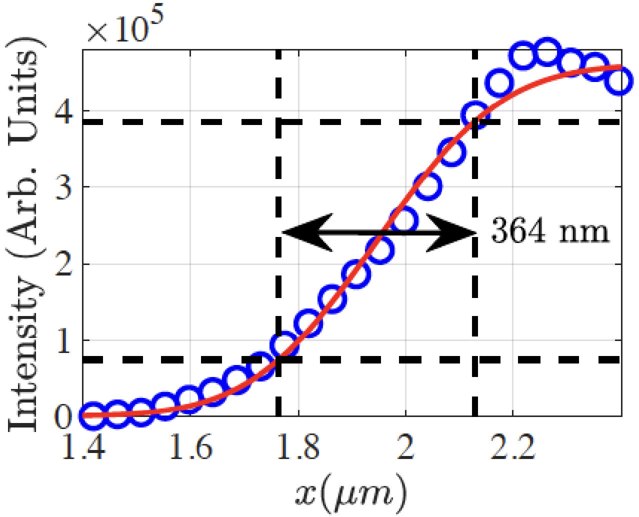






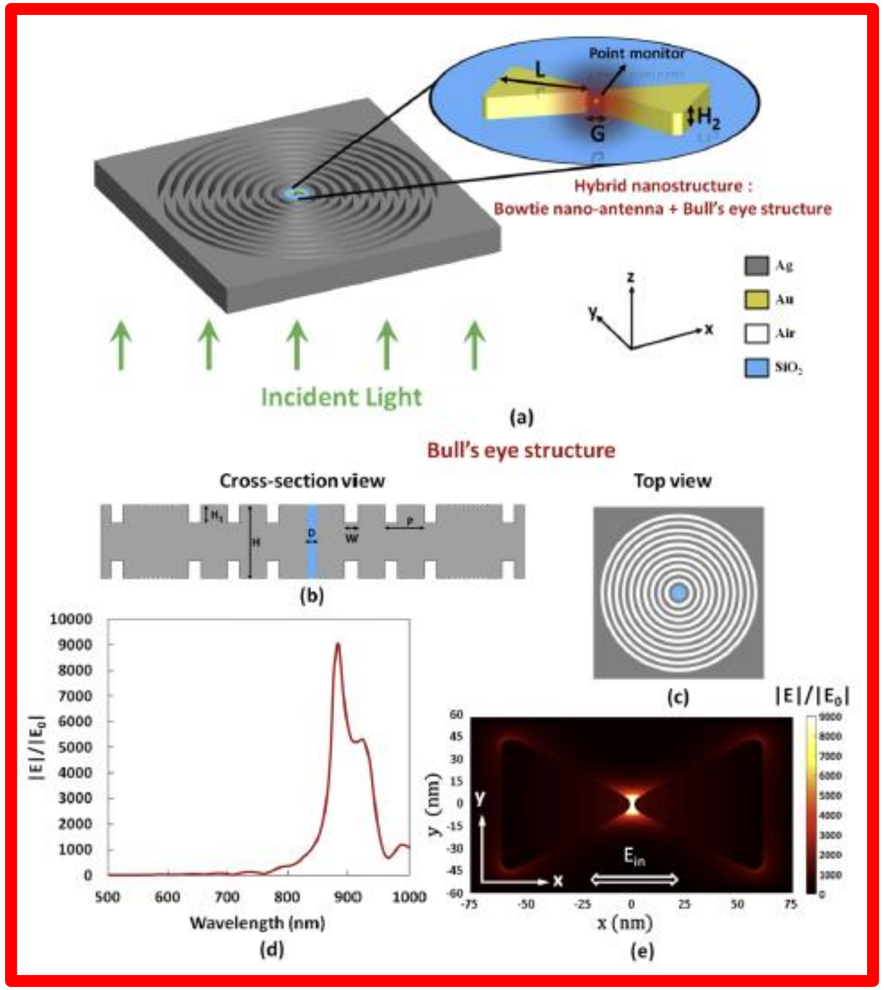
Confined emission achieved down to 1 μm!



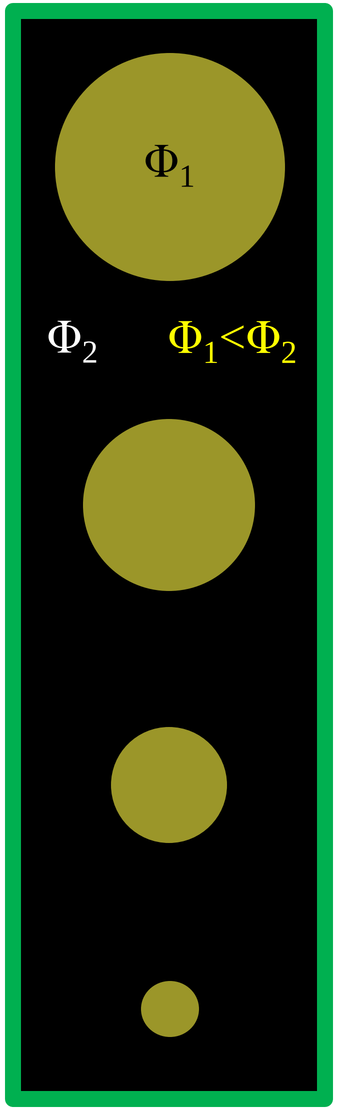


Future Work

- 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^{2}Sr)
- Photonics Integrated Cathodes with NEA-GaAs
- Work function engineered electron sources
- Test in Accelerator Environment beginning with ASU cryocooled DC electron gun



Osa Continuum 4.1 (2021): 193-211



Acknowledgements

- **ASU**
  - **Prof. Siddharth Karkare**
  - Prof. Oksana Chubenko (Now at Northern Illinois University)
  - Dr. Mansoure Moeini Rizi

- **Collaborators (Photonics Integrated Cathodes)**
  - Prof. Rehan Kapadia
  - Dr. Raghib Ahsan
  - Dr. Hyun Uk Chae

- **Collaborators (Plasmonic Spiral)**
  - Prof. Jared Maxson
  - Dr. Chris Pierce
  - Dr. Danielle Filippetto

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