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Bright Electron Beams from Plasmonic Spiral Photocathode

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Arizona State University

Outline

- **Introduction**
- **Reducing Emittance**
- **Plasmonic Spiral Photocathode**
  - FDTD Simulation
  - Fabrication and Characterization: Past and Present Attempts
- **Characterization Using Photoemission Electron Microscope**
  - Electron Emission Spot Size
  - Mean Transverse Energy (MTE)
  - Emittance
  - 4D-Brightness
- **Conclusion**
- **Future Work**

Introduction

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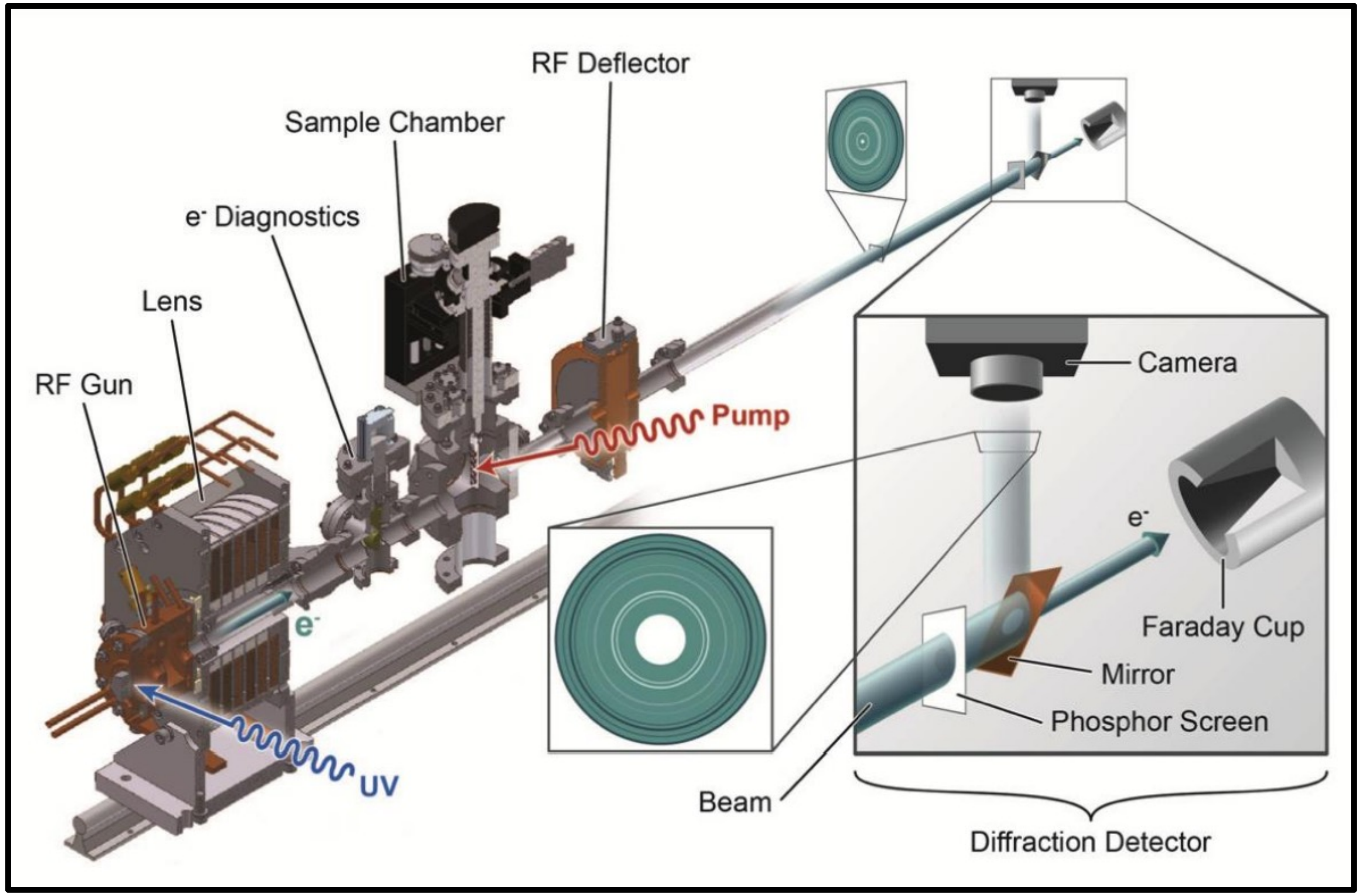


Physical Review Special Topics-Accelerators and Beams 17.12 (2014): 120701.

Coherence Length

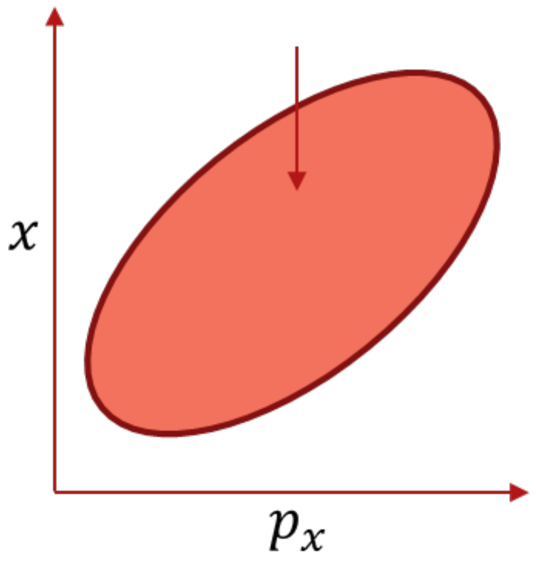
$$L_c = \lambda\!\!\!^{-} \frac{\sigma_e}{\varepsilon_n}$$

L = Coherence Length
ƛ = Reduced Compton Wavelength
σ_e = RMS electron beam size
ε_n = Normalized Emittance

Reduce ε_n to increase L_c

Emittance

ε_{nx} - Emittance



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

Emittance

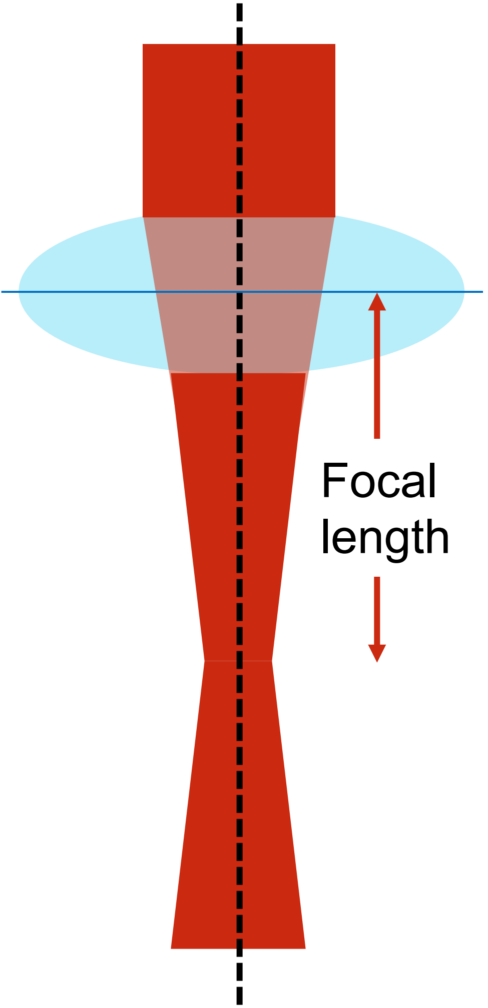
$\sqrt{\text{MTE}}$ σ_x

Reduce MTE

Reduce σ_x

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

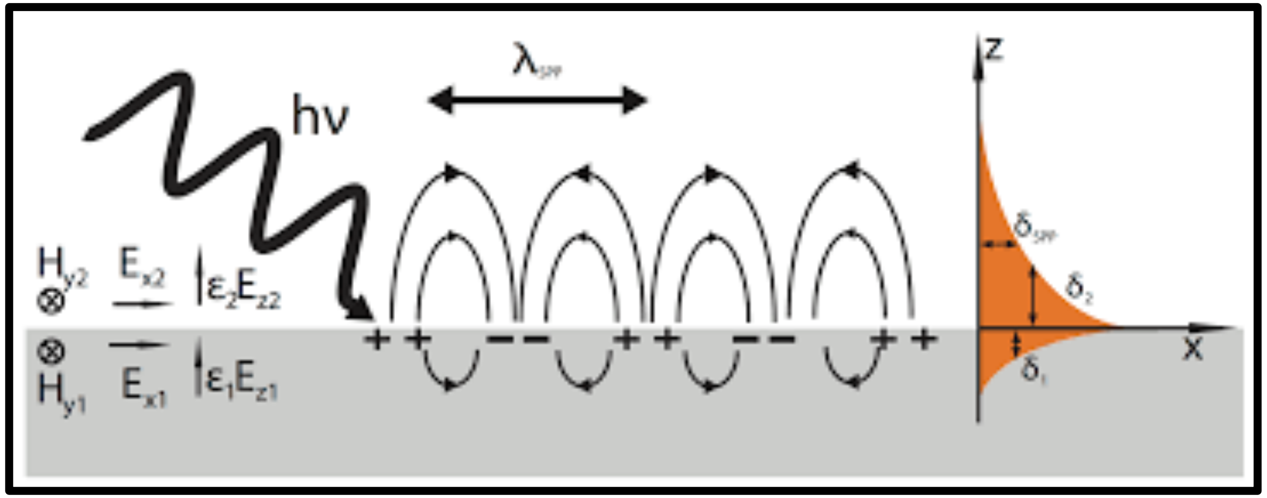
Structural Dynamics 9.2 (2022)

Physical review letters 110.7 (2013): 074801

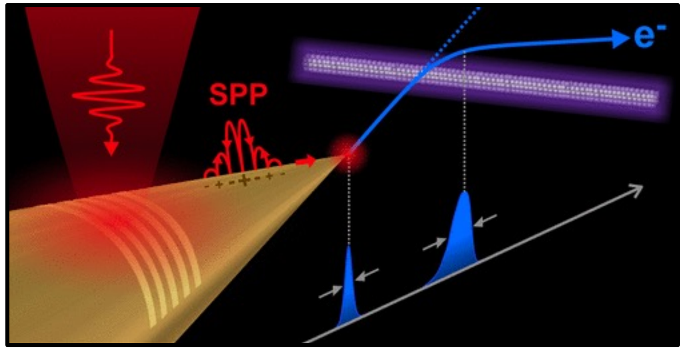
Physical Review Applied 19.3 (2023): 034034

Acs Photonics 3.4 (2016): 611-619

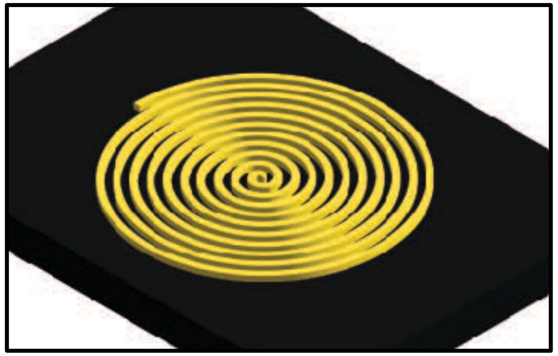
Surface Plasmon Polariton



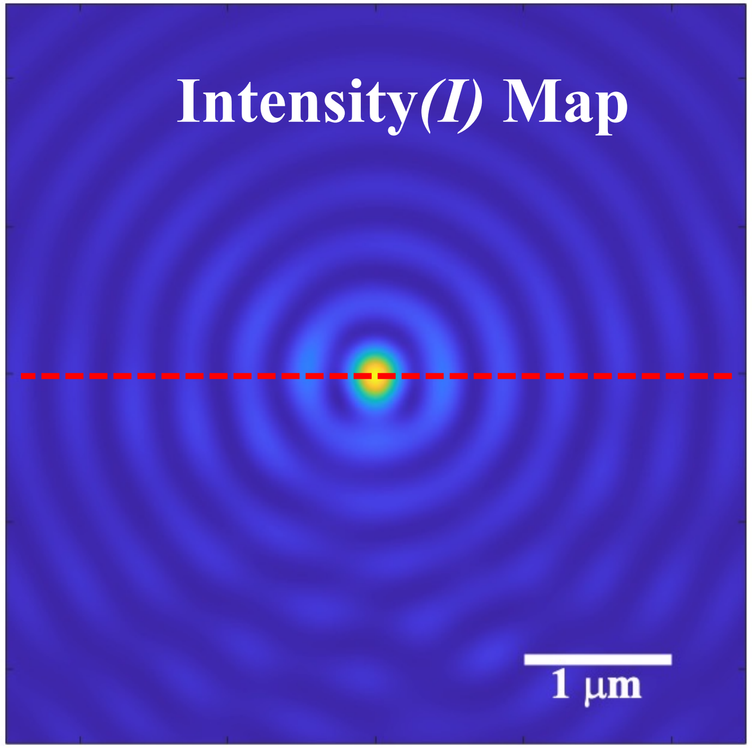
Gold Nanotip

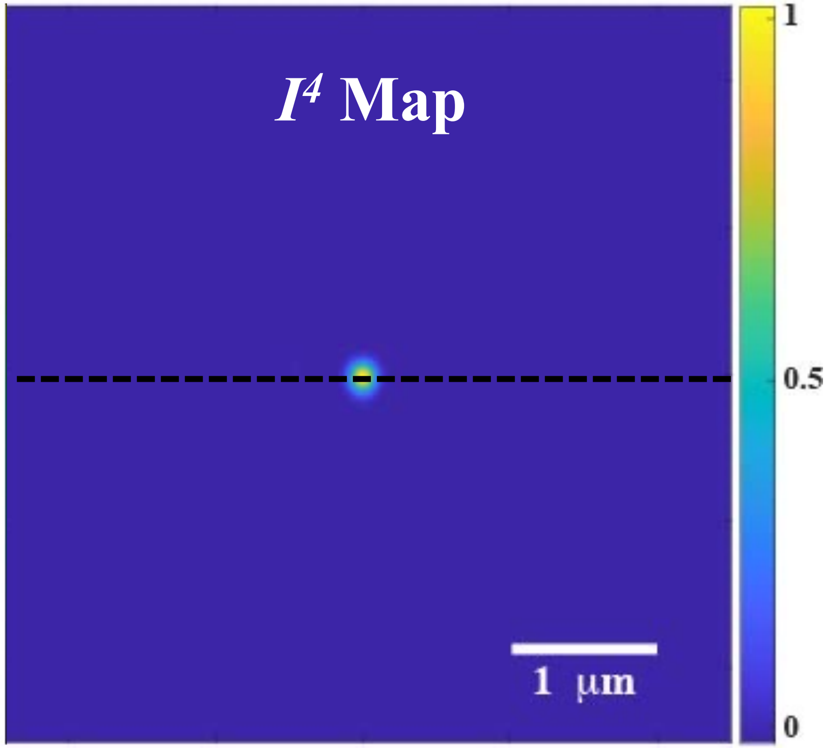


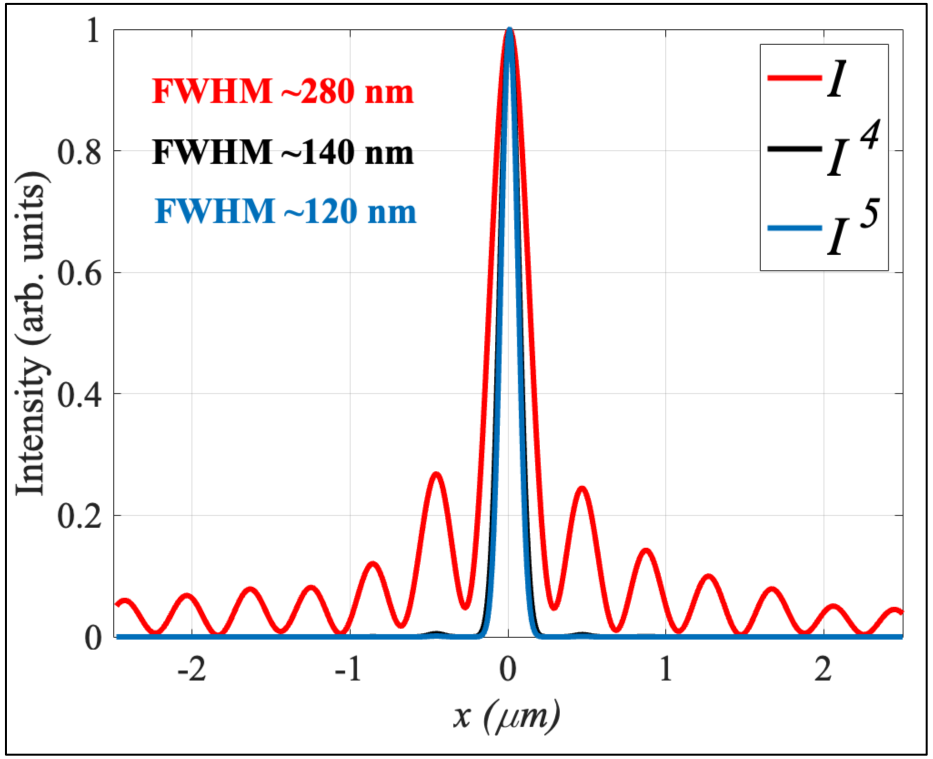
Gold Spiral



Plasmonic Spiral Photocathode: FDTD Simulation







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

Fowler Dubridge:
$J_n \; \alpha \; I^n$

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

Non-Linear Photoemission: electron source size ~140 nm

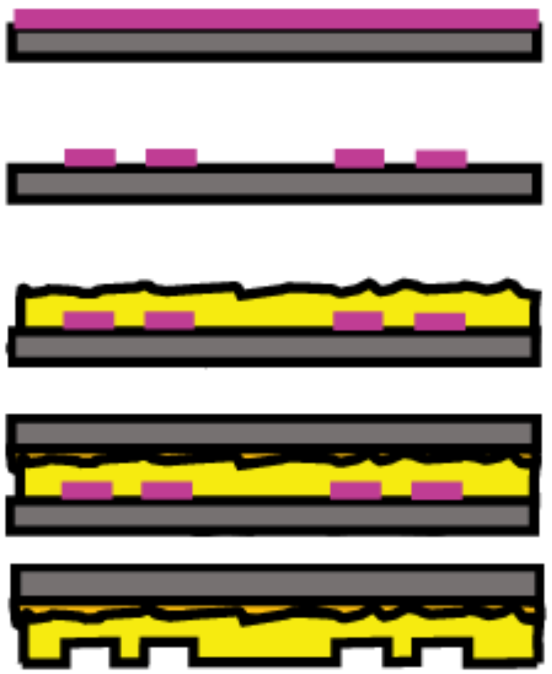
Physical review letters 104.8 (2010): 084801.

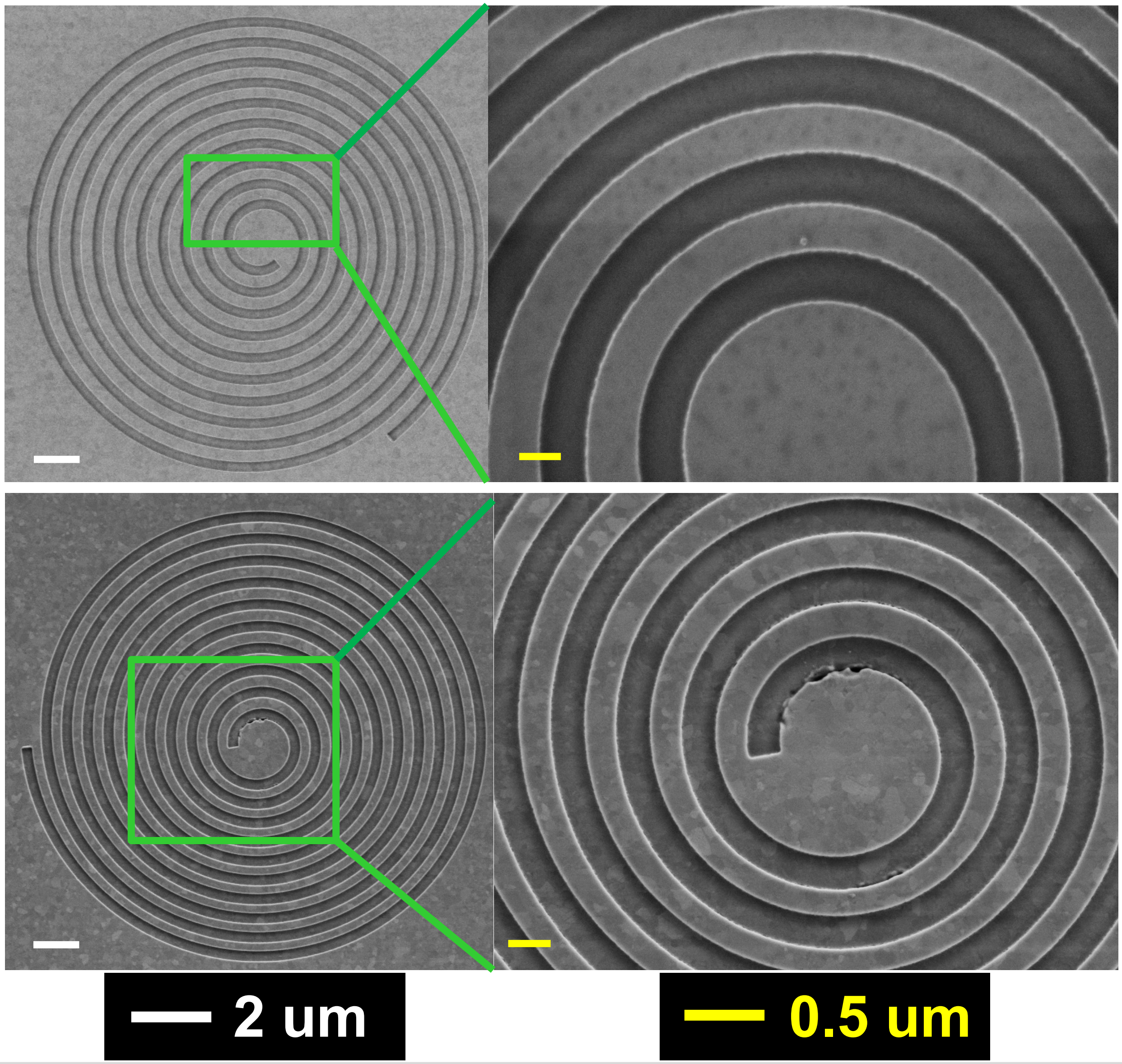
Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 601.1-2 (2009): 123-131.

Past Attempts: Fabrication

Template Stripping Method

1. Spin coat resist
2. Expose, develop
3. Evaporate gold
4. Apply epoxy
5. Peel off



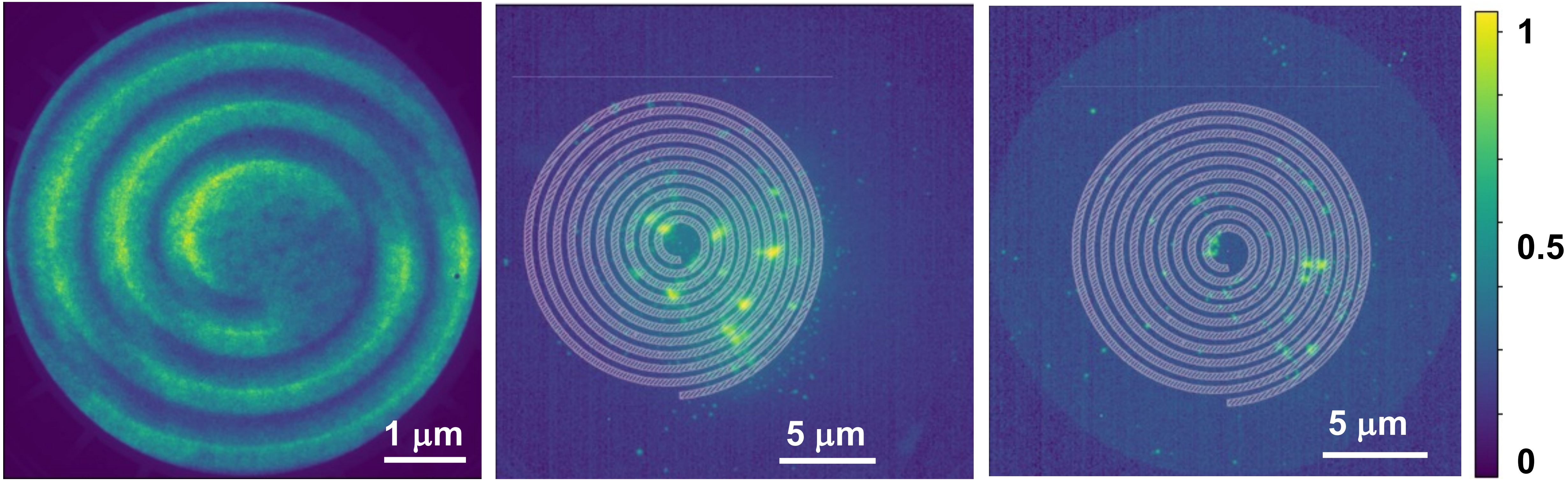


Physical Review Applied 12.5 (2019): 054057.

akachwal@asu.edu

Past Attempts: PEEM Images

PEEM Hg Lamp | **Before LASER cleaning** | **After LASER cleaning**

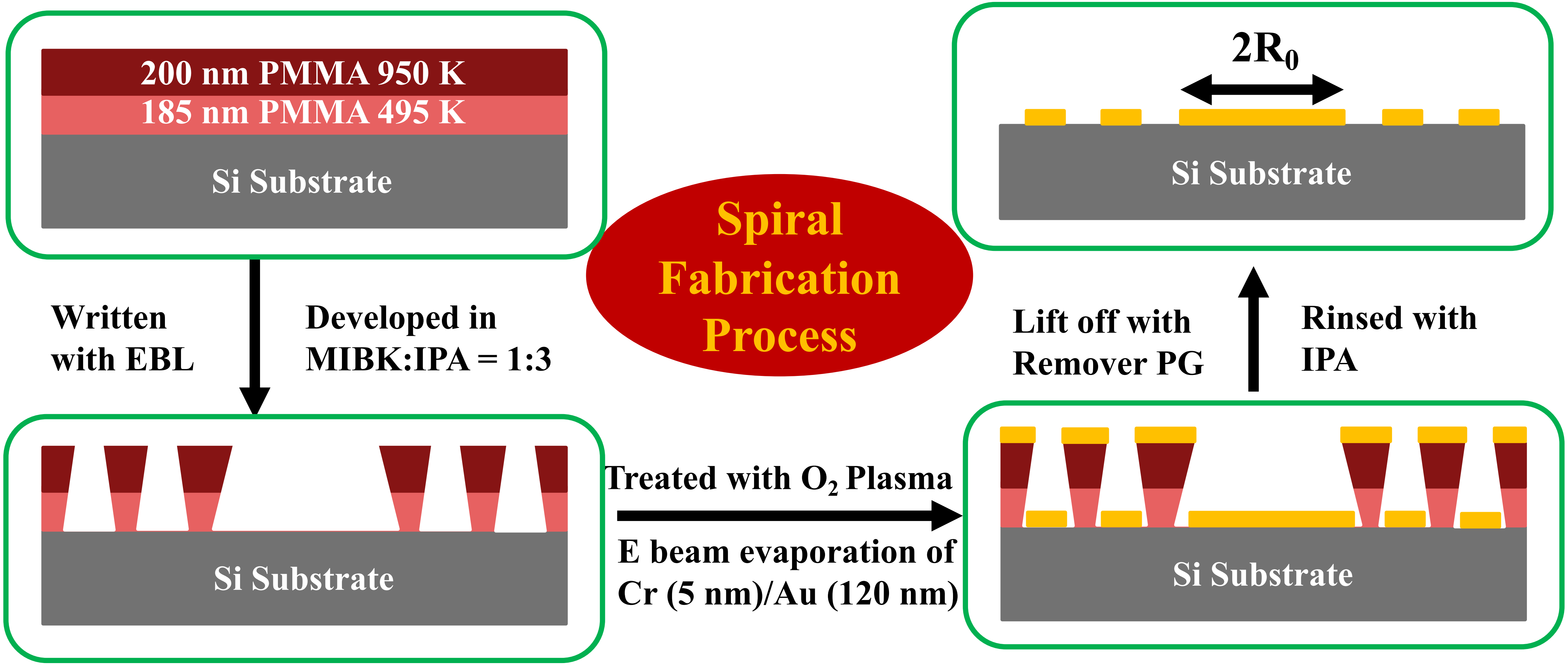


LASER “cleaning” for 15 hours reduces hot spots

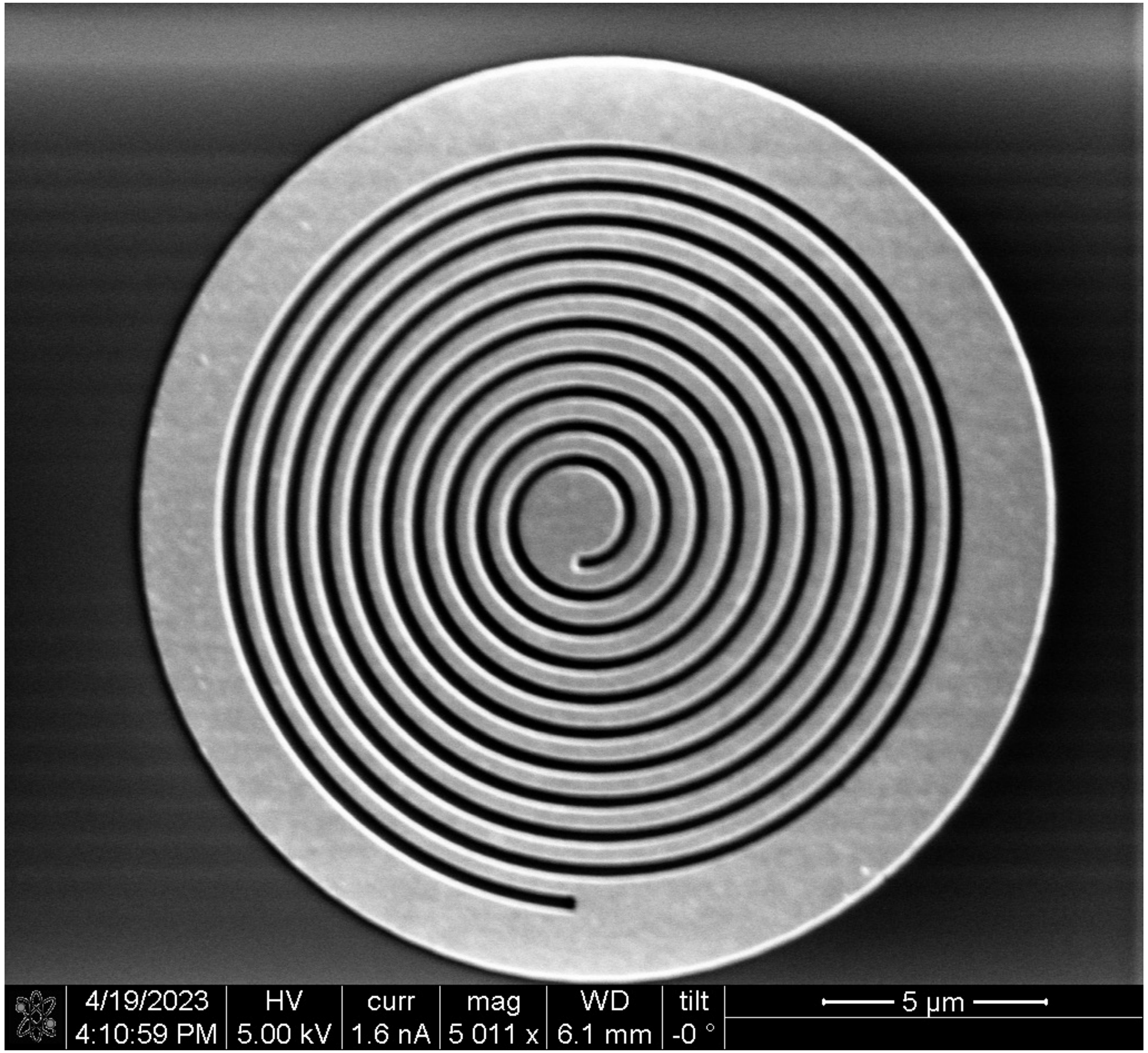
No Emission Spot at the Center

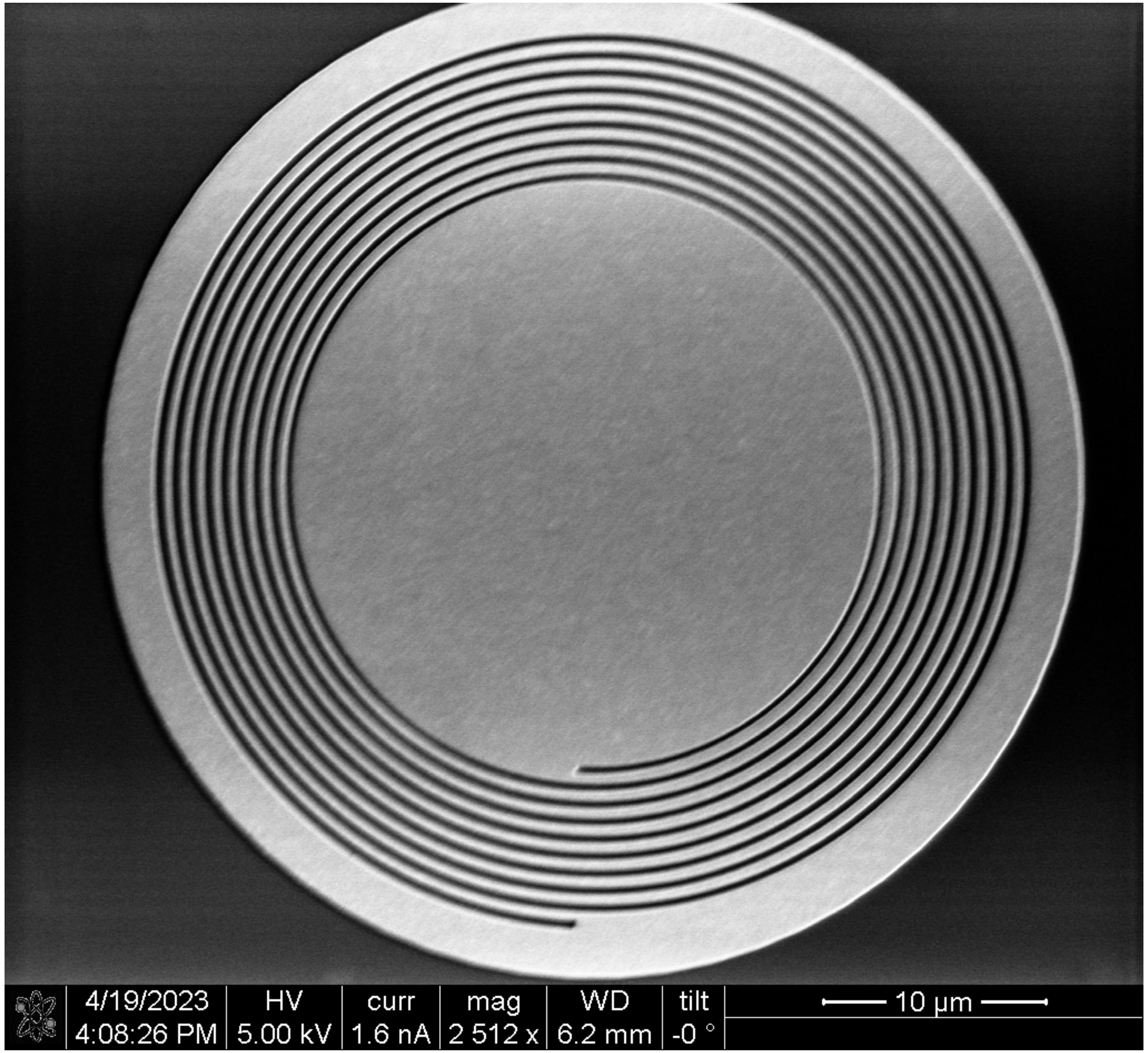
- Change Fabrication Method
- Large Start Radius

New Fabrication Technique

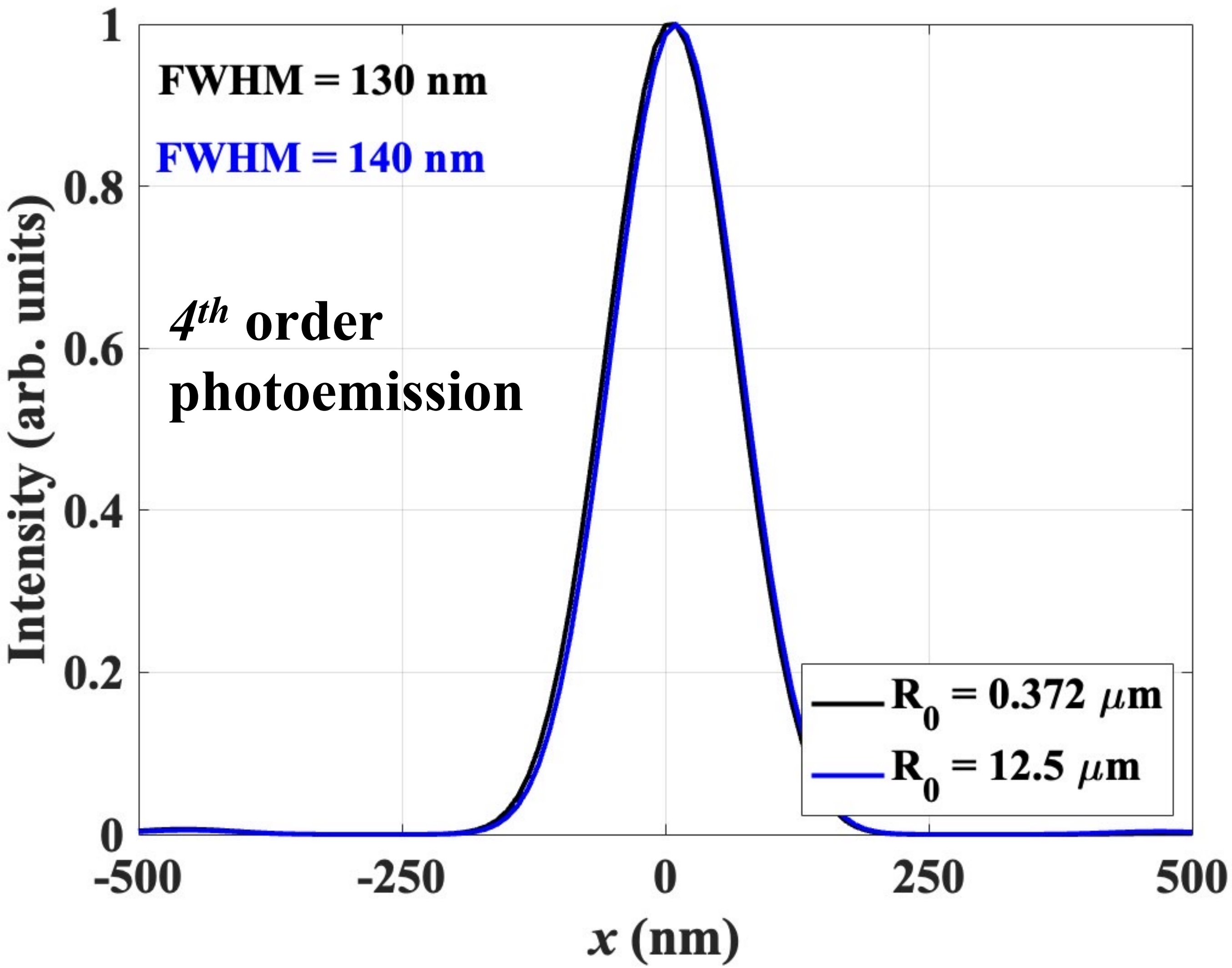


New Fabrication: SEM Images





FDTD Simulation



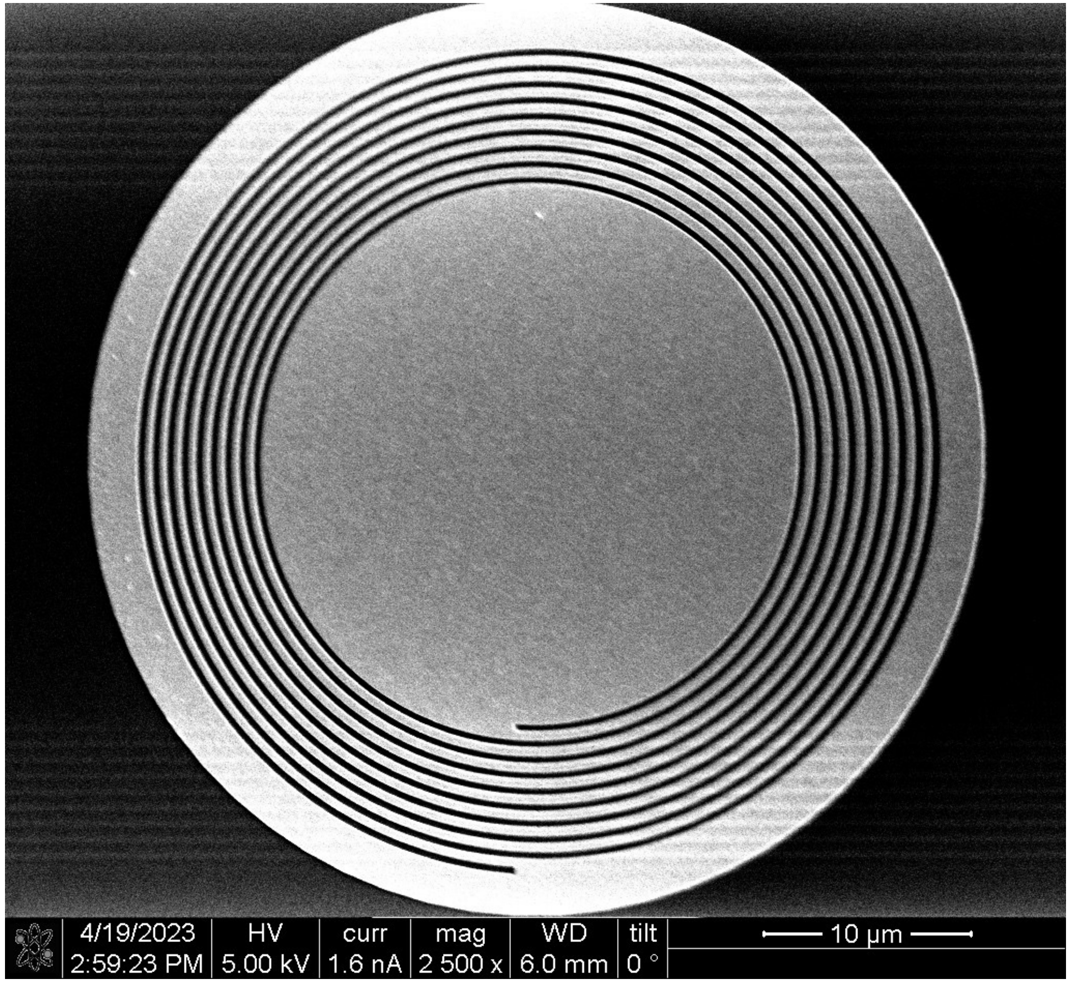
For constructive interference at the center of the spiral,

$$p = \lambda_{spp}$$

Where p = pitch of the spiral

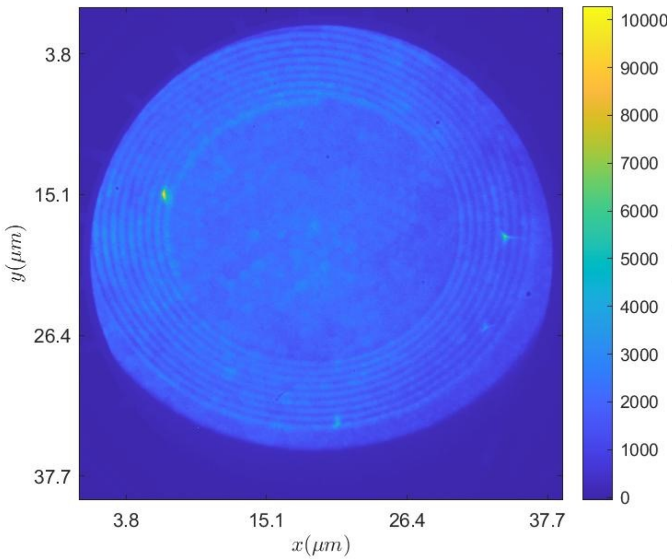
Hence, interference at the center of the spiral is totally independent on the starting radius

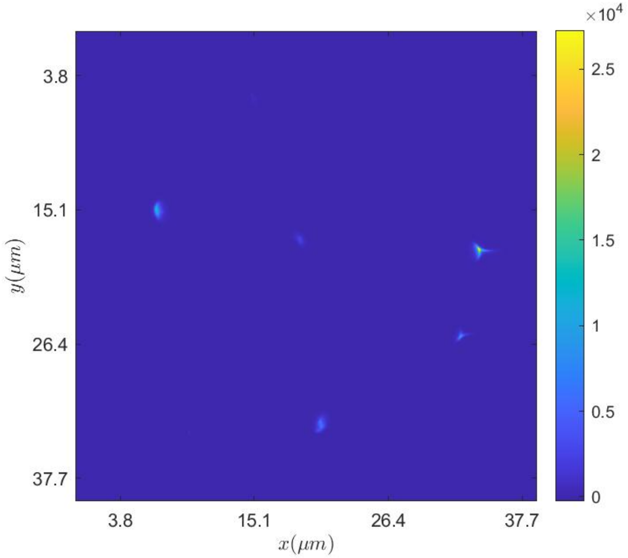
Spiral Photocathode: Study & Characterization



SEM

LASER cleaning of Hot-Spots





LASER Parameters

λ = 800 nm; Pulse Length = 150 fs; Rep. Rate = 500 kHz

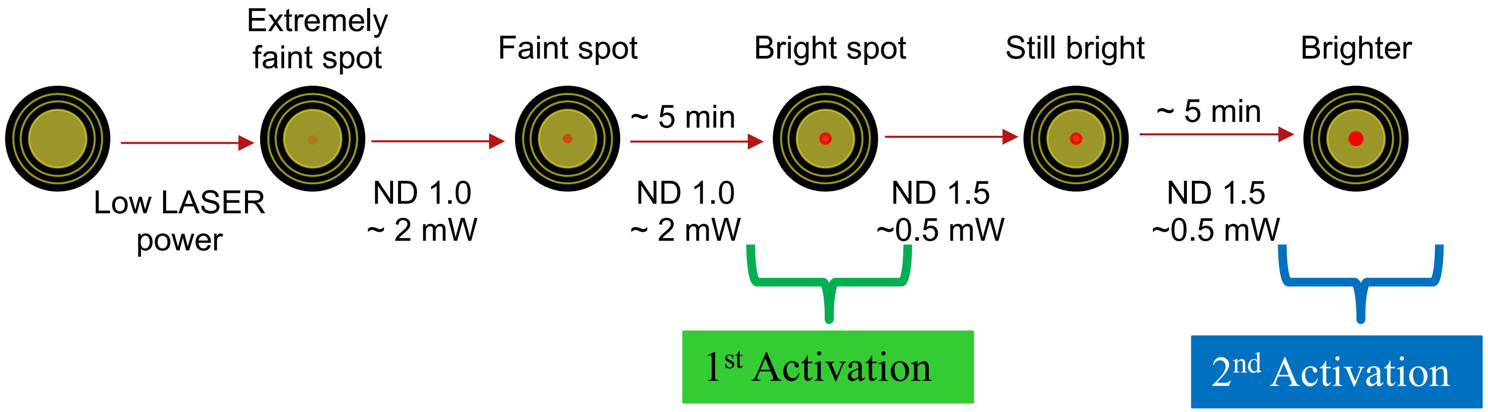
- Overnight exposure of Average Power = 0.5 mW
- Hot Spots disappeared after overnight exposure (Spiral Cleaned)

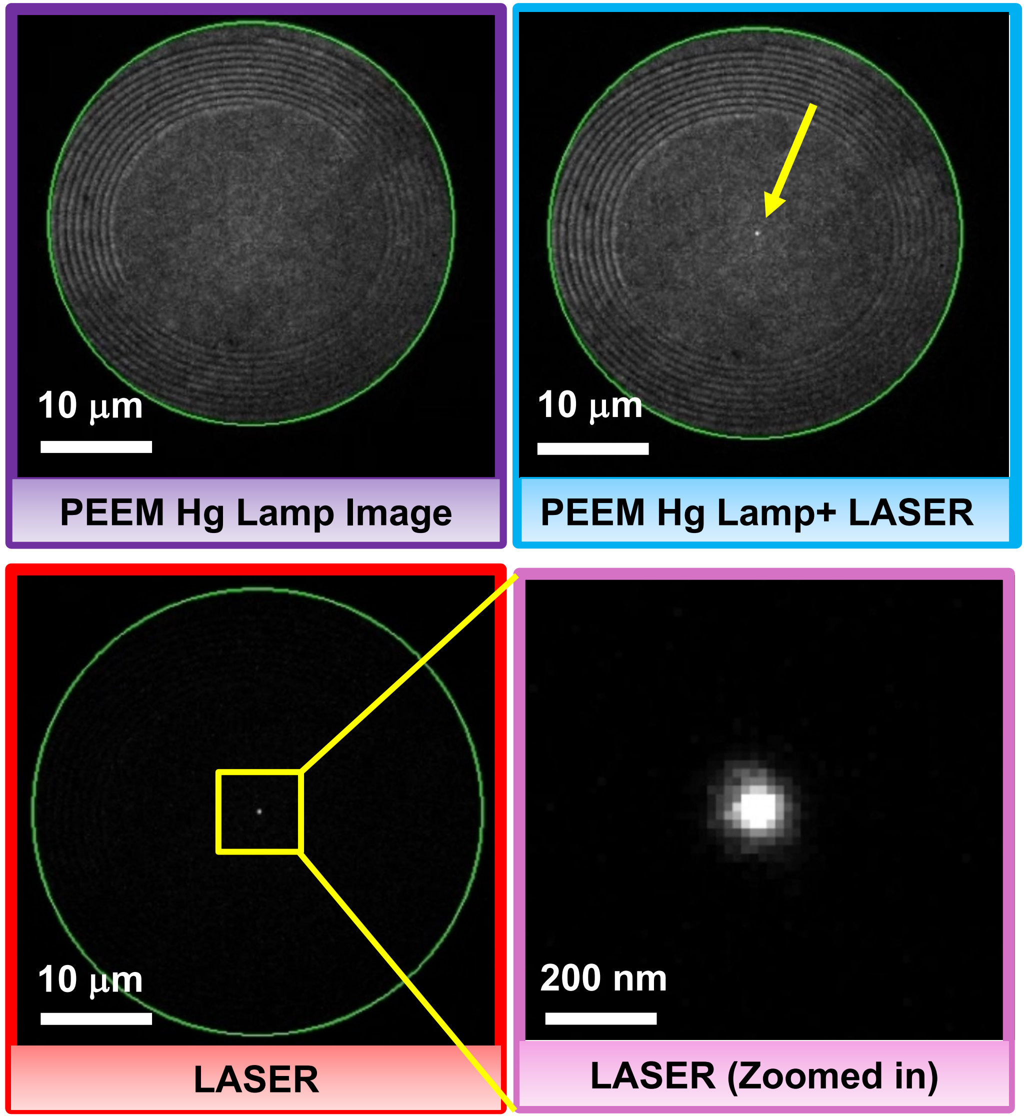
Spiral Photocathode: Study & Characterization

LASER Parameters

λ = 800 nm; Pulse Length = 150 fs Rep. Rate = 500 kHz

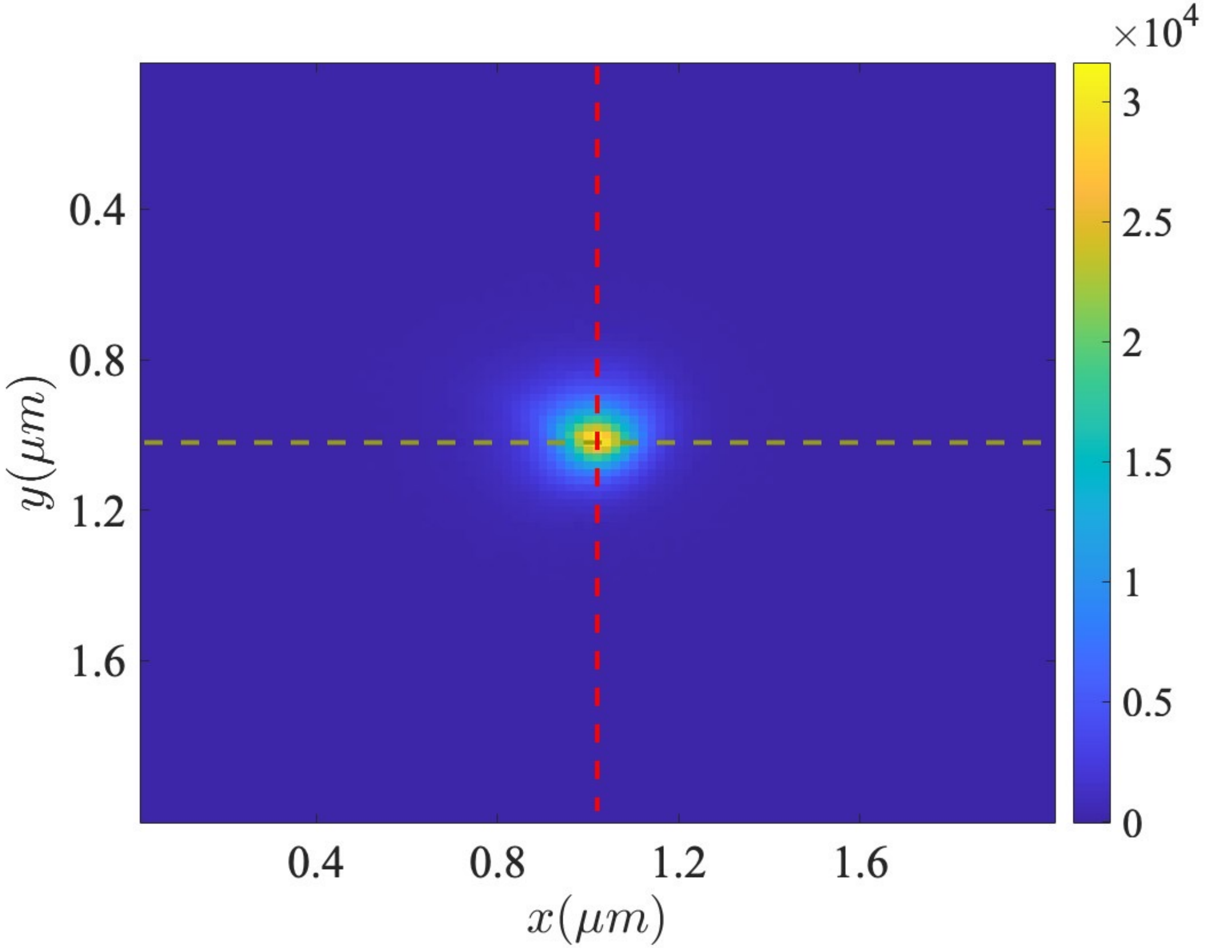
Photoemission Measurement: Spiral Activation

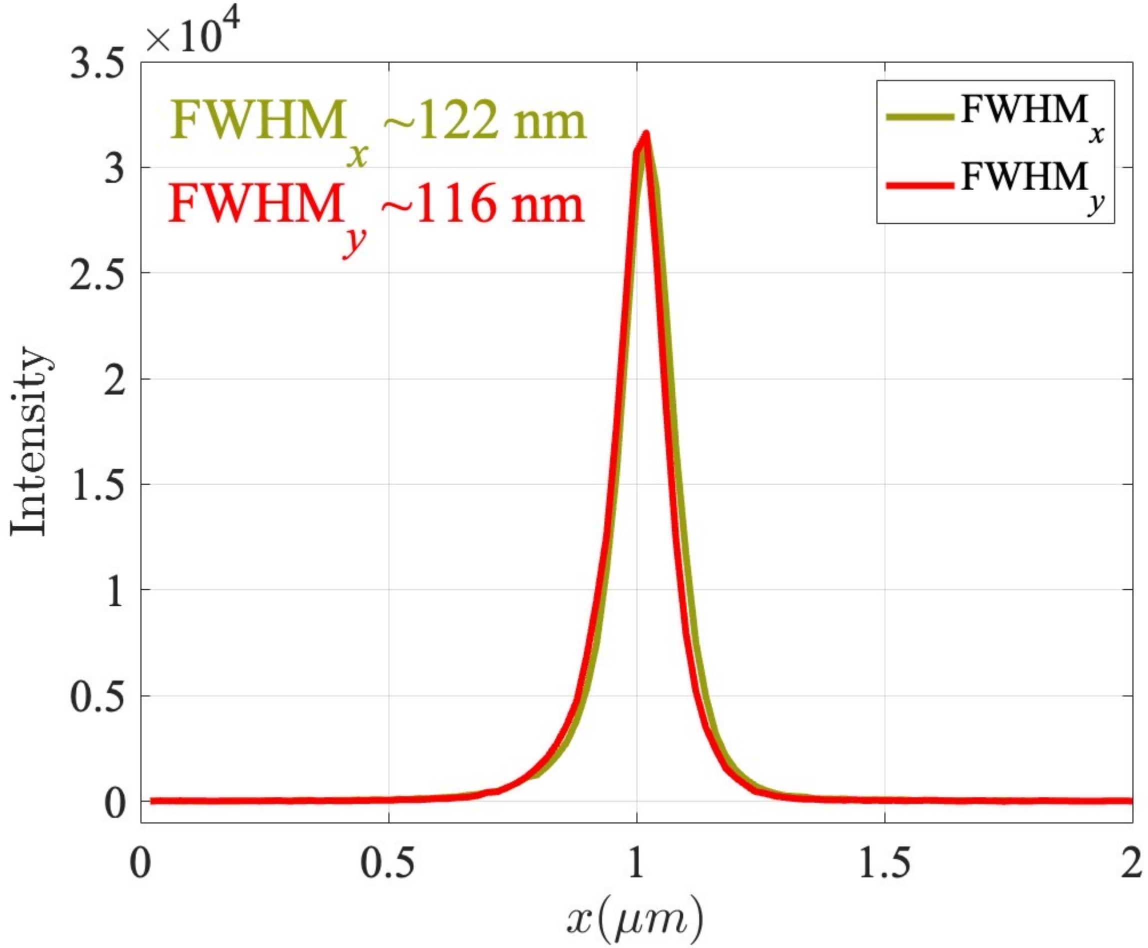




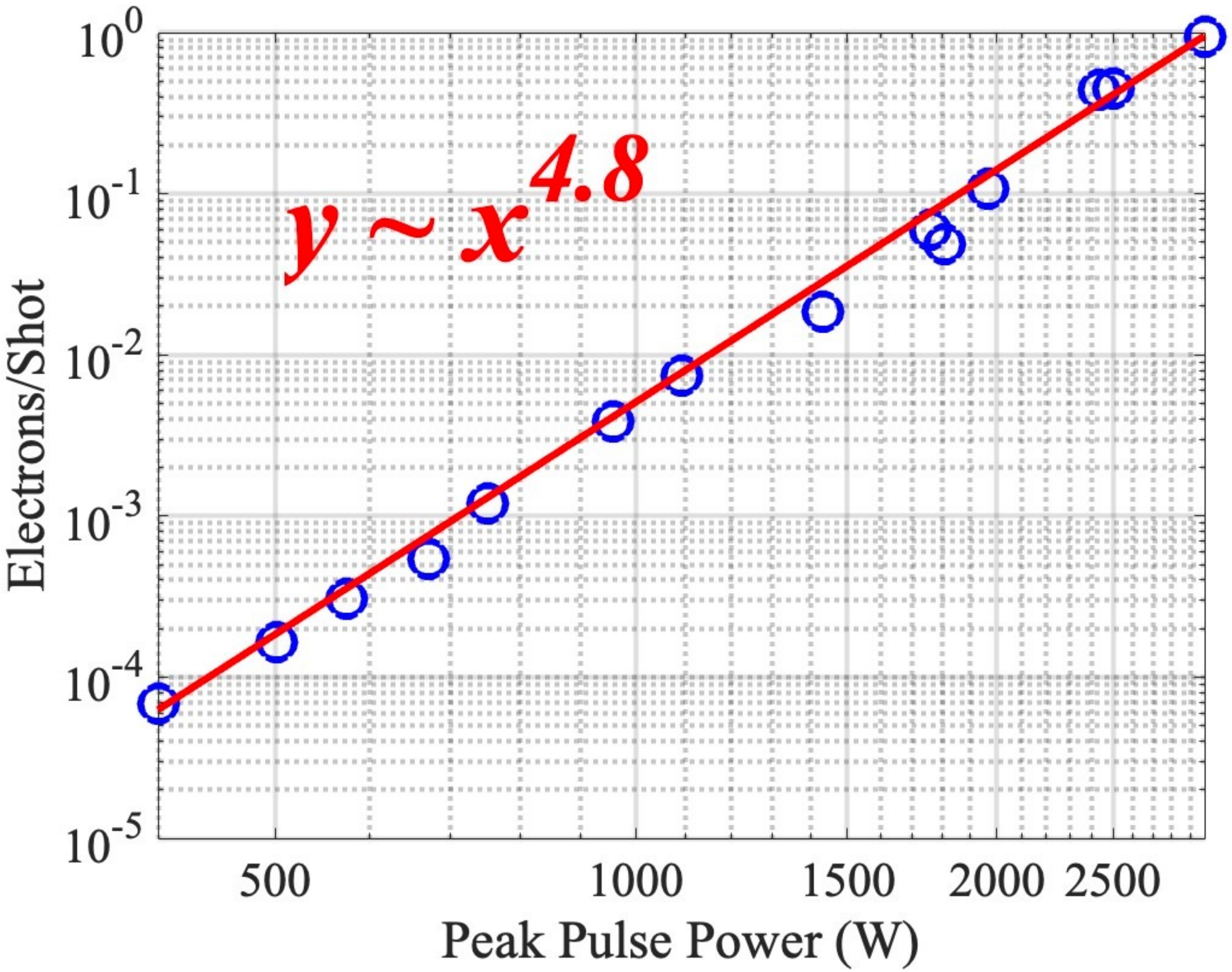
Spiral Photocathode: Study & Characterization

Electron Emission spot; Average incident LASER power = 136 μW



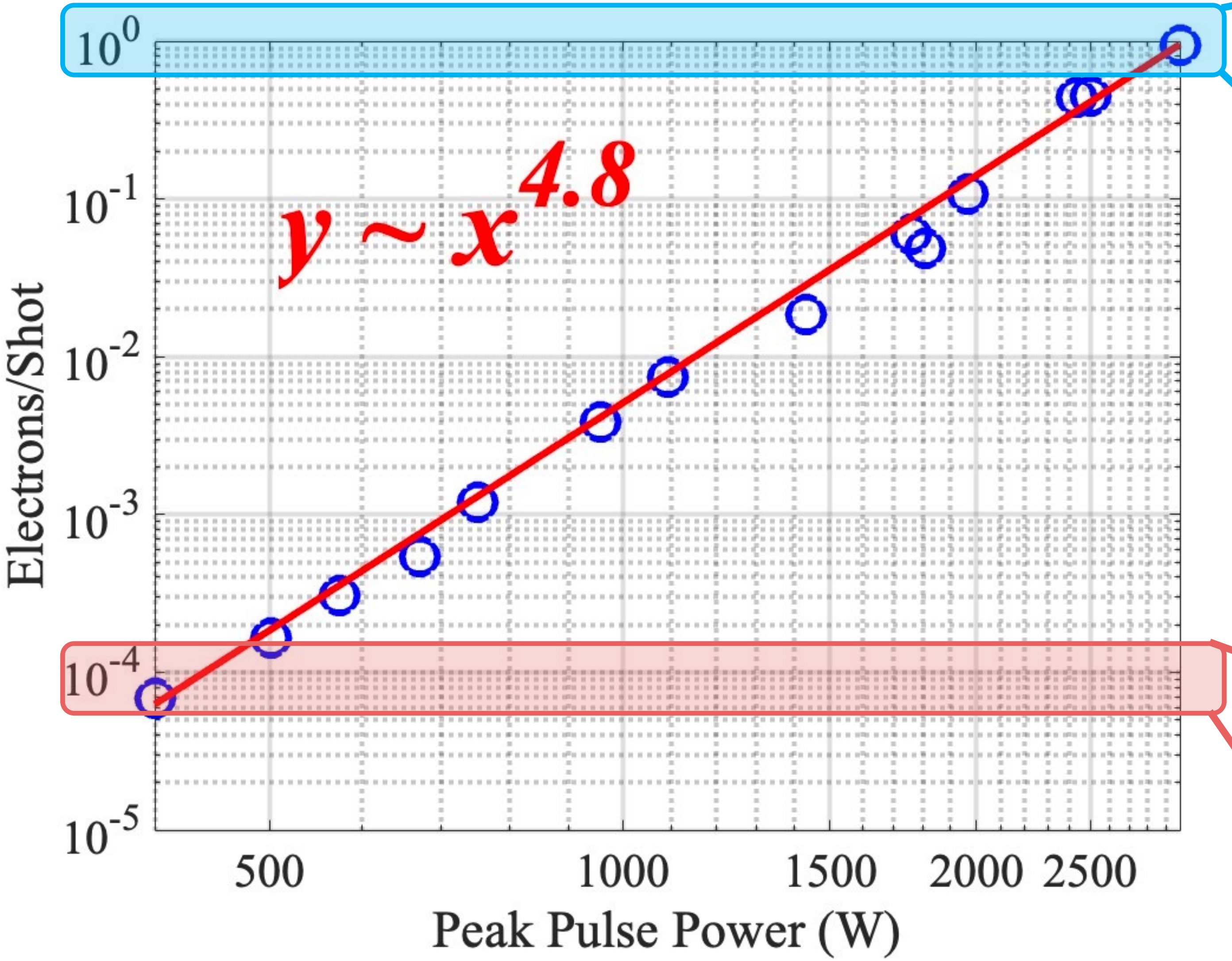


Spiral Photocathode: Order of Emission



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

Spiral Photocathode: Order of Emission

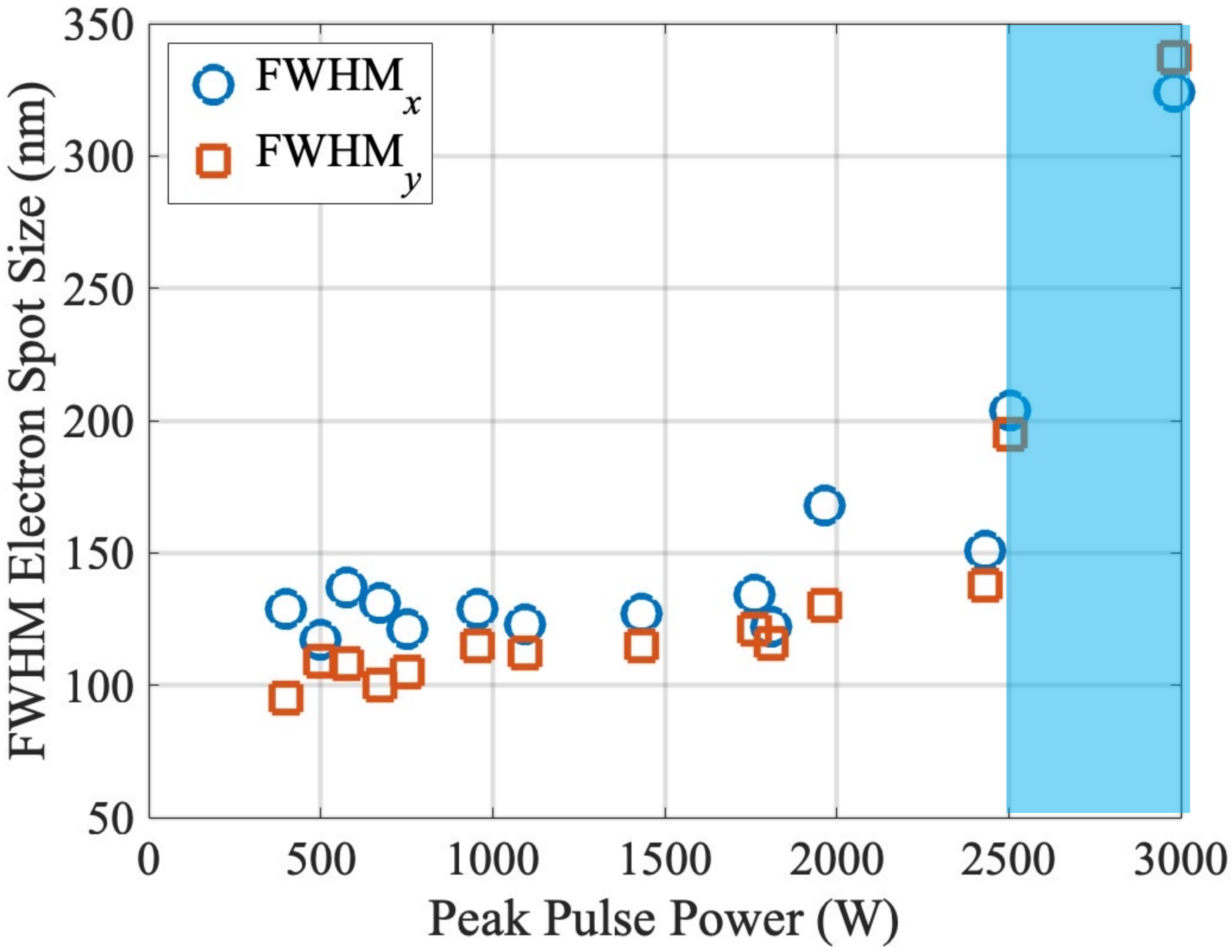


1 electron/shot

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

10^{-4} electrons/shot

Spiral Photocathode: Spot Size



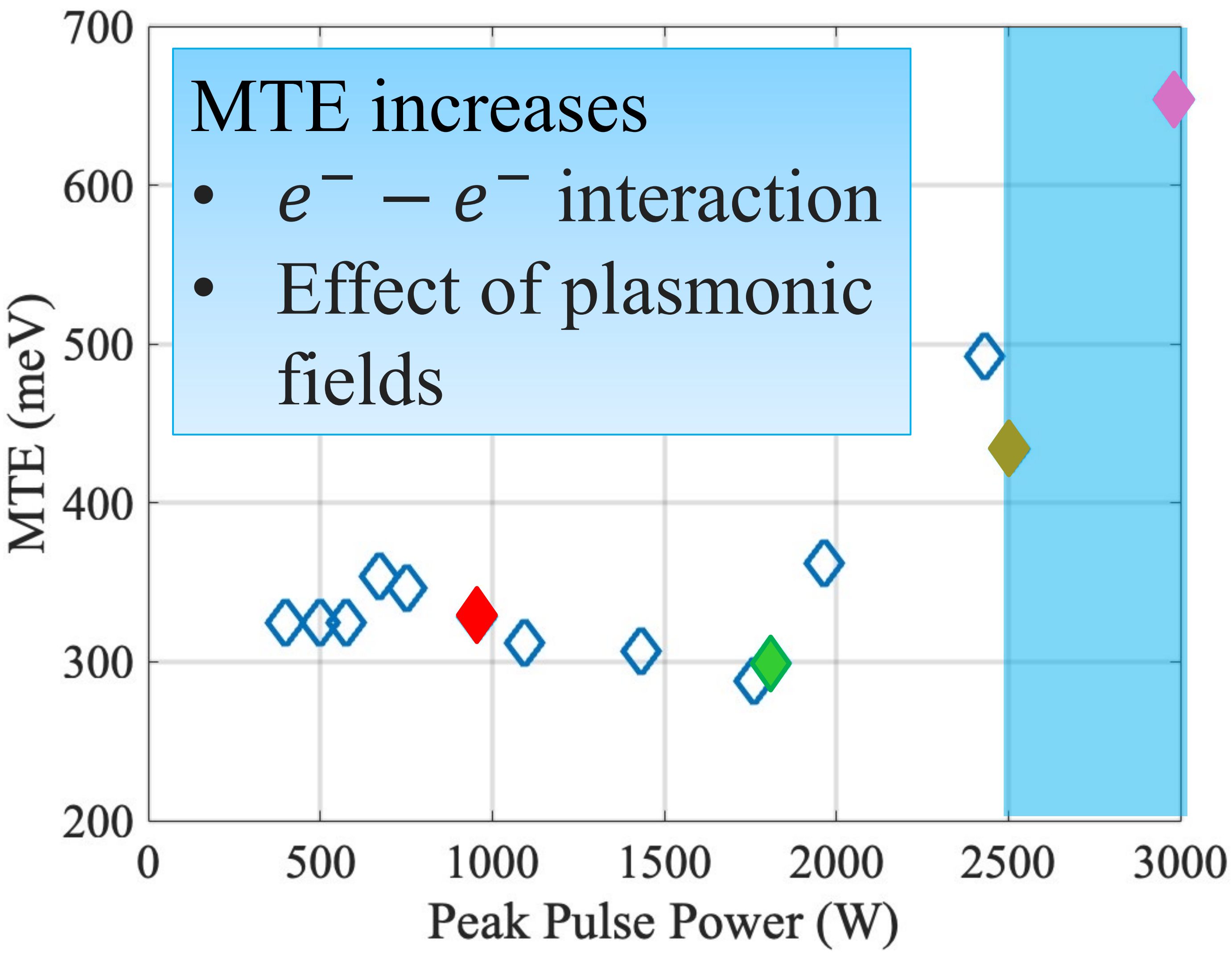
~120 nm electron emission spot size over wide range of LASER power

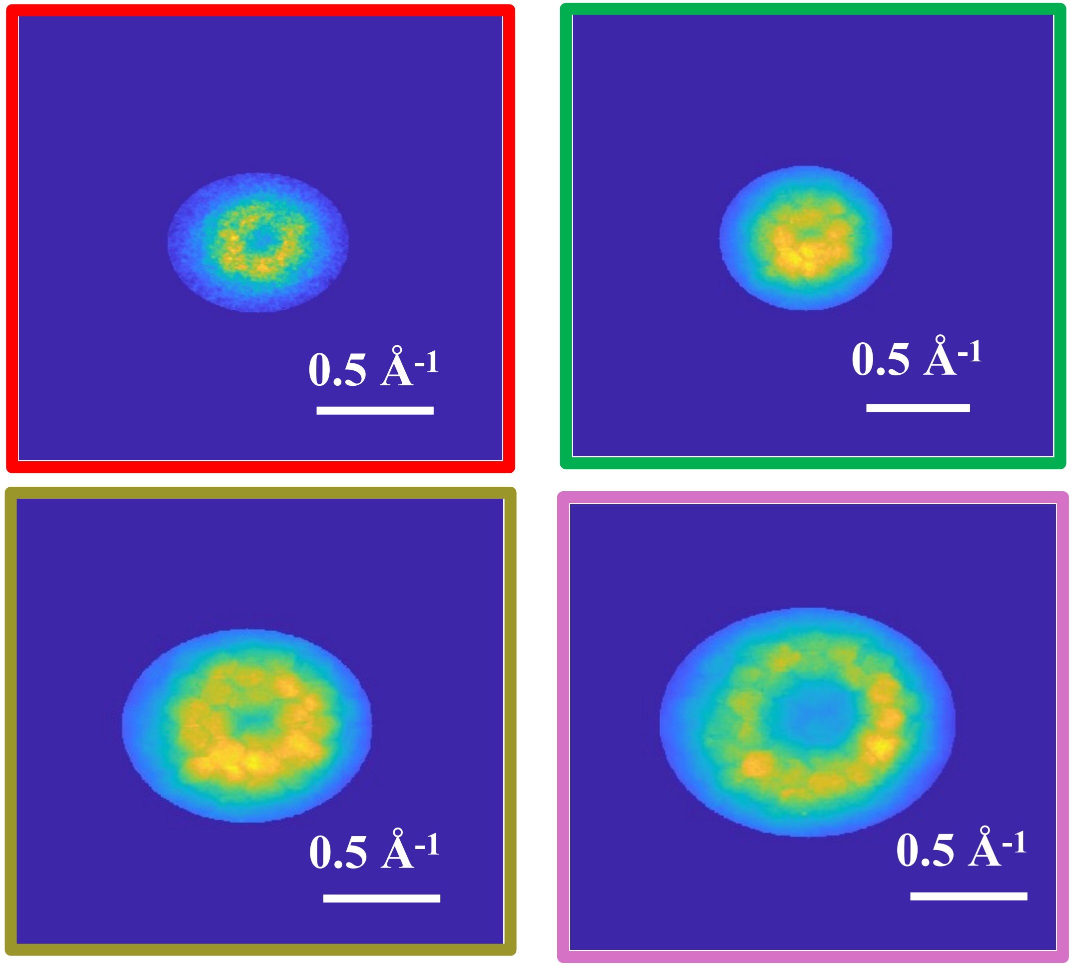
Spot size increases

- $e^- - e^-$ interaction
- Effect of plasmonic fields

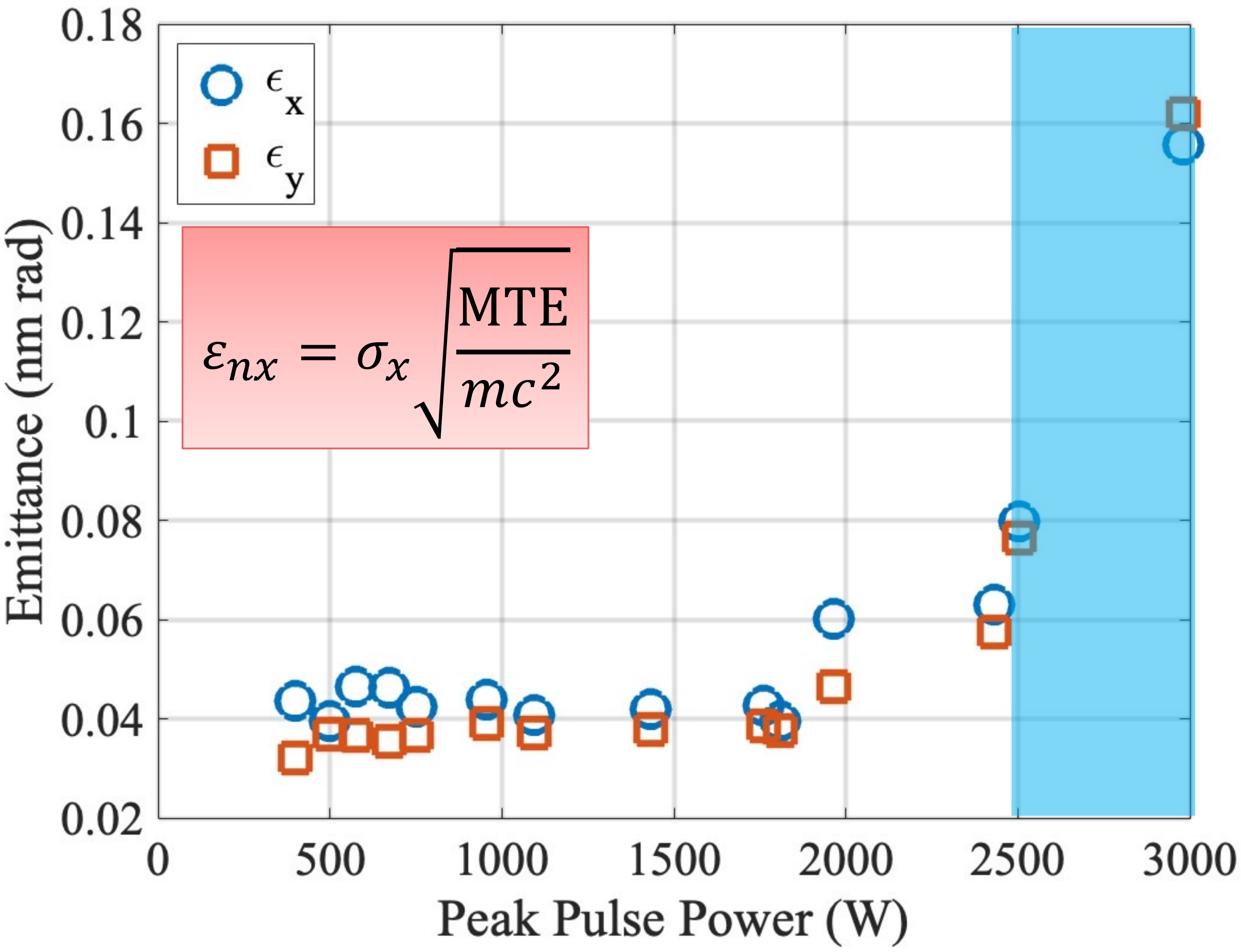
Spiral Photocathode: MTE

MTE increases
- $e^- - e^-$ interaction
- Effect of plasmonic fields





Spiral Photocathode: Emittance



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

Record $\boldsymbol{\varepsilon_n}$ **~30 pm rad** achieved from a flat metal photocathode without the use of any pinholes

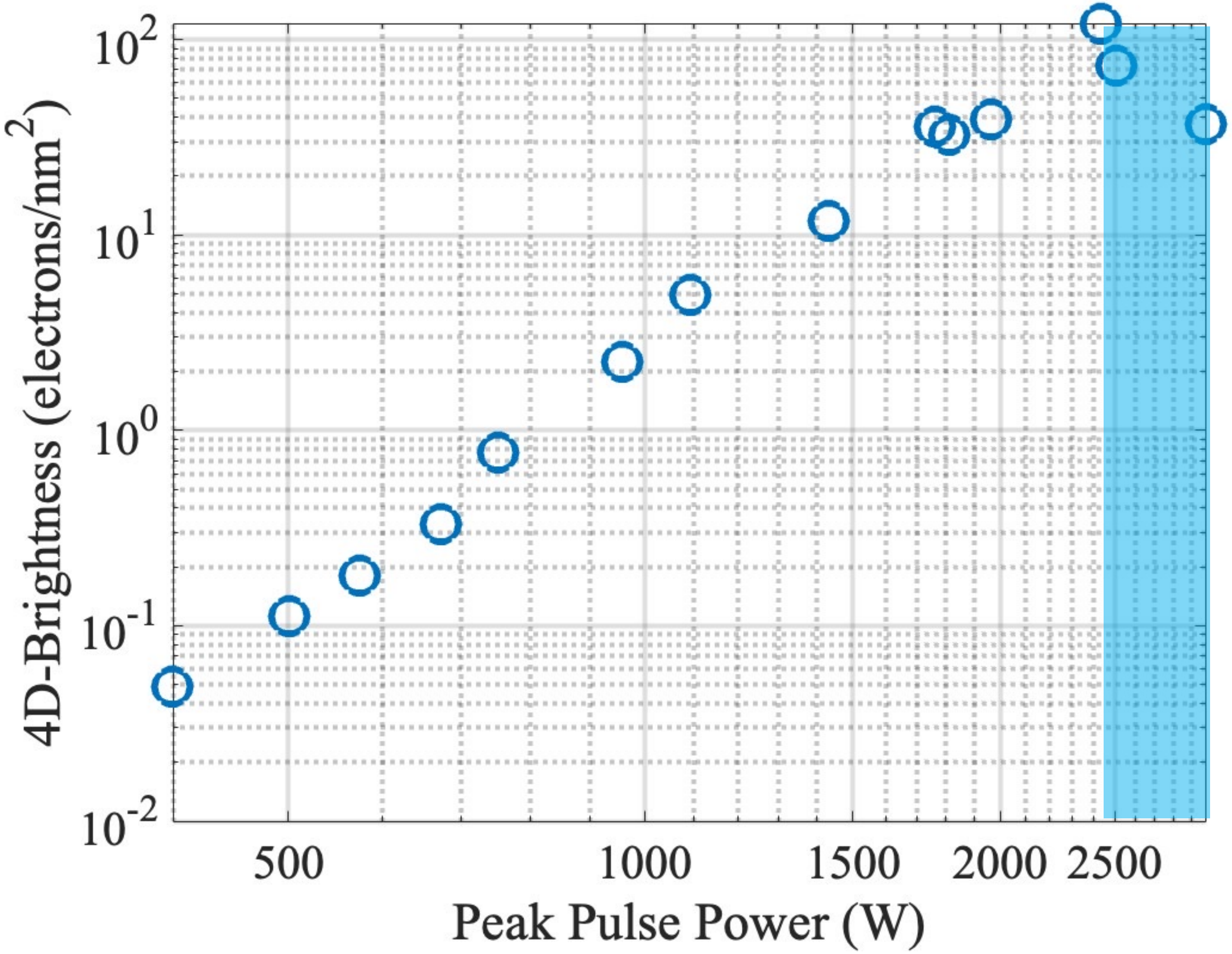
- 2 pm rad from ZrO/W emitter tip in an Electron Microscope [*Ultramicroscopy* 176 (2017): 63-73]
- 700 pm rad from flat cathode in a photoinjector after the pinhole [*Structural Dynamics* 9.2 (2022)]

ε_n increases

- $e^- - e^-$ interaction
- Effect of plasmonic fields

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

Spiral Photocathode: 4D-Brightness



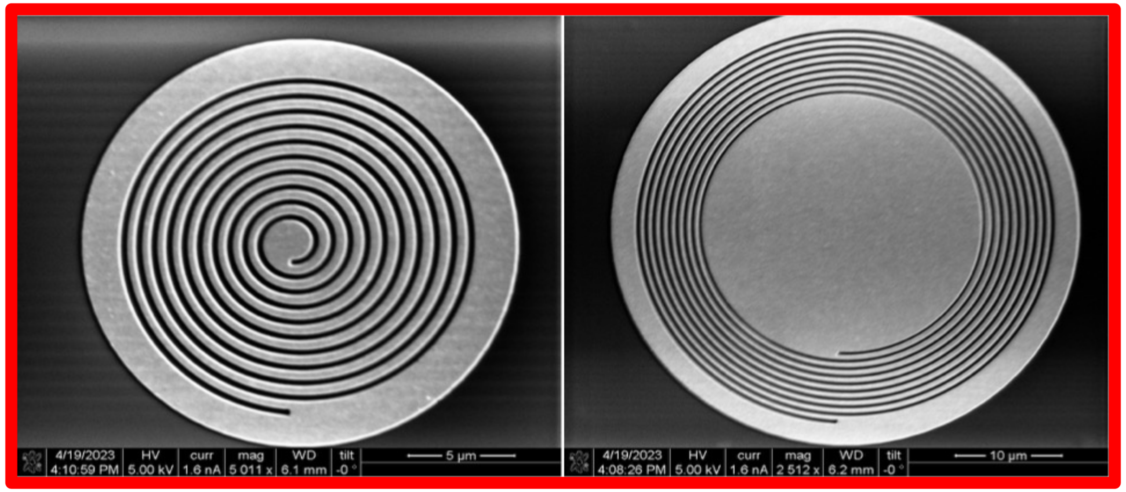
Maximum 4-D Brightness achieved: 120 electrons/nm^2

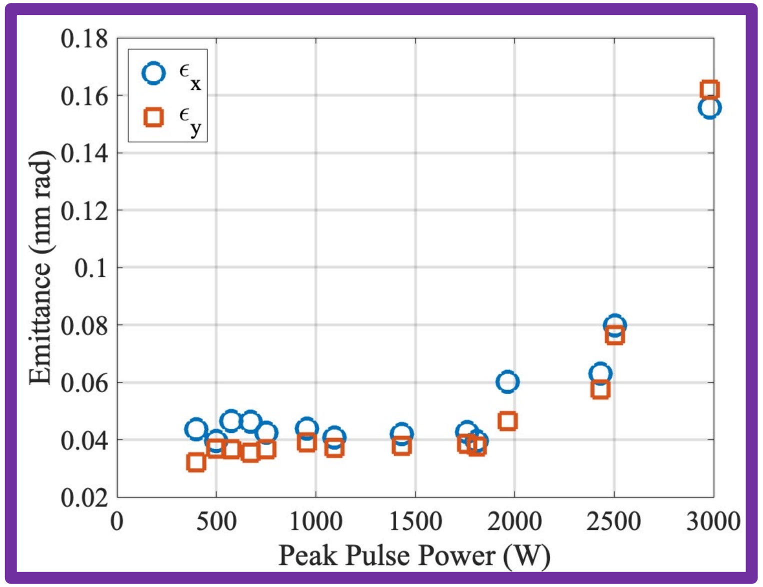
Brightness decreases
- $e^- - e^-$ interaction
- Effect of plasmonic fields

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

Conclusion

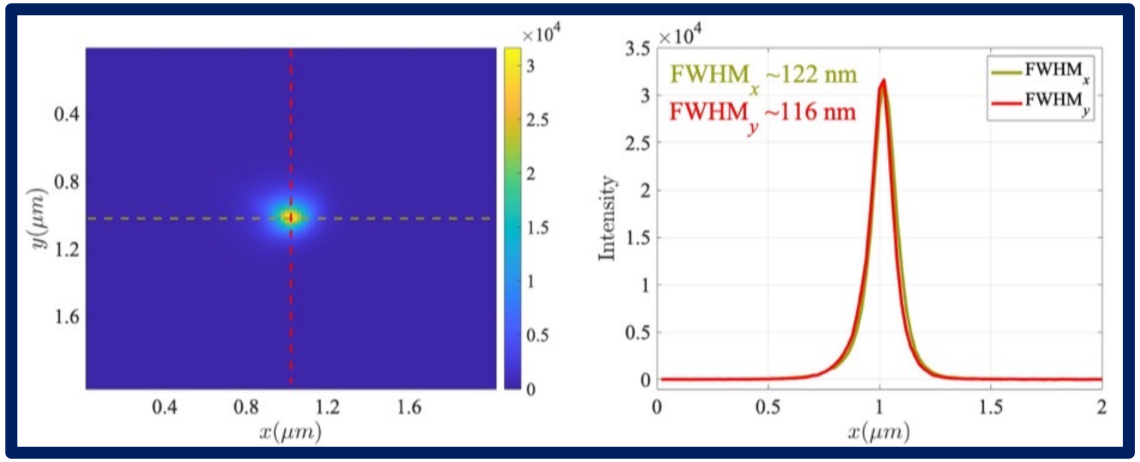
Fabrication

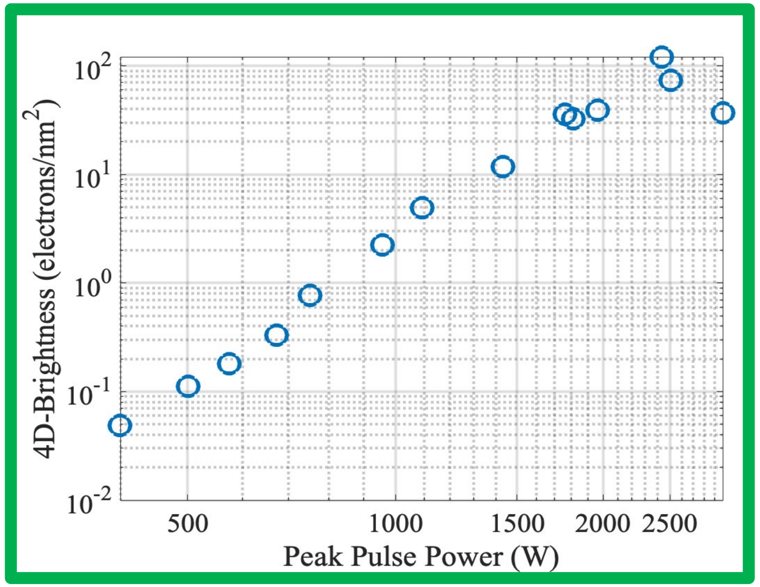




Record ε_n ~30 pm rad achieved from a flat metal photocathode

Electron Spot Size ~120 nm





Maximum 4-D Brightness achieved: 120 electrons/nm^2

B_{4D} = 120 electrons/nm^2; ε_n <60 pm rad

Future Work

- Explain the spiral activation process
- Explain the ring like structure in $k\ -space$ images
- Measure the spiral with small start radius (R_0 = 0.372 μm)
- Study dependence on wavelength (design for multiphoton emission closer to threshold)
- Integrate these spiral cathodes with high QE (low MTE) alkali antimonide films

Acknowledgement

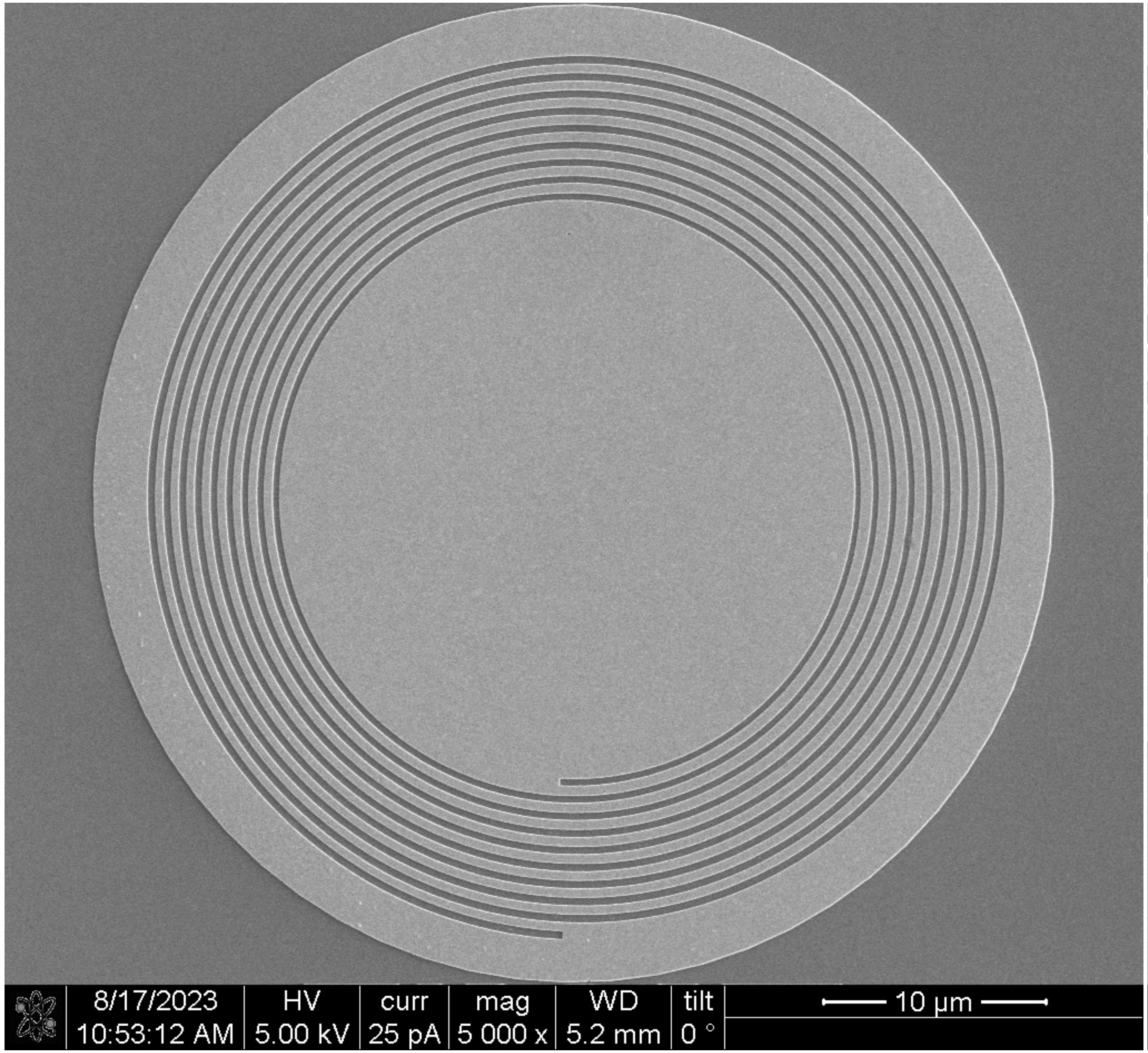
- Arizona State University
  - Mansoure Rizi
  - Siddharth Karkare (PI)
- University of Chicago
  - Christopher Pierce
- Cornell University
  - Jared Maxson
- Lawrence Berkeley National Lab
  - Daniele Filippetto

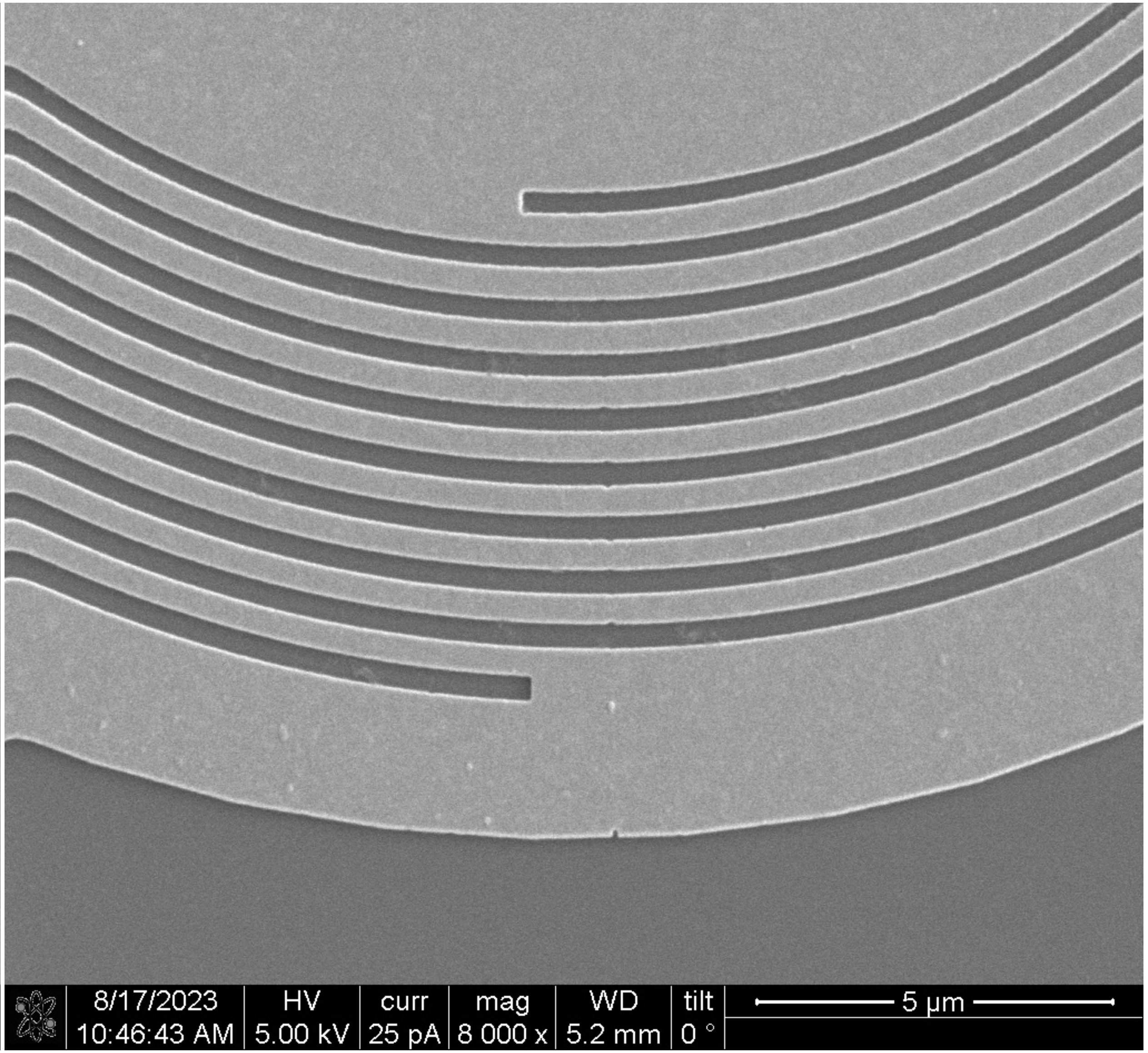
Thank You!

Questions? Comments?

Back Up Slides

SEM Images: After LASER Exposure





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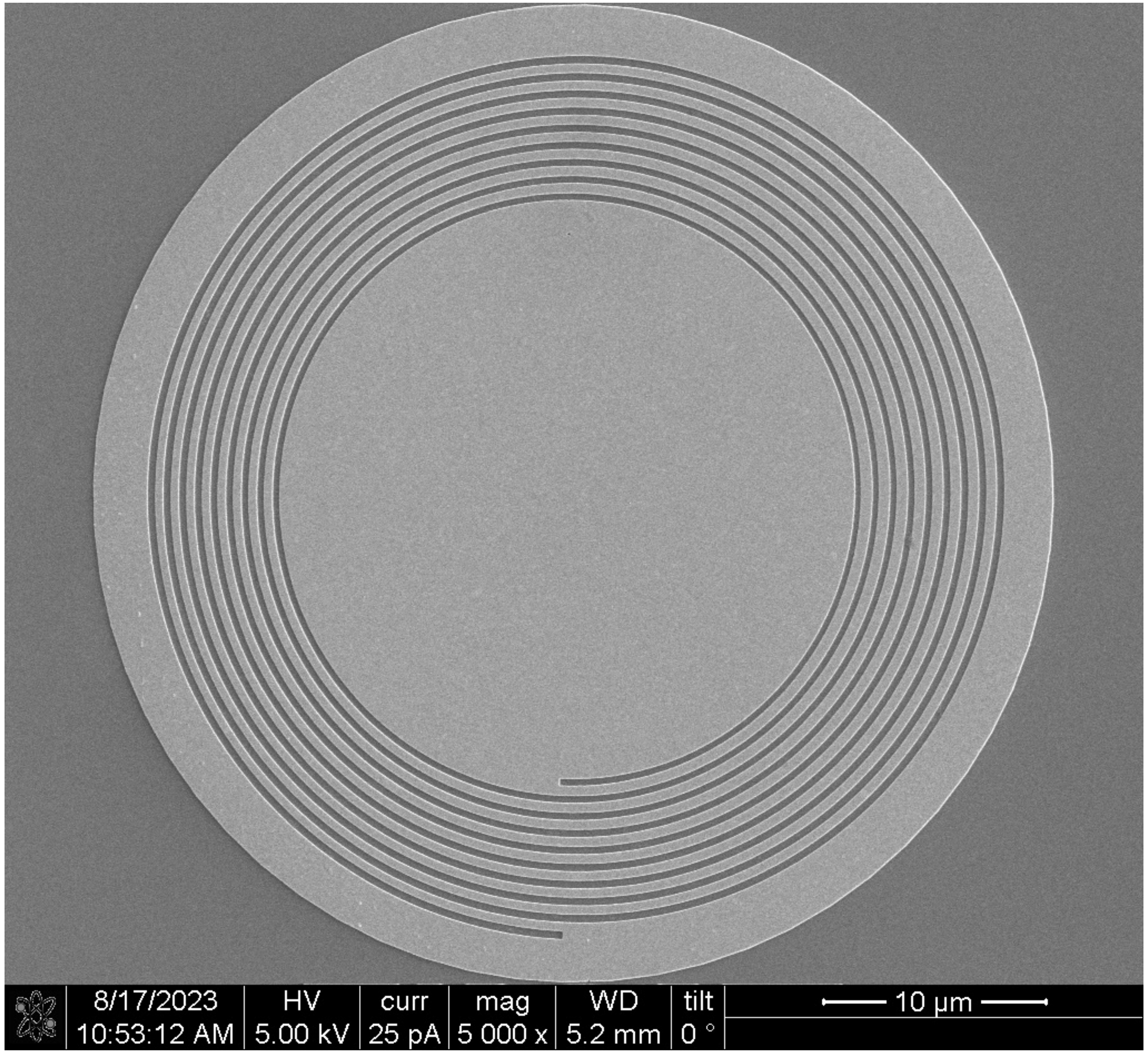

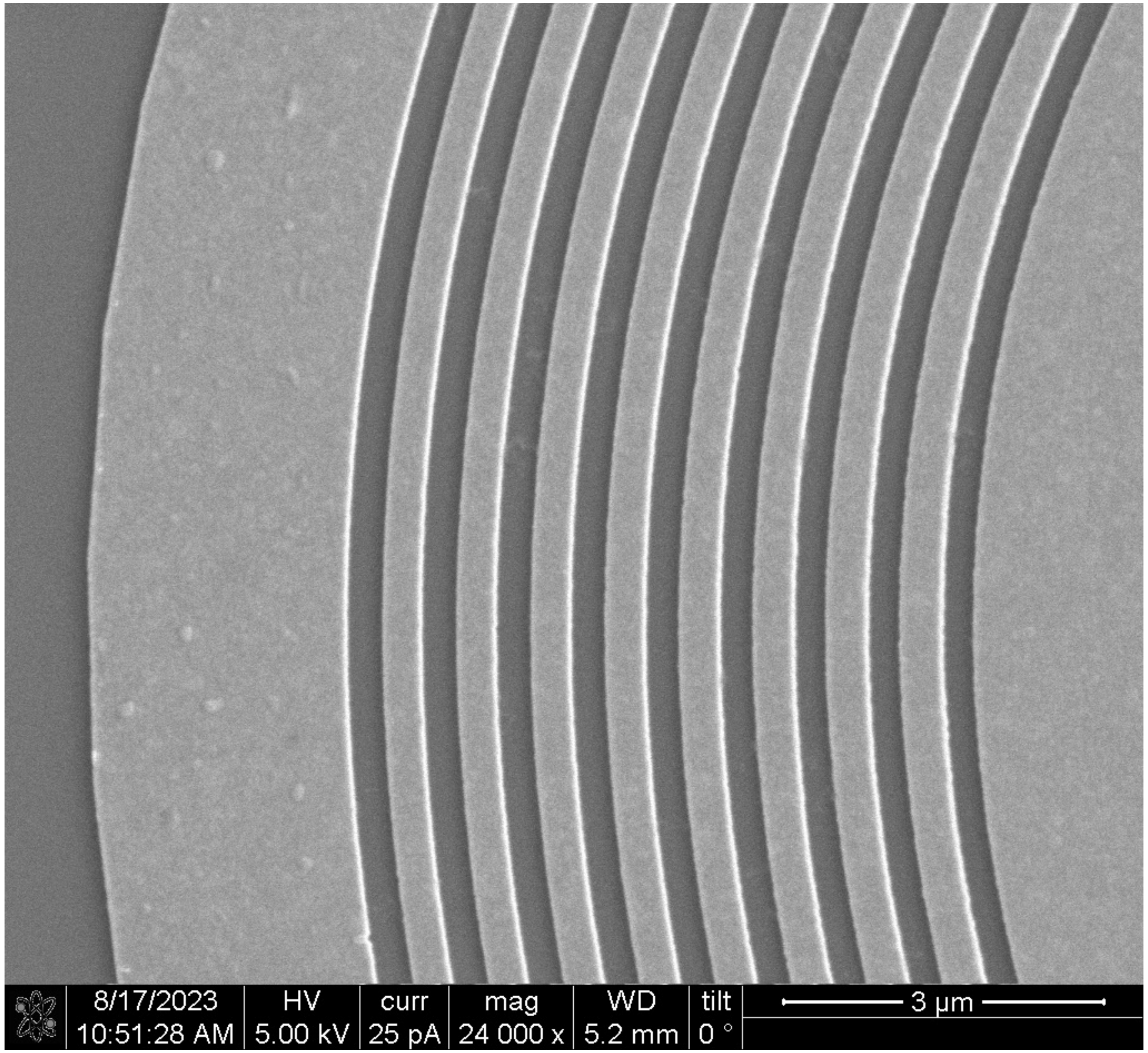

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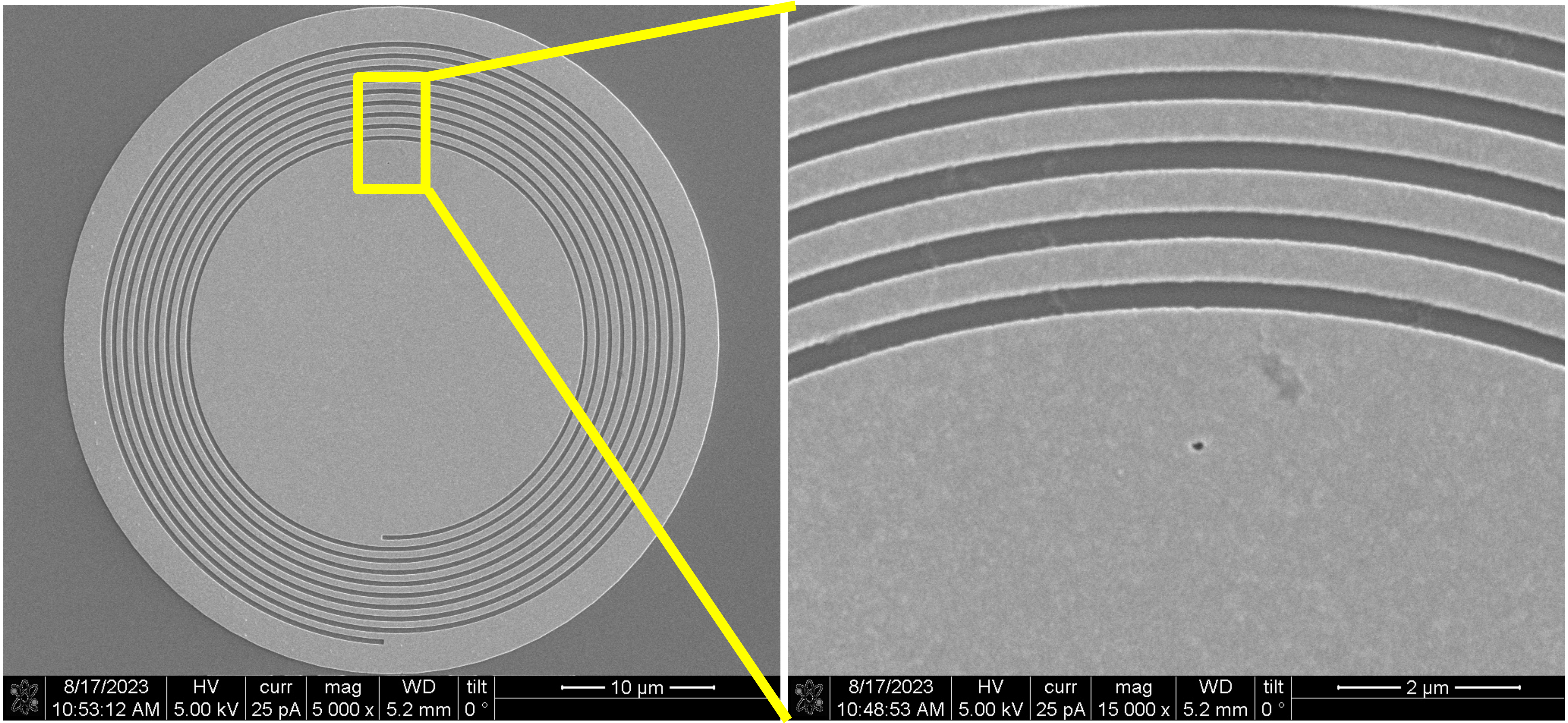

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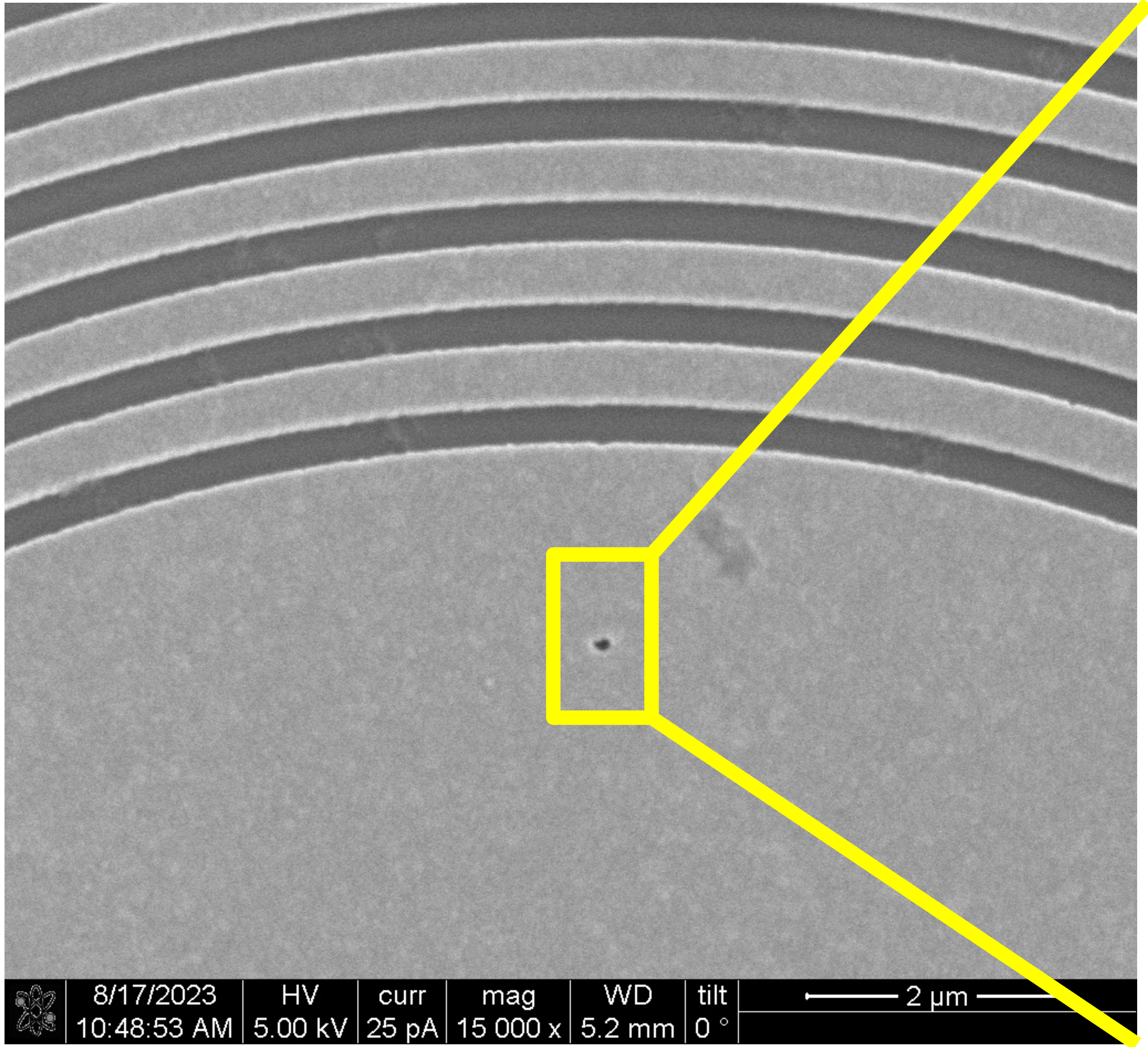
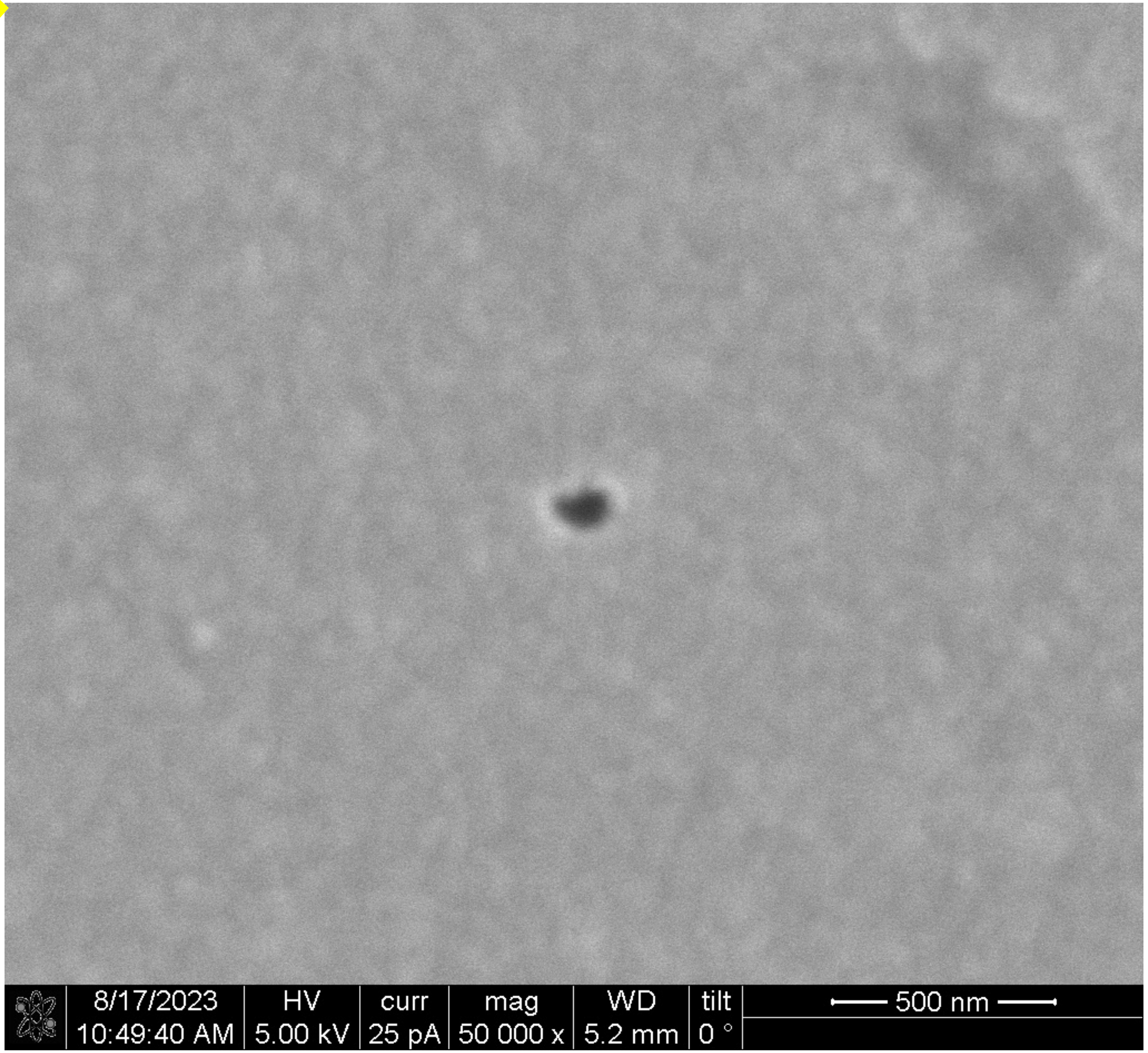
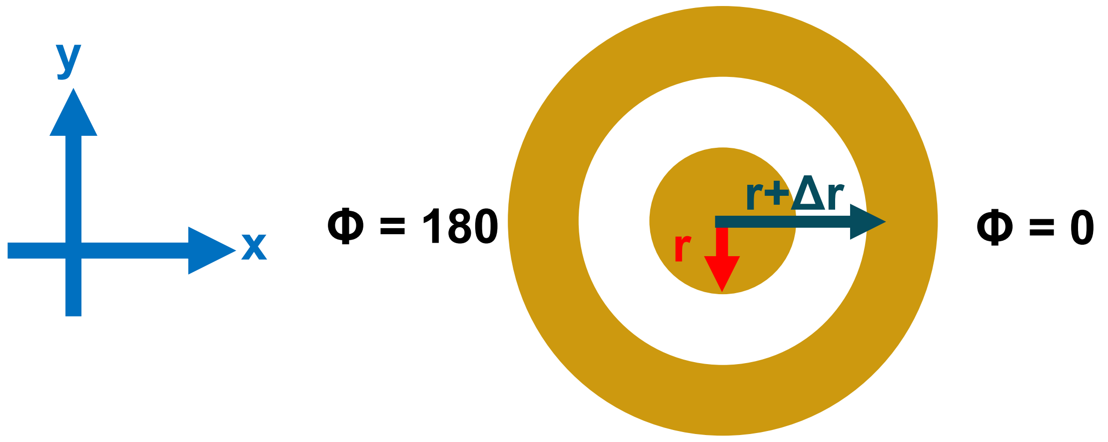




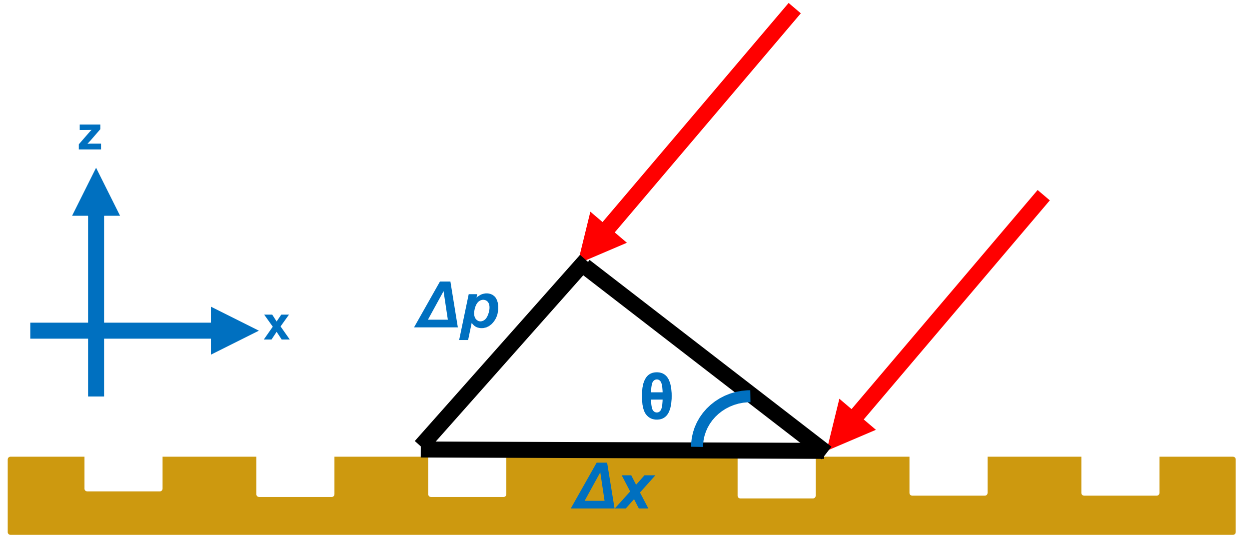
Spiral Tilt Compensation



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

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

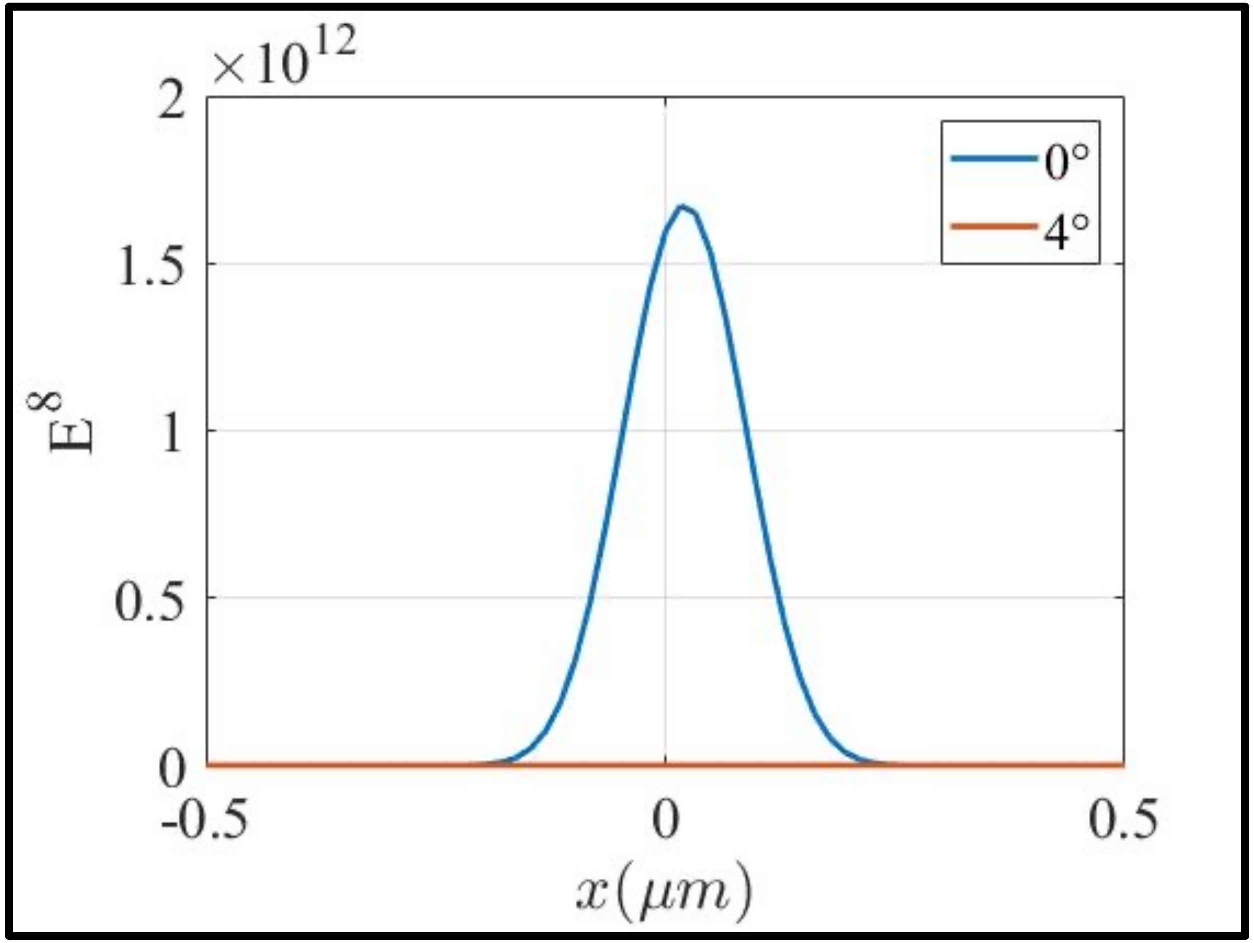
$$\Delta r = \frac{(\Delta p)(\lambda_{sp})}{\lambda} = \frac{(\Delta x sin(\theta))(\lambda_{sp})}{\lambda}$$

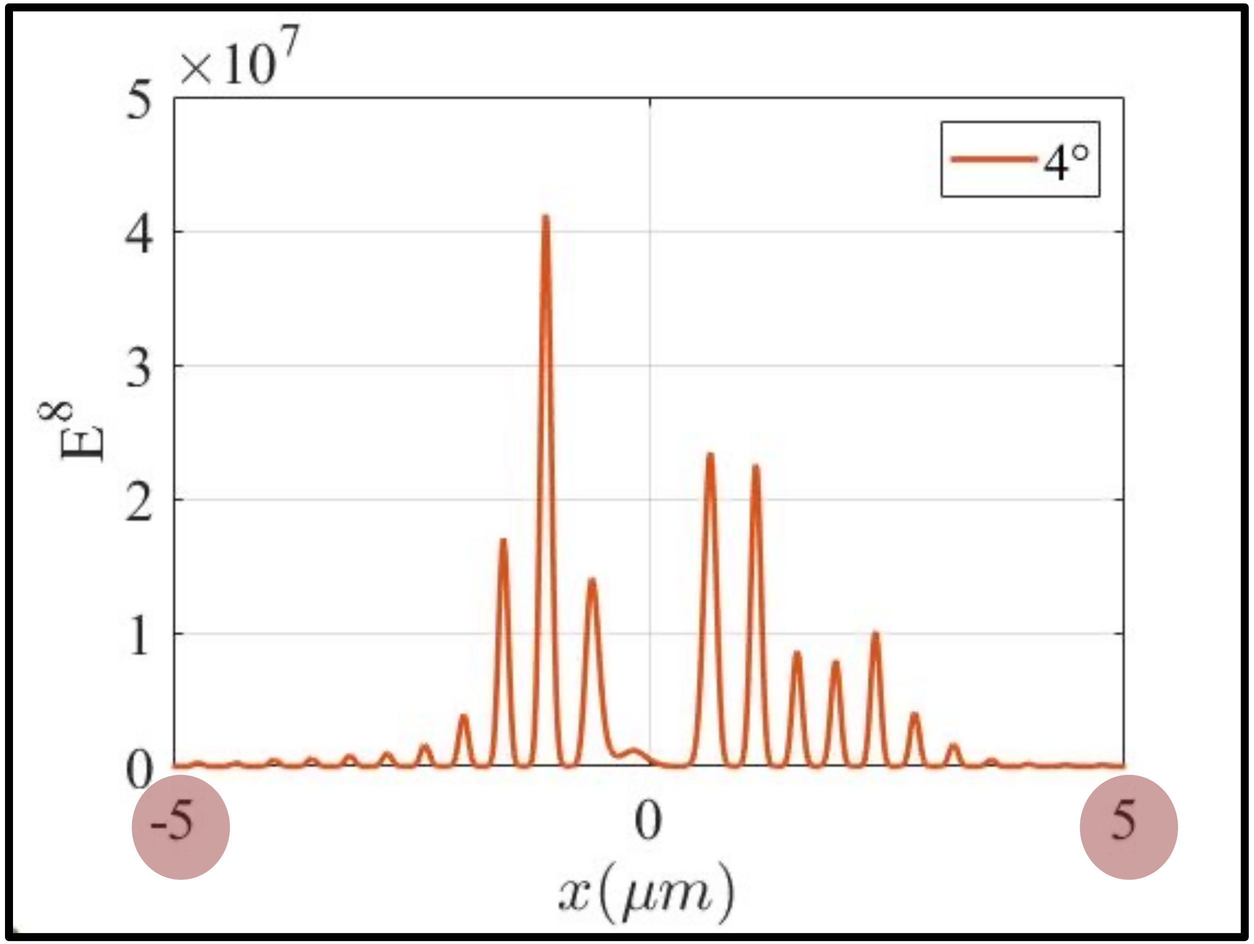


$$x' = r\cos(\phi) + r\cos(\phi) sin(\theta) \left(\frac{\lambda_{sp}}{\lambda}\right) \cos(\phi)$$

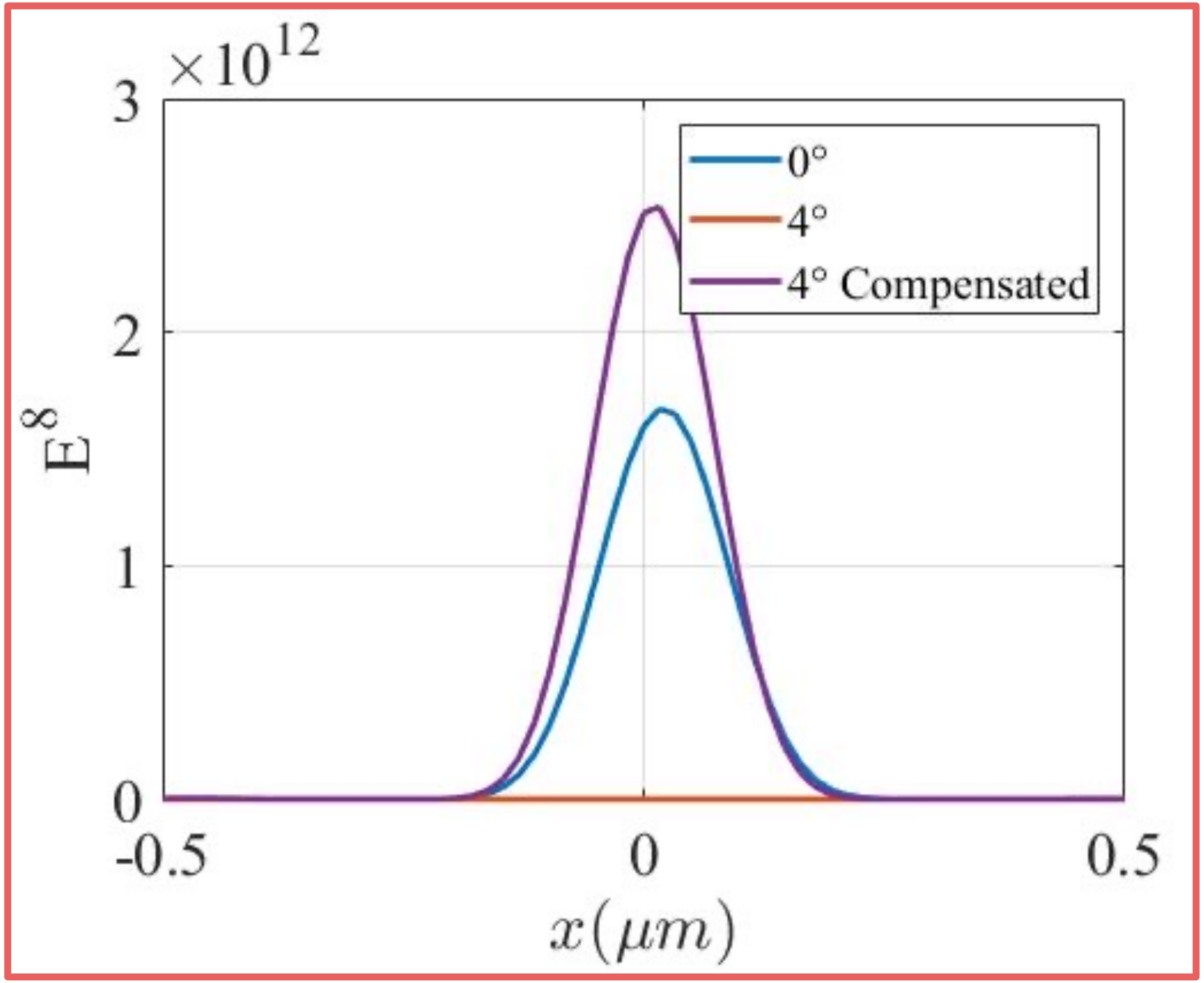
$$y' = r\sin(\phi) + r\cos(\phi) sin(\theta) \left(\frac{\lambda_{sp}}{\lambda}\right) sin(\phi)$$

Plasmonic Spiral: Tilt Compensation



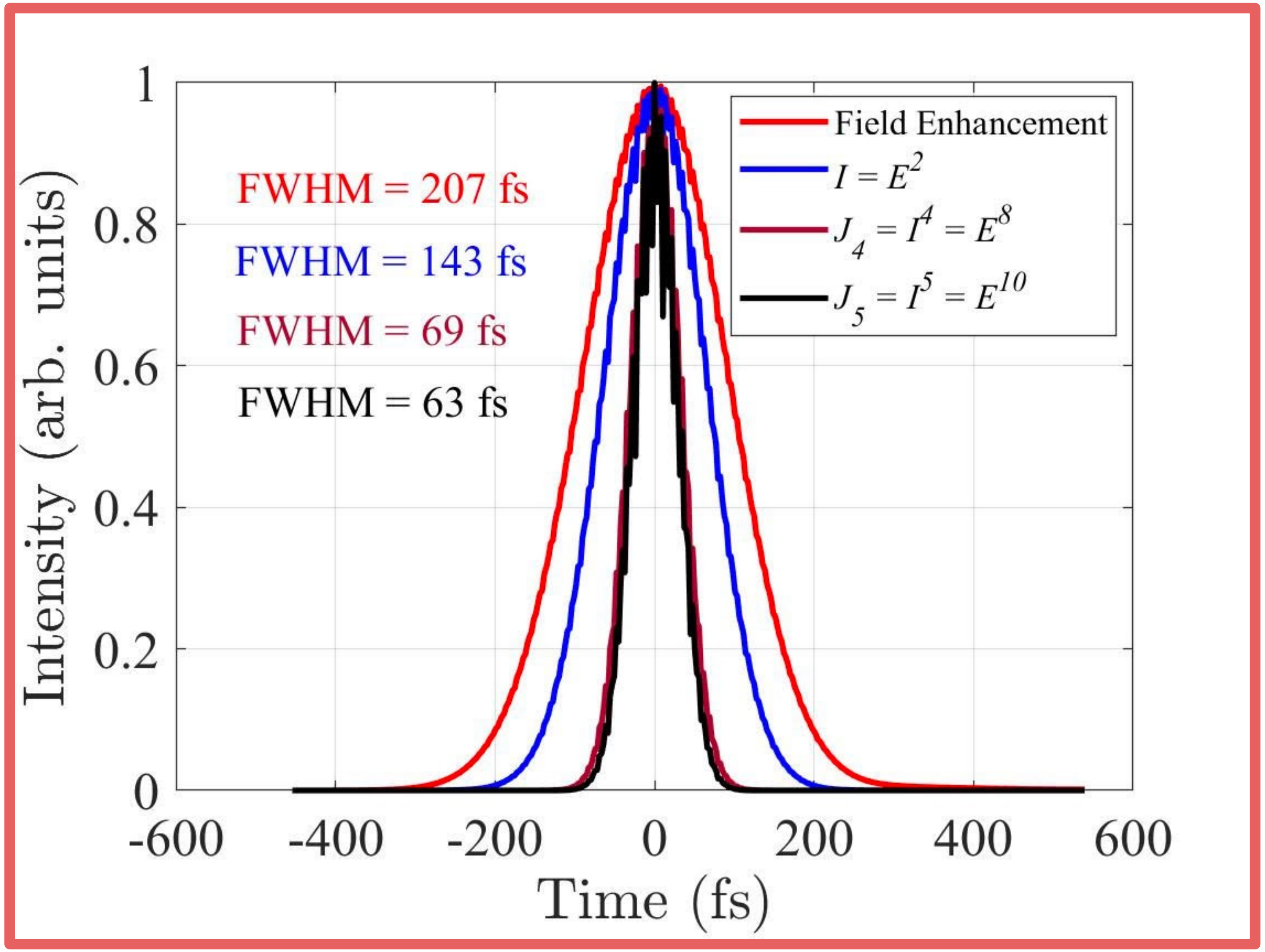


Plasmonic Spiral: Tilt Compensation



FWHM ~ 140 nm

Plasmonic Spiral: Response Time

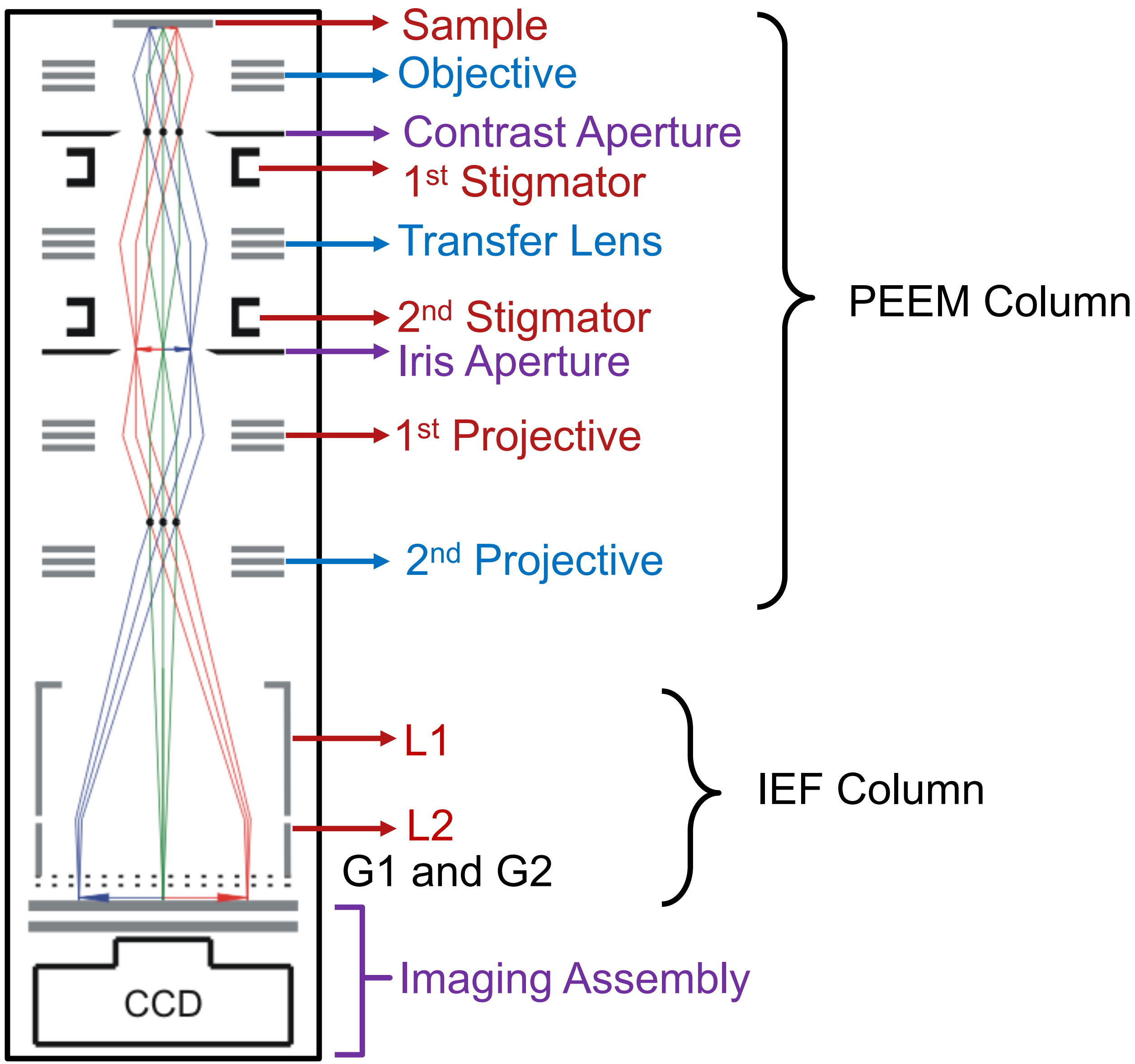


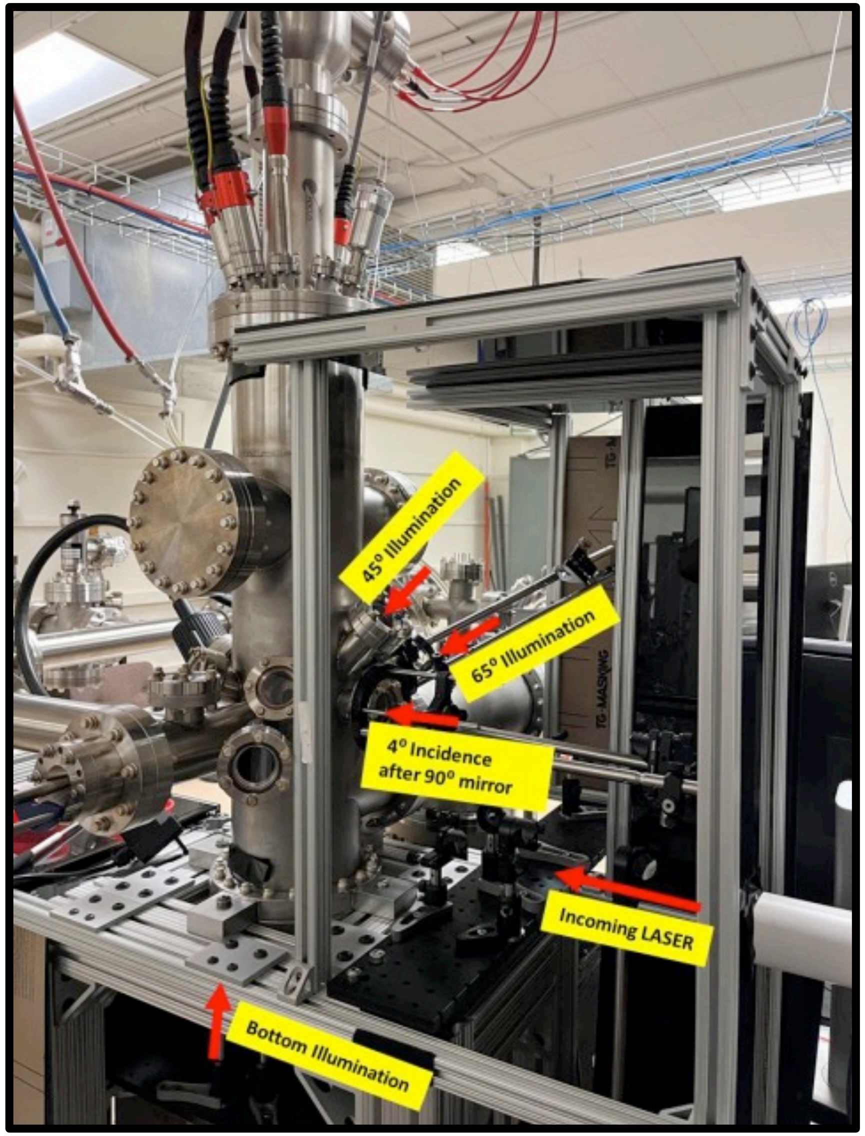
Response Time: FDTD Simulation

Incident Pulse Length: 150 fs

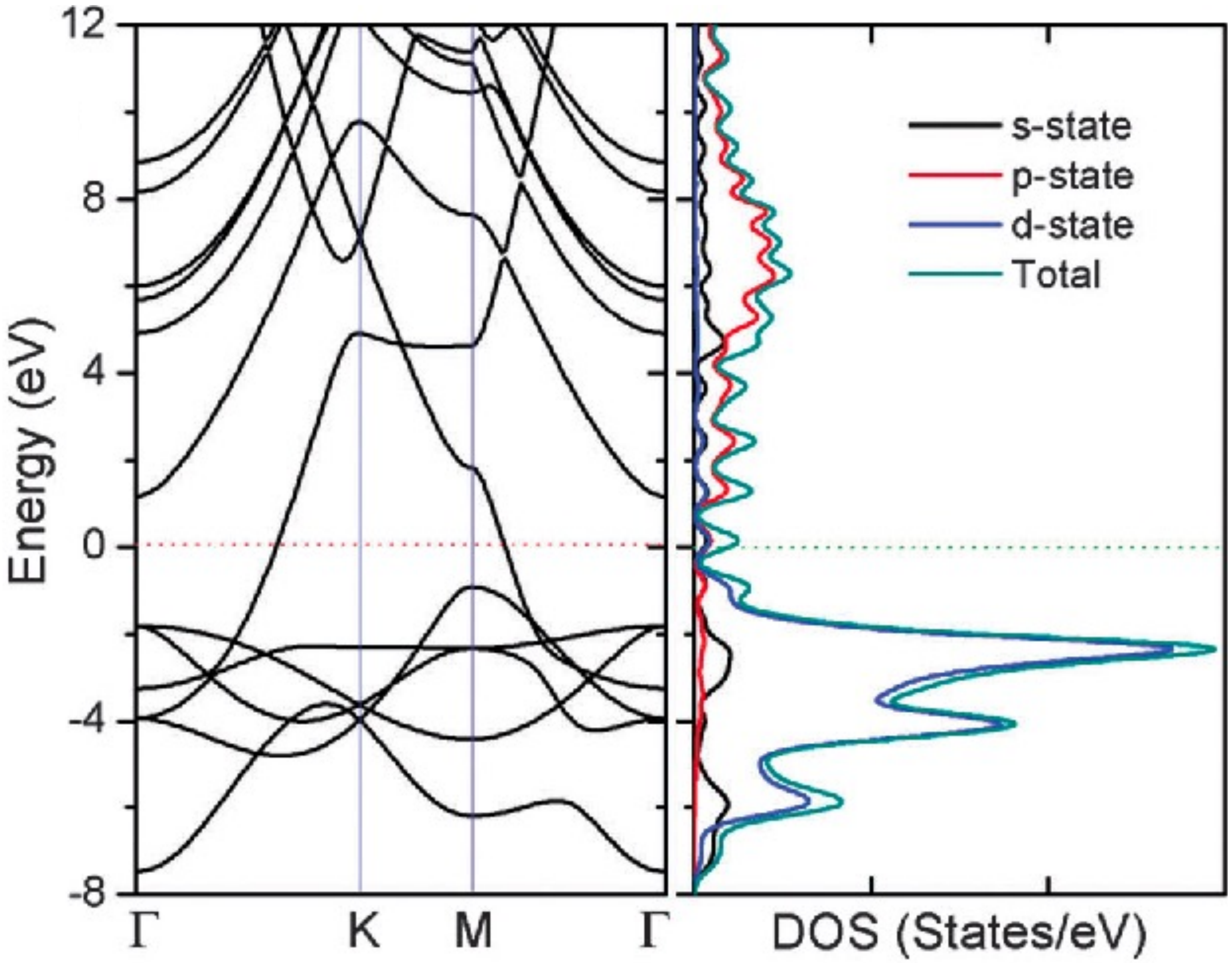
Polarization: Circular

Brief Description of PEEM





Density of States: Gold



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

Electron Bunch Parameters

- Brightness of Electron Bunch
- Charge density in phase space

$$B\ \alpha\ \frac{Q_{bunch}}{\varepsilon_n^2}$$

B = Brightness of Electron Bunch
Q_{bunch} = Bunch Charge
$\mathcal{E}_n$ = Normalized Emittance

- Increase Amount of Charge Extracted
- Reduce Emittance/Mean Transverse Energy (MTE)

- Coherence Length

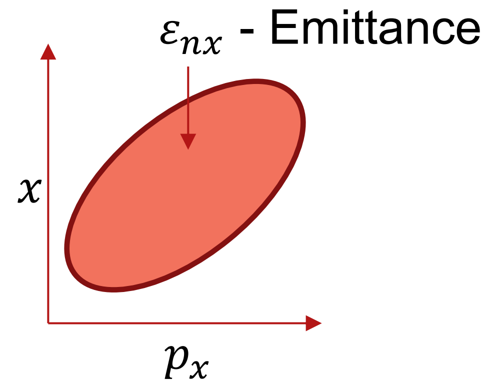
$$L_c = \lambda\!\!\!^{-} \frac{\sigma_e}{\varepsilon_n}$$

L = Coherence Length
$\lambda\!\!\!^{-}$ = Reduced Compton Wavelength
σ_e = RMS electron beam size
$\mathcal{E}_n$ = Normalized Emittance

Proteins: ~ 4 - 100 nm

$L_c \geq 4$ nm
$\sigma_e \leq 200$ µm
$\varepsilon_n \leq 20$ nm rad.

The electron beam emitted from the photocathode is contained within a phase space volume, known as the emittance



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

- Reduce Emission Area
- Reduce Mean Transverse Energy (MTE)