High Aspect Ratio Si Photoelectron Emitter Arrays

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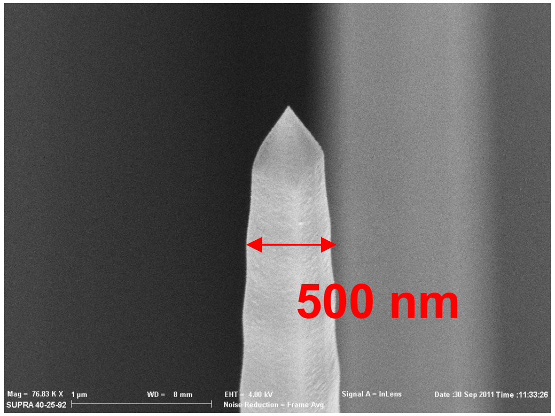
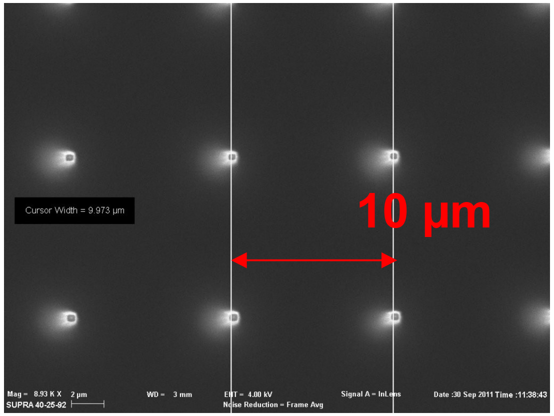
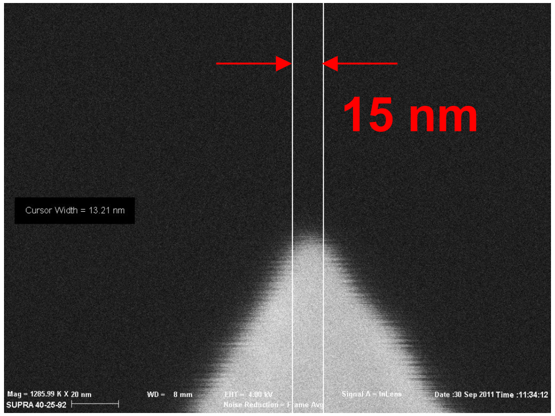
Why Nano-Tip Electron Emitters?

- Localized field enhancement → prevents damage from high input energies
- Tunneling regime accessible via optical excitation → intense attosecond electron bursts
- Localized emission → lower emittance from individual tips
- Structured electron beams → emittance exchange[1]







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[1] W. S. Graves, F. X. Kaertner, D. E. Moncton, and P. Piot, arXiv:1202.0318, Feb. 2012.

Experimental Setup for Photo-Electron Energy Characterization

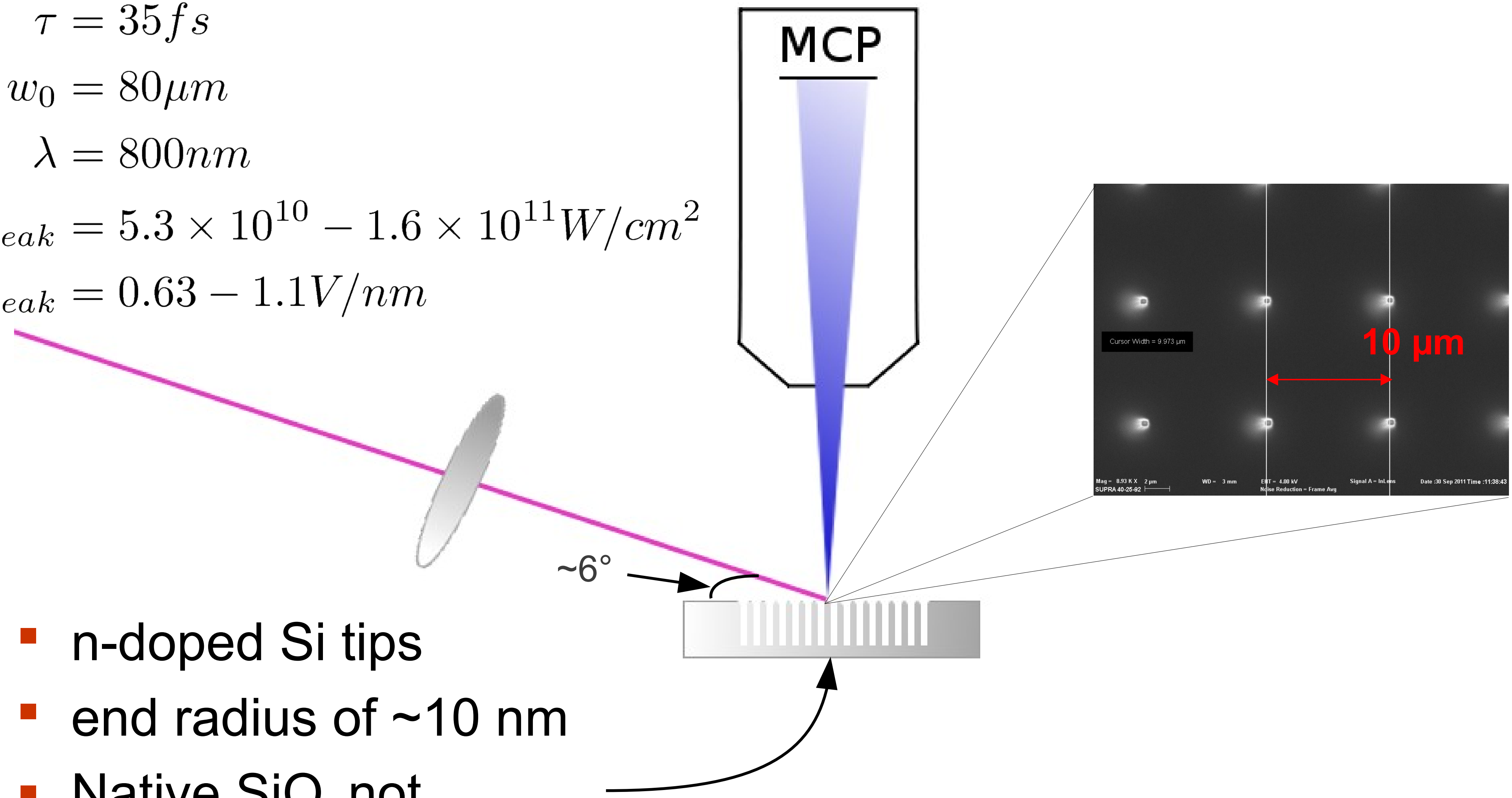
$$\tau = 35fs$$

$$w_0 = 80\mu m$$

$$\lambda = 800nm$$

$$I_{peak} = 5.3 \times 10^{10} - 1.6 \times 10^{11} W/cm^2$$

$$\mathcal{E}_{peak} = 0.63 - 1.1 V/nm$$

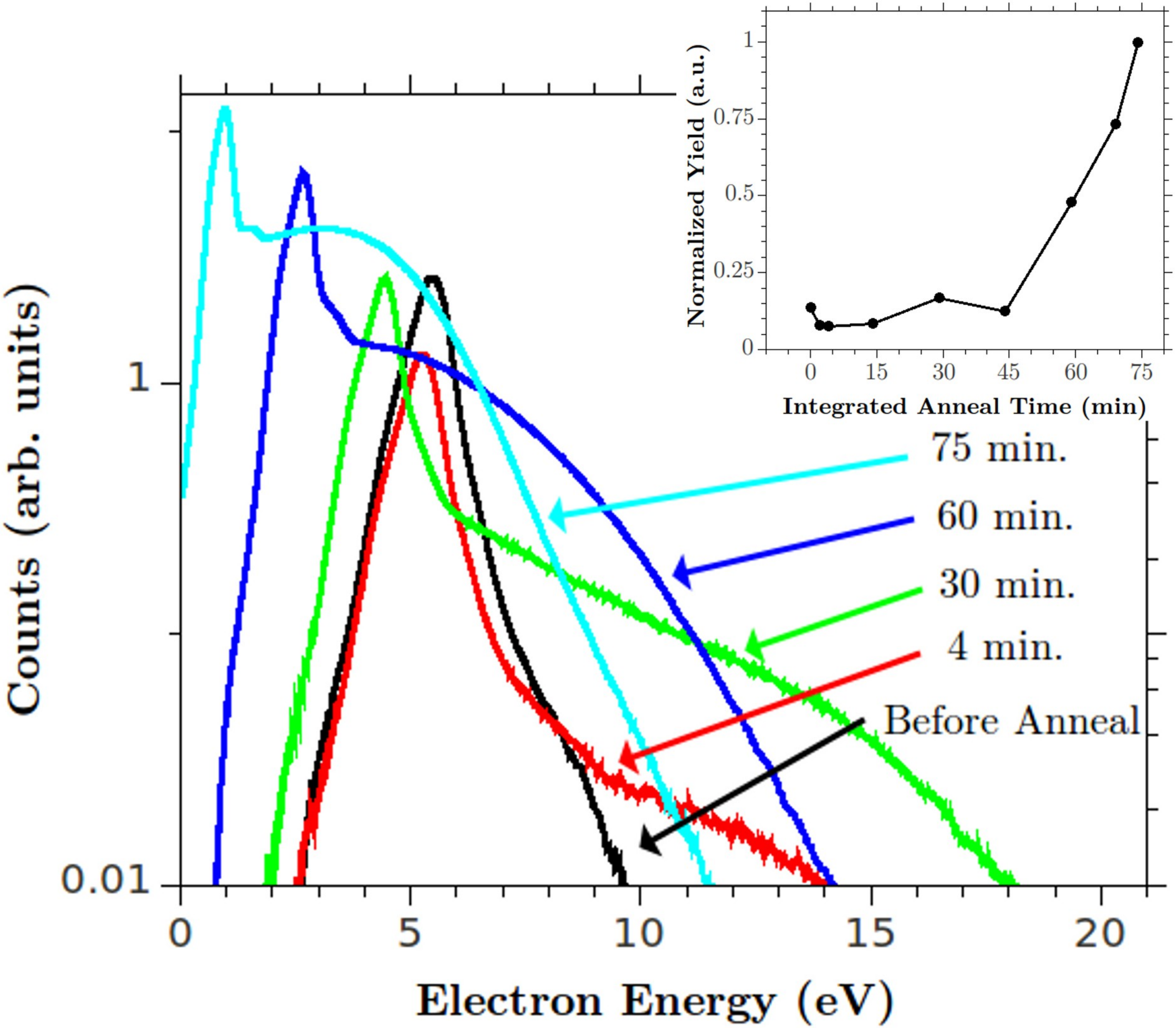


- n-doped Si tips
- end radius of ~10 nm
- Native SiO_2 not removed

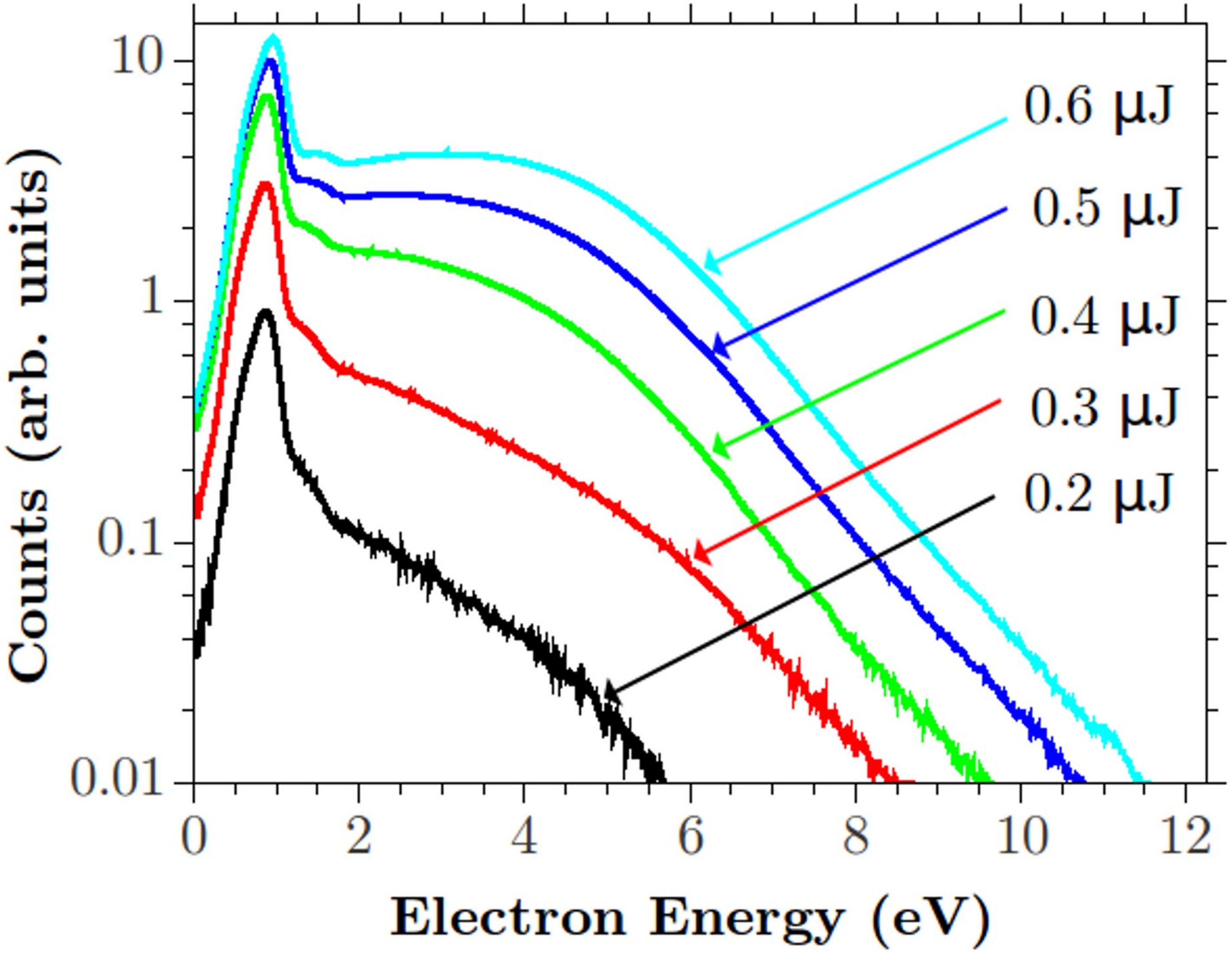
Initial Observations

- First exposure to low incident pulse energy, < 0.7 µJ → No change in spectra
- Second exposure to high incident pulse energy, > 1.0 µJ → Systematic changes. Induces:
  - Red Shift
  - Onset of plateau
- Repeat low energy tests

Energy Spectra After Anneals – 0.6 µJ

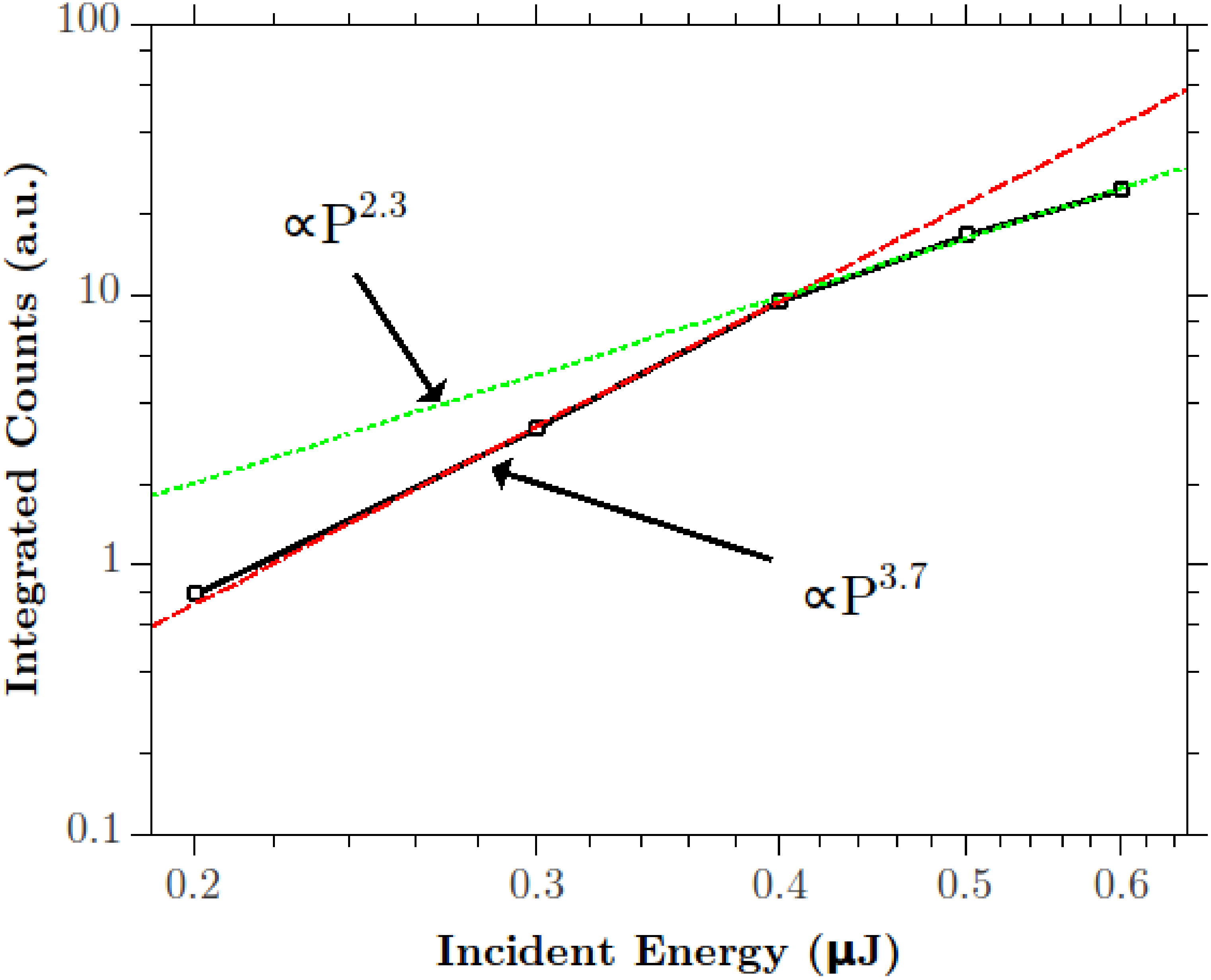


Power Scaling of Energy Spectra

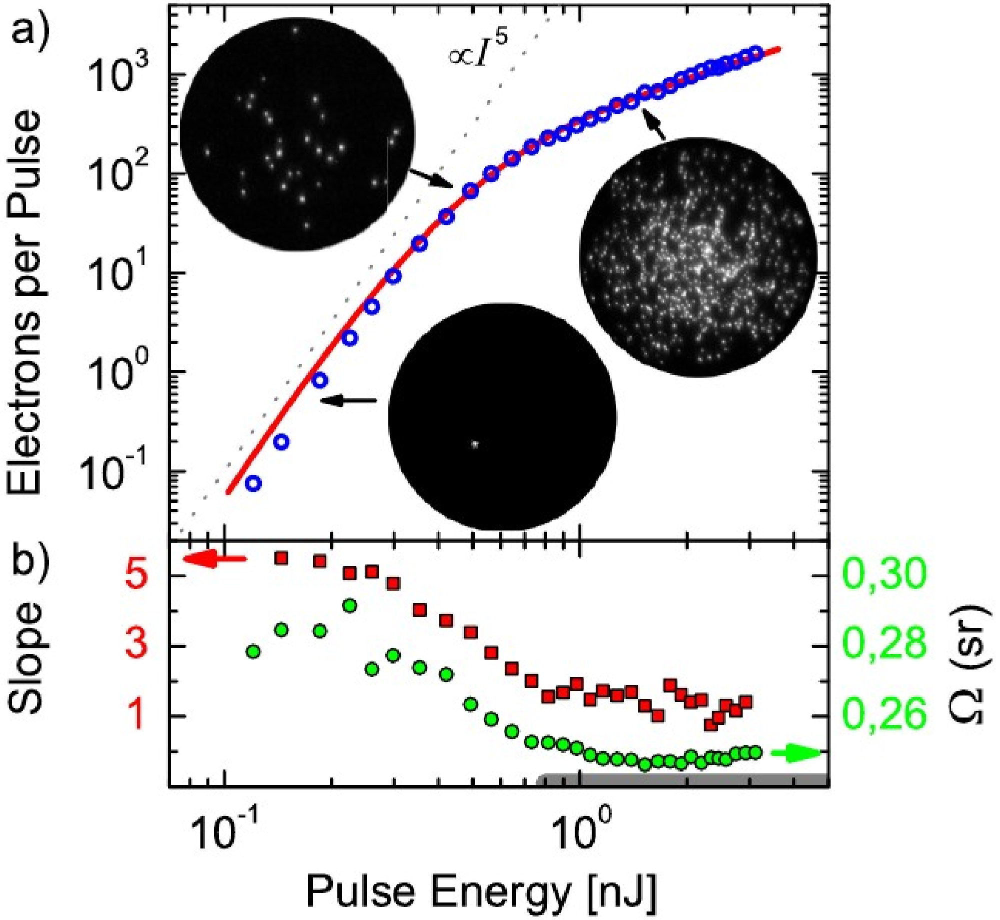


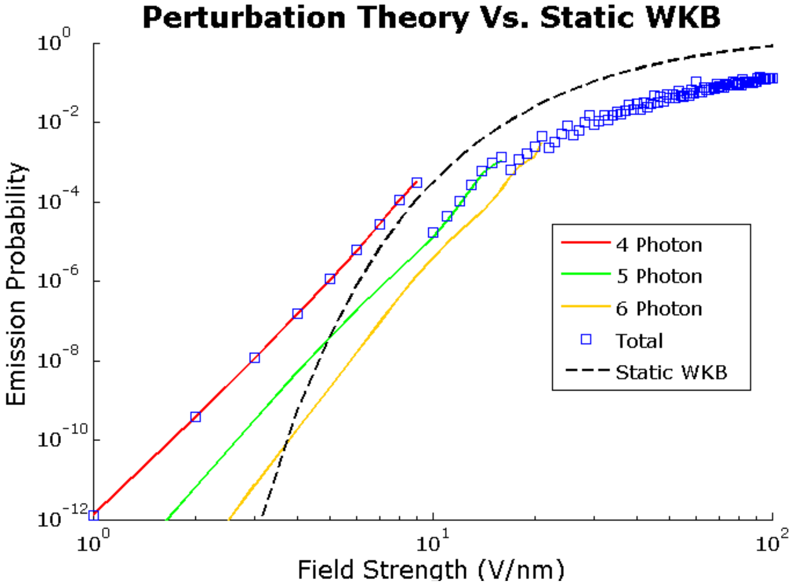
- Main peak almost fixed with increased incident energy
- Higher energy plateau extends with increased intensity
- No significant change in main peak width

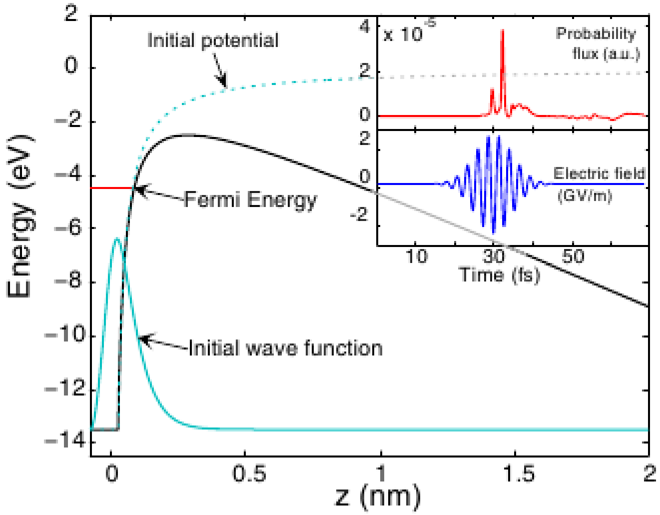
Total Current Yield – After Total Anneal



Possible Mechanisms







Left & Top Right: Image taken from R. Bormann, M. Gulde, A. Weismann, S. V. Yalunin, and C. Ropers, Phys. Rev. Lett., vol. 105, no. 14, p. 147601, 2010. Red curve is SFA of photoemission from step potential with work function ~5eV. Calculation based on their results.

Bottom Right: Example of potential barrier bending. Taken from P. Hommelhoff, et al., Phys. Rev. Lett., vol. 97, no. 24, p. 247402, Dec. 2006.

Modeling the Emission Process

- The Keldysh parameter, γ, is figure of merit for determining emission regime – tunneling or multi-photon
- Transition to tunneling regime when[1]: $\gamma = \sqrt{\frac{\Phi}{2U_p}} \approx 2$
- Where $U_p = \frac{e^2 F_{peak}^2}{4m\omega^2}$ is the ponderomotive potential.
- Transition point measured leads to enhancement of 10-14.
- At a 12x field enhancement, with 0.6 μJ incident energy we have

$$\boxed{\gamma \approx 1.2}$$

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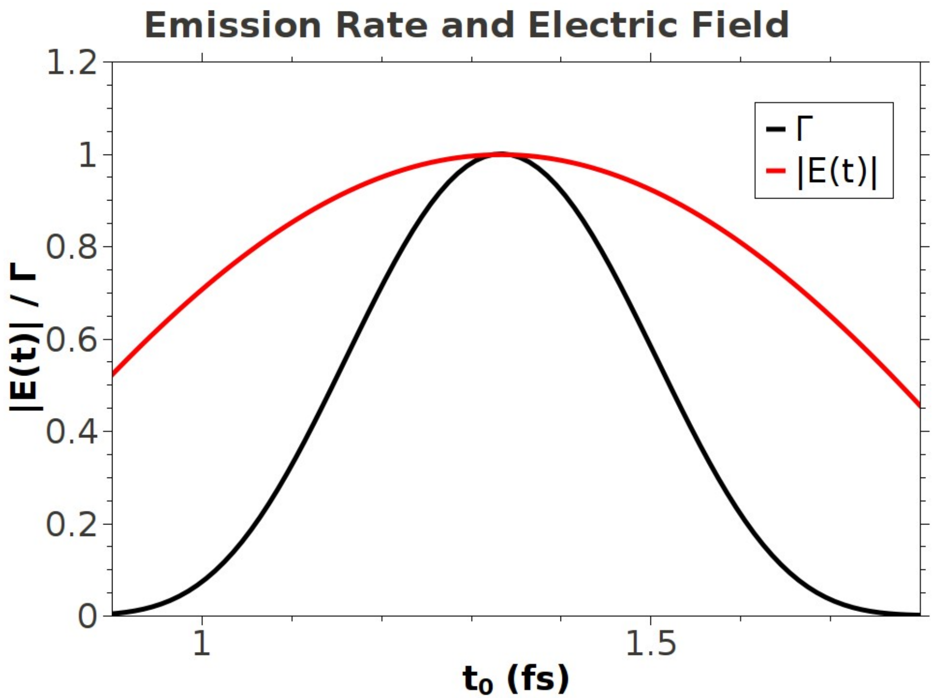
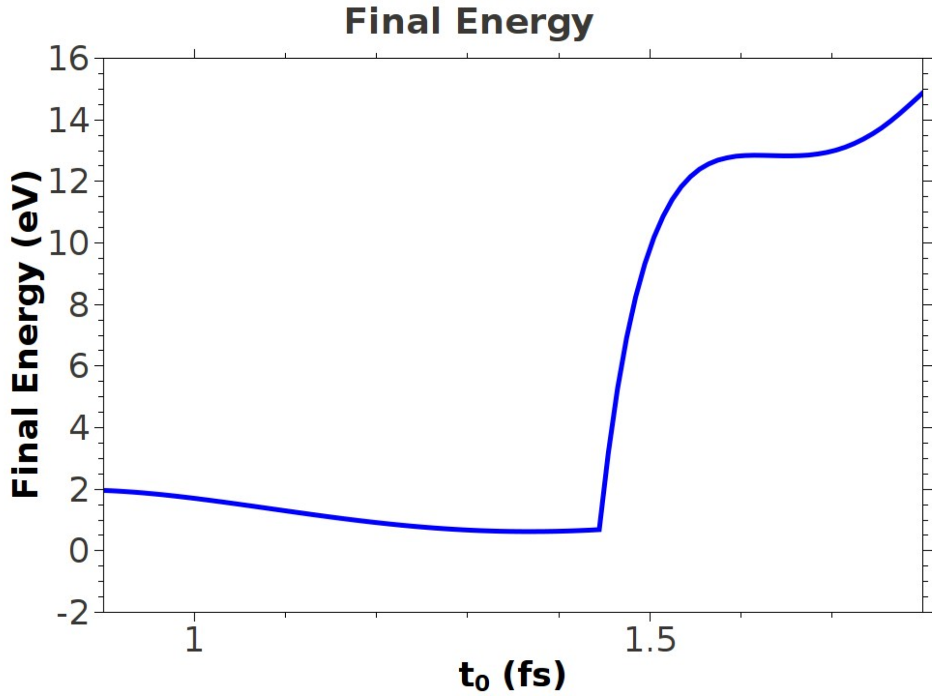
[1] R. Bormann, M. Gulde, A. Weismann, S. V. Yalunin, and C. Ropers, Phys. Rev. Lett., vol. 105, no. 14, p. 147601, 2010.

Modeling the Emission Process

- Given tunneling regime, we have a 3-step process for each electron orbit beginning at t_0 (similar to[1]):
  - Electron emitted at time t_0, with tunneling rate Γ (Fowler-Nordheim emission), at the tunnel exit
  - Strong-field accelerates the electron (classical mechanics)
  - When electron returns to z=0, elastically scatter off of tip
- Each orbit final momentum has weight $\Gamma(t_0)$ when calculating energy spectra





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[1] G. Herink, D. R. Solli, M. Gulde, and C. Ropers, Nature, vol. 483, no. 7388, pp. 190–193, Mar. 2012.

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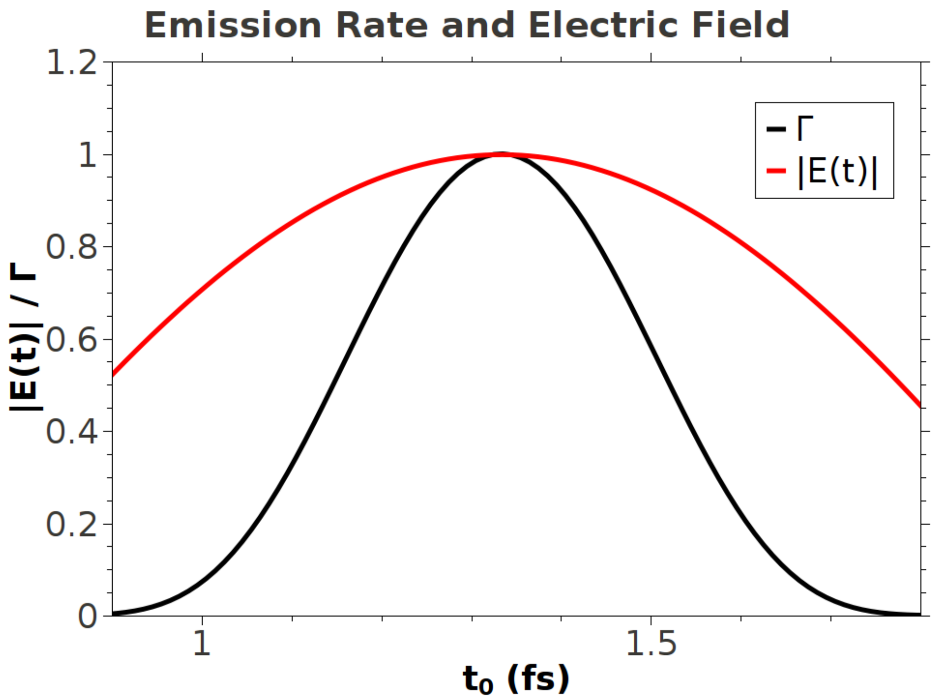
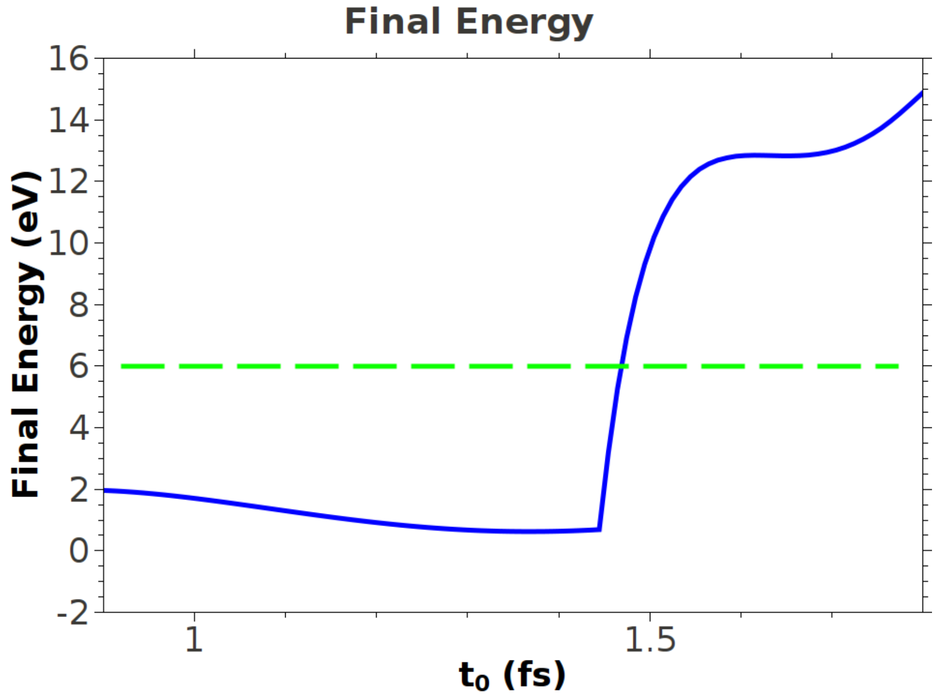

Emission Rate and Electric Field


Final Energy

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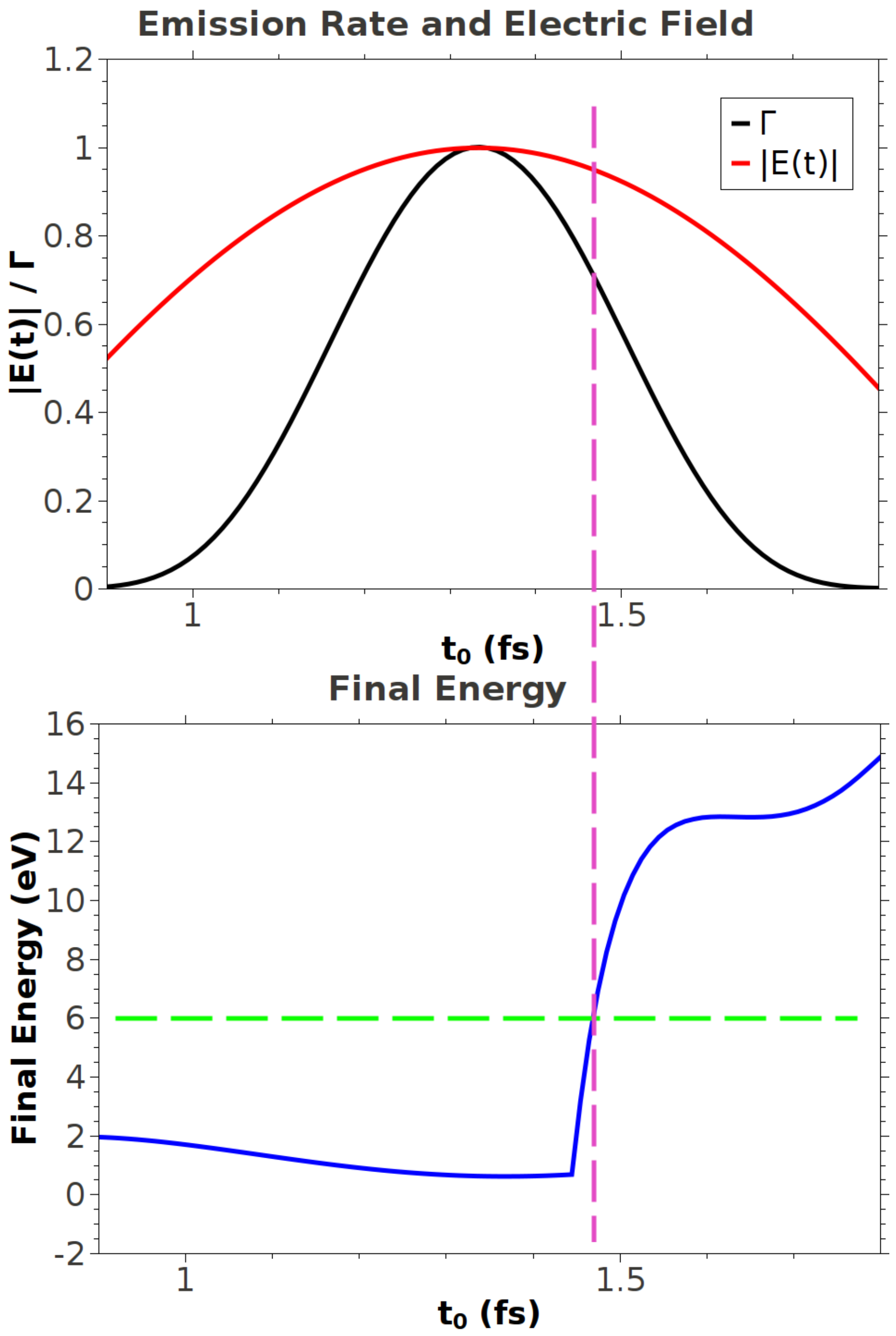

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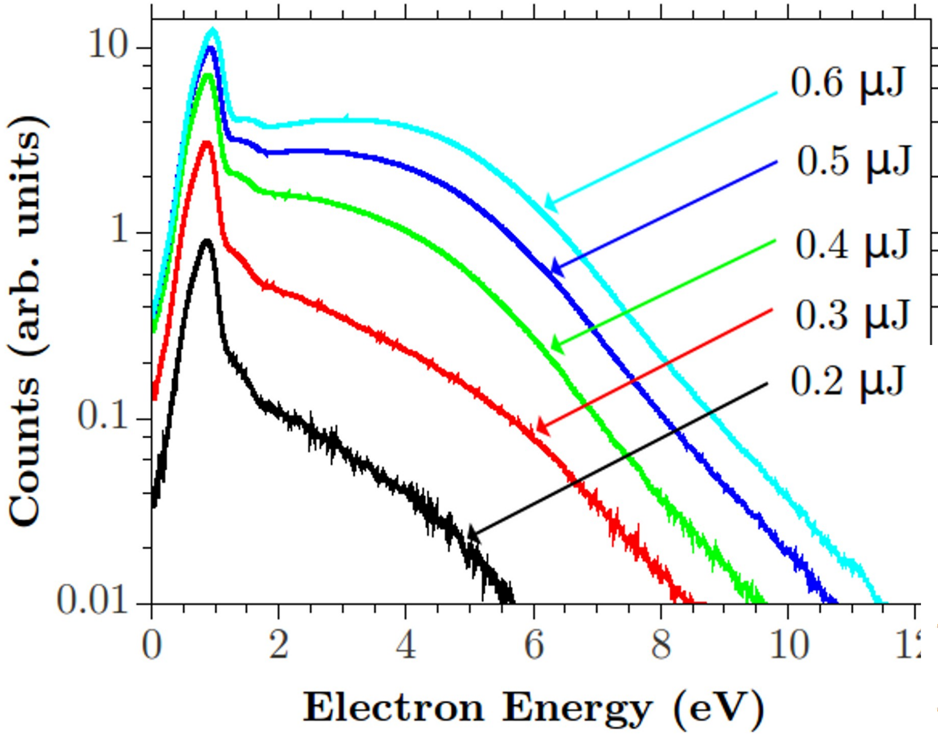
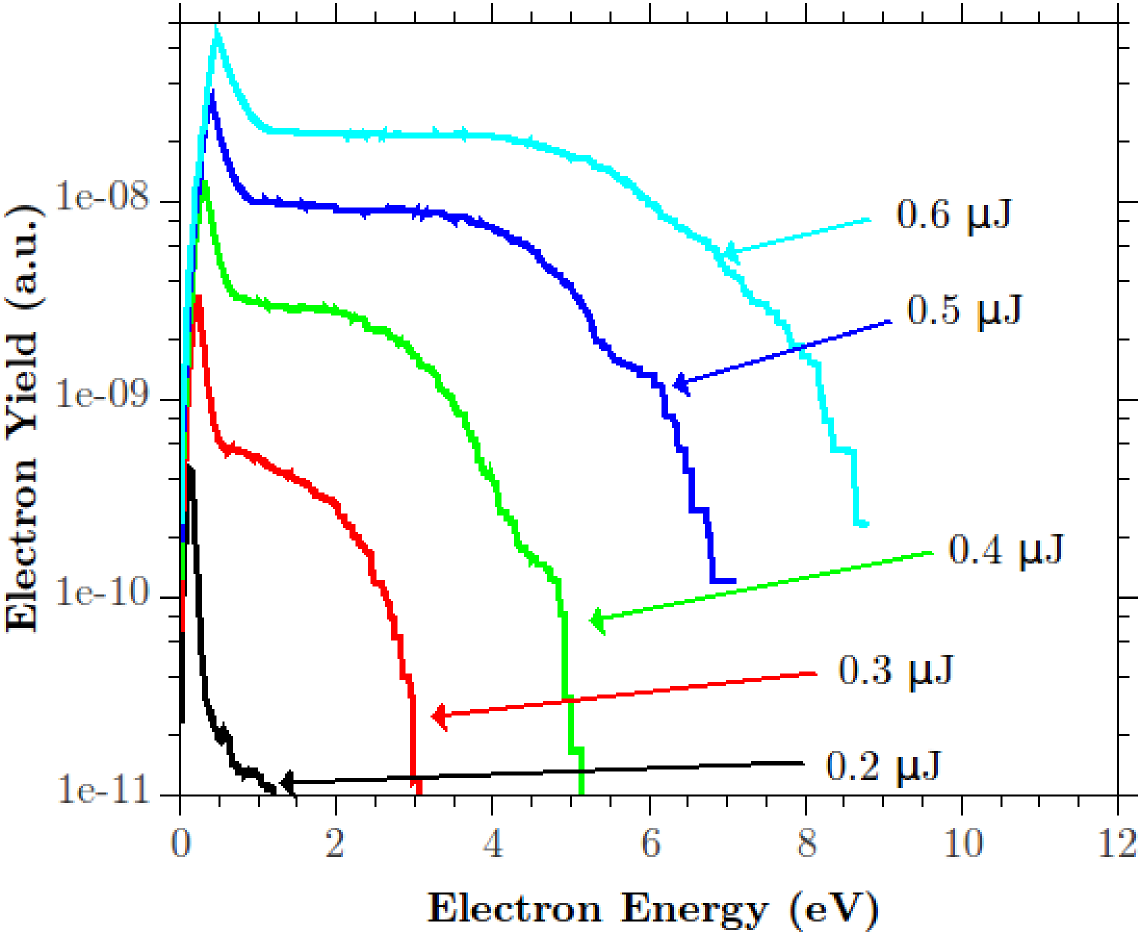
Model Results and Comparison To Experiment



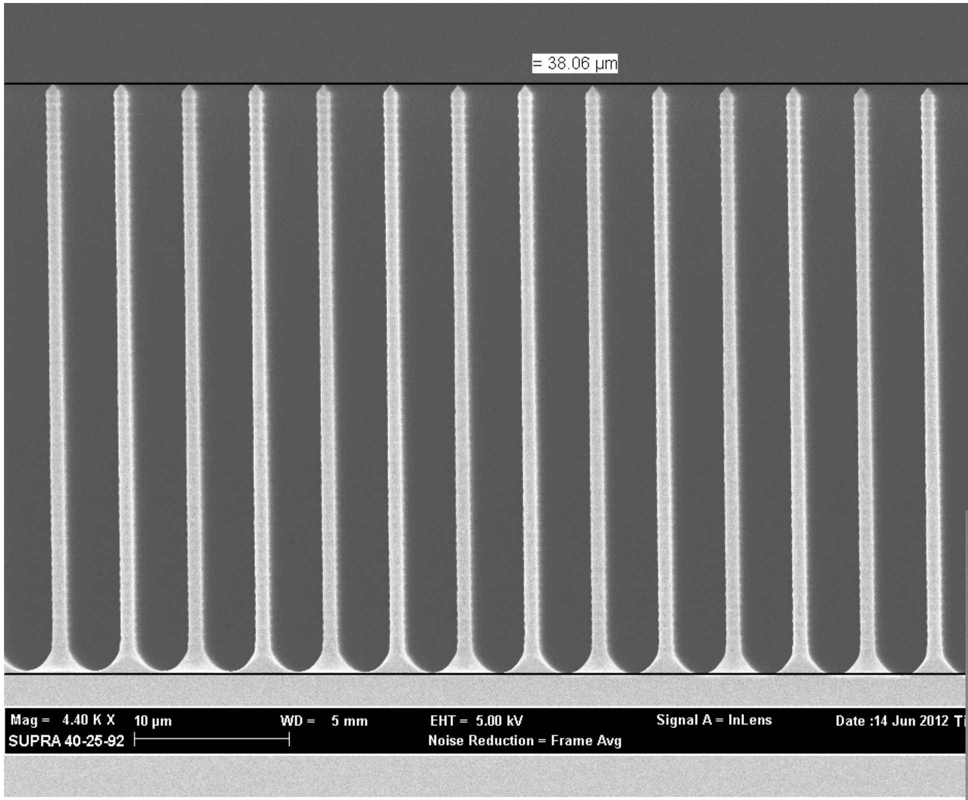
Experimental Results

Model Results

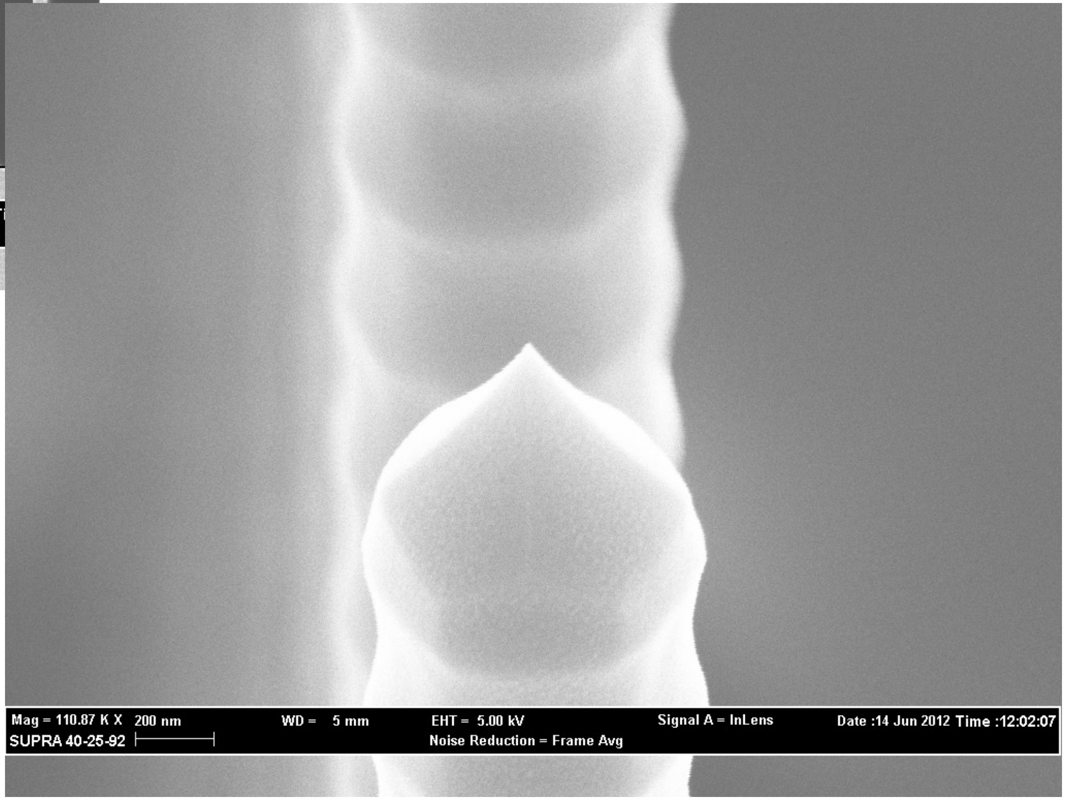


Total Current Characterization

- Similar structures
  - High aspect ratio
  - 10 nm tip radius of curvature
- Same laser parameters, slightly higher rep-rate
  - 3 kHz vs. 1 kHz



- Preparation
  - HF dipped before testing



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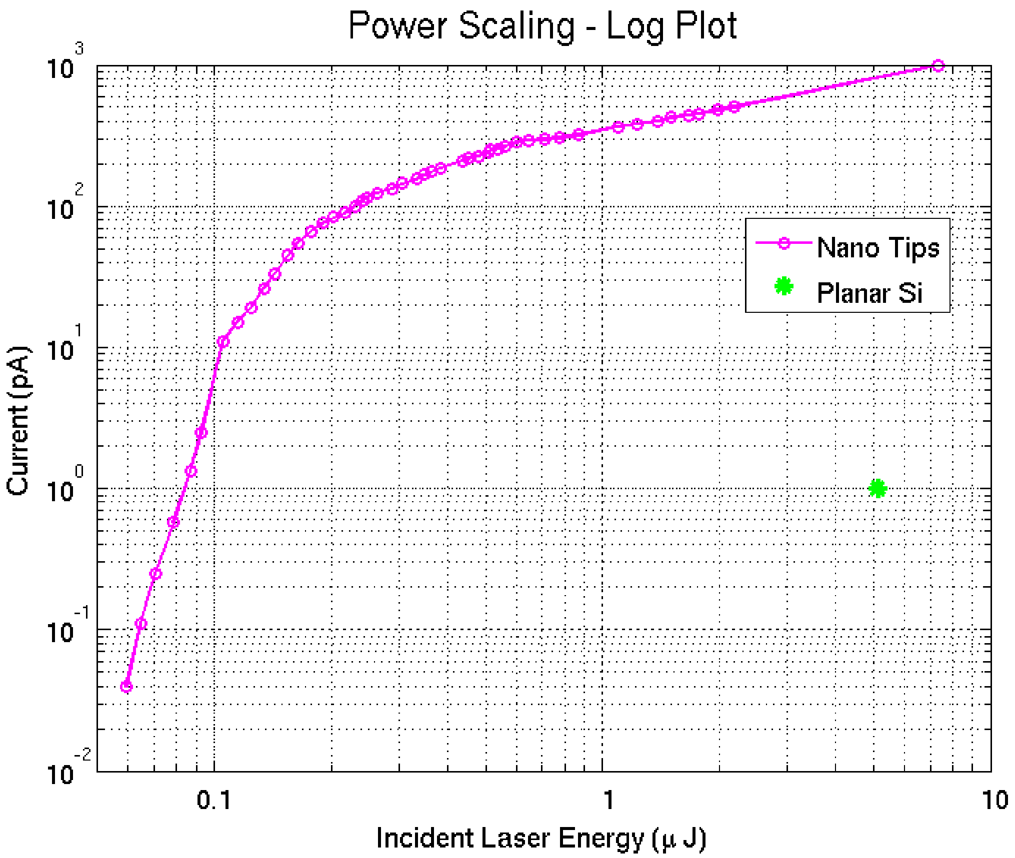
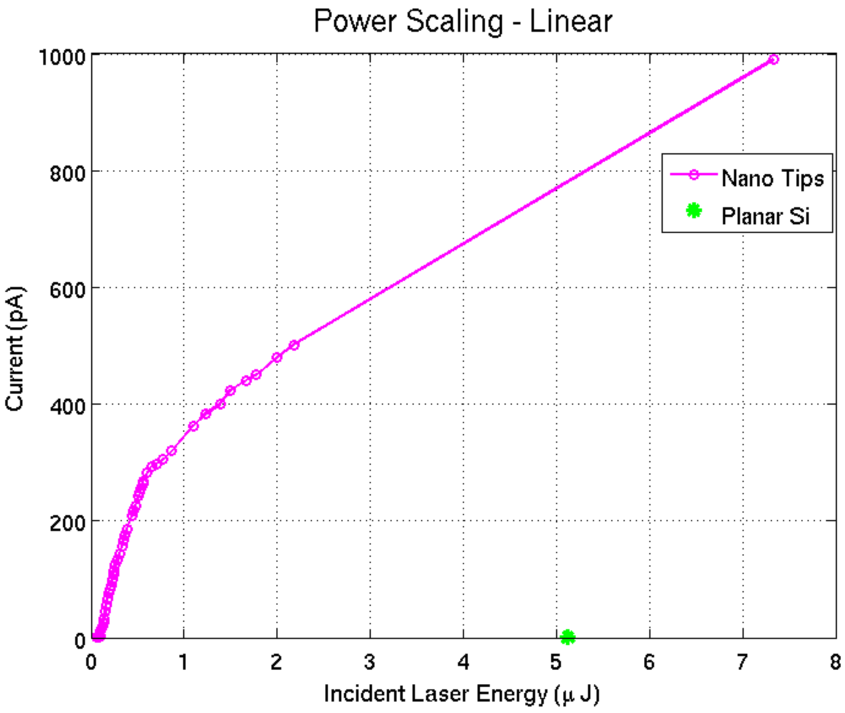
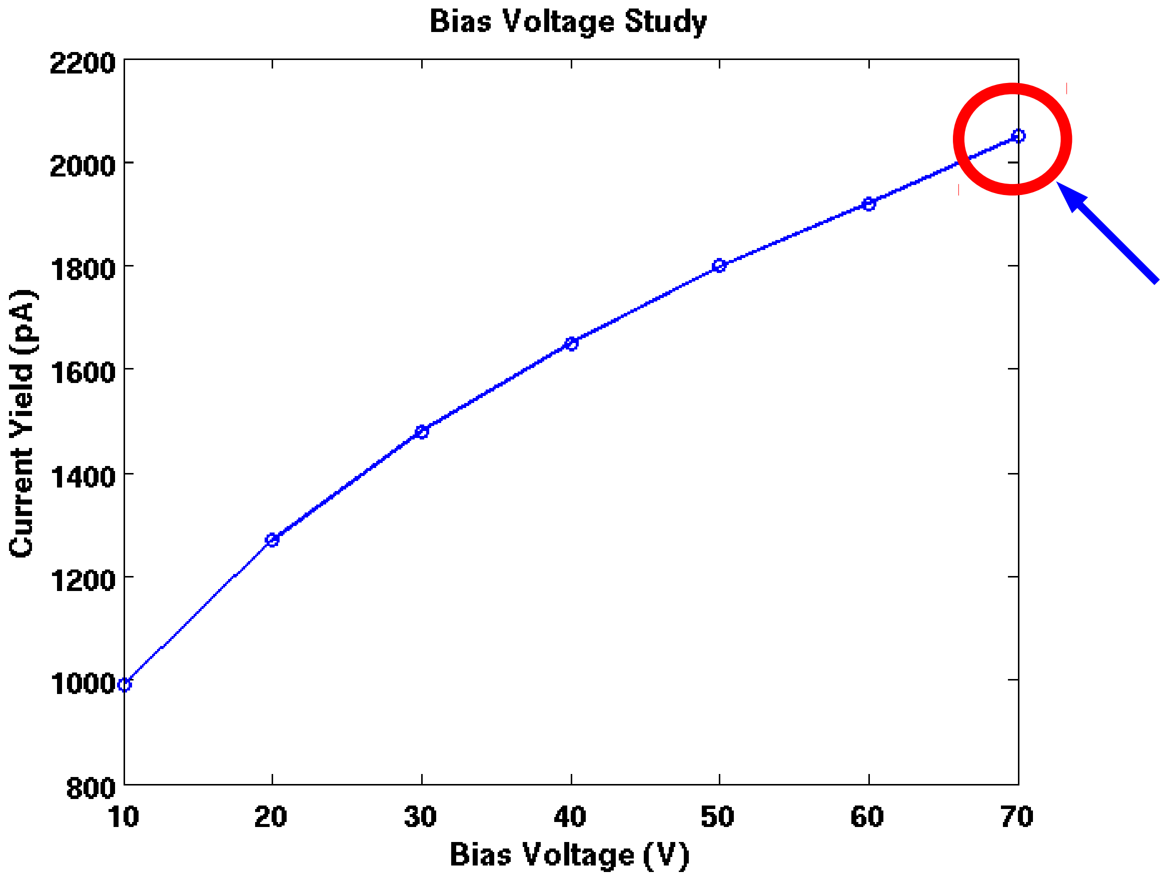

Power Scaling - Log Plot


Power Scaling - Linear

Effect of Bias Voltage – 7 μJ



$$Q = 0.66 \text{ pC/bunch}$$

$$\mathrm{QE}_{\mathrm{eff}} = \frac{0.66 \text{ pC} \times 1.55\text{eV/photon}}{7\ \mu\ \text{J}} = 1.5 \times 10^{-7} \text{ electrons/photon}$$

$$\text{Fractional Area} = \frac{\text{Tip Area}}{\text{Cell Area}} = \frac{\pi * 25 \text{ nm}^2}{21.65\ \mu\text{m}^2} = 3.63 \times 10^{-6}$$

$$\mathrm{QE}_{\mathrm{tip}} = .041$$

Summary

- Photo-electron from Si tips with native oxide studied
- Laser-induced annealing process observed through spectral changes
  - Broad plateau observed extending more than 10 eV beyond main spectral peak
  - Red shift of main spectral peak
- Theoretical model introduced
  - Tunneling regime modeled through three step “simple-man” model
  - Reproduces
    - Onset of plateau → due to electron re-scattering
- Total Electron Yield Characterization
  - 0.66 pC/bunch
  - Effective QE = $1.5\mathrm{x}10^{-7}$

Future Directions

- Better modeling of field profiles around structure
  - Quantitatively improved simulations
  - 3D Model of electron emission → full emittance model
- Transverse profile measurements
  - Emittance measurements for electron source applications
- Engineering FEA tip designs
  - Prevent re-scattering → high flux monochromatic electron beams
- Temporal Characterization
  - Verify sub-cycle duration of emitted electrons at surface