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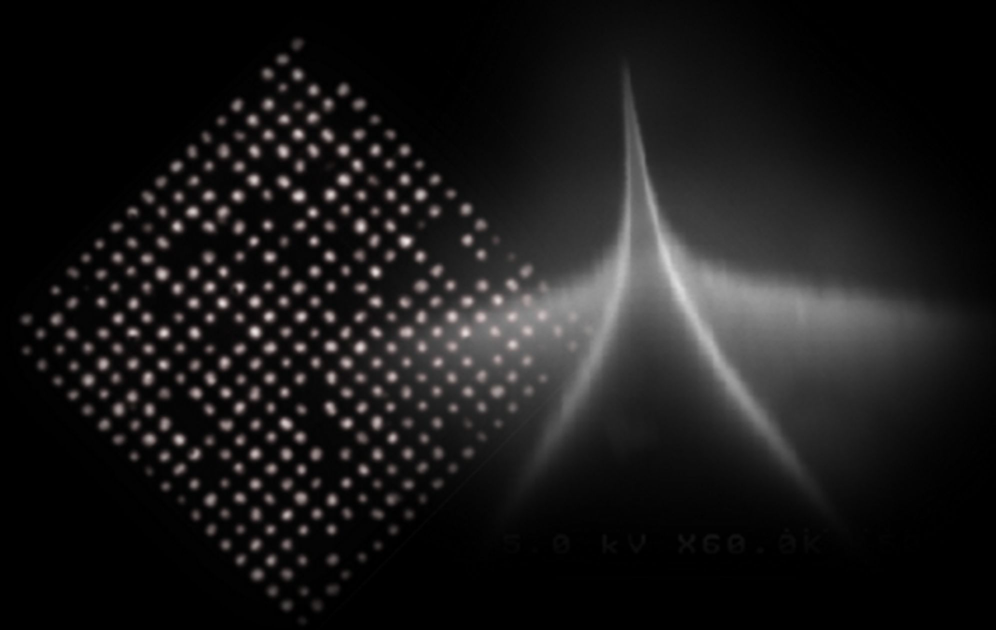
High-Brightness Field-Emission Cathodes for Accelerator Applications

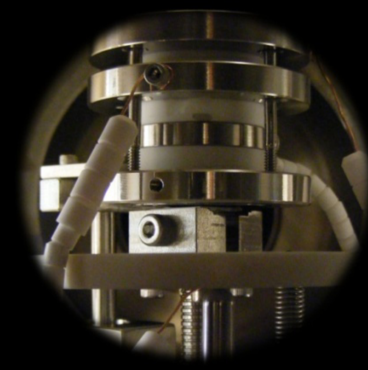


J. D. Jarvis, H. L. Andrews, C. A. Brau, & C. L. Stewart

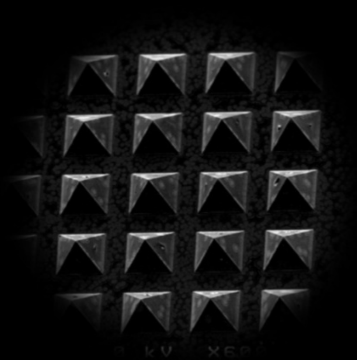
Department of Physics and Astronomy

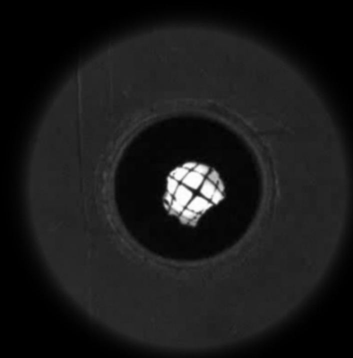
Y. M. Wong, B. K. Choi, J. Davidson, & W. Kang

Department of Electrical and Computer Engineering



- Brightness and Quantum Degeneracy
- Diamond Field-Emitter Arrays
- Carbon-Nanotube Field-Emission Cathodes
- Conclusions





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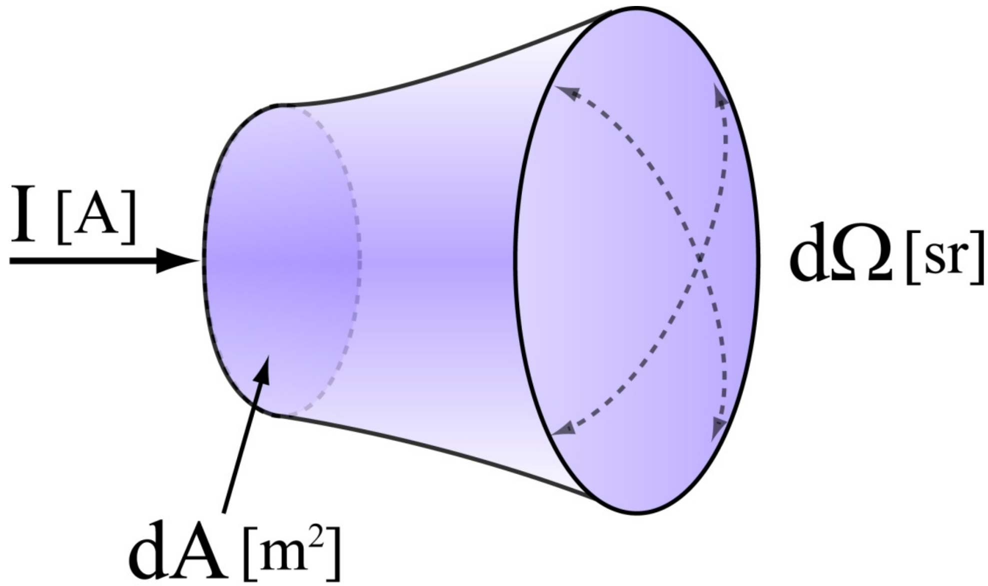
Normalized brightness describes the quality of an electron beam:

- Indicates how much current passes through a given area into a given angular extent

- The maximum achievable brightness is set by the electron source

- The 6-D brightness is the density of the beam ensemble in 6-D phase space

$$B_N = \frac{1}{\beta^2\gamma^2}\frac{d^2 I}{dA\,d\Omega}$$

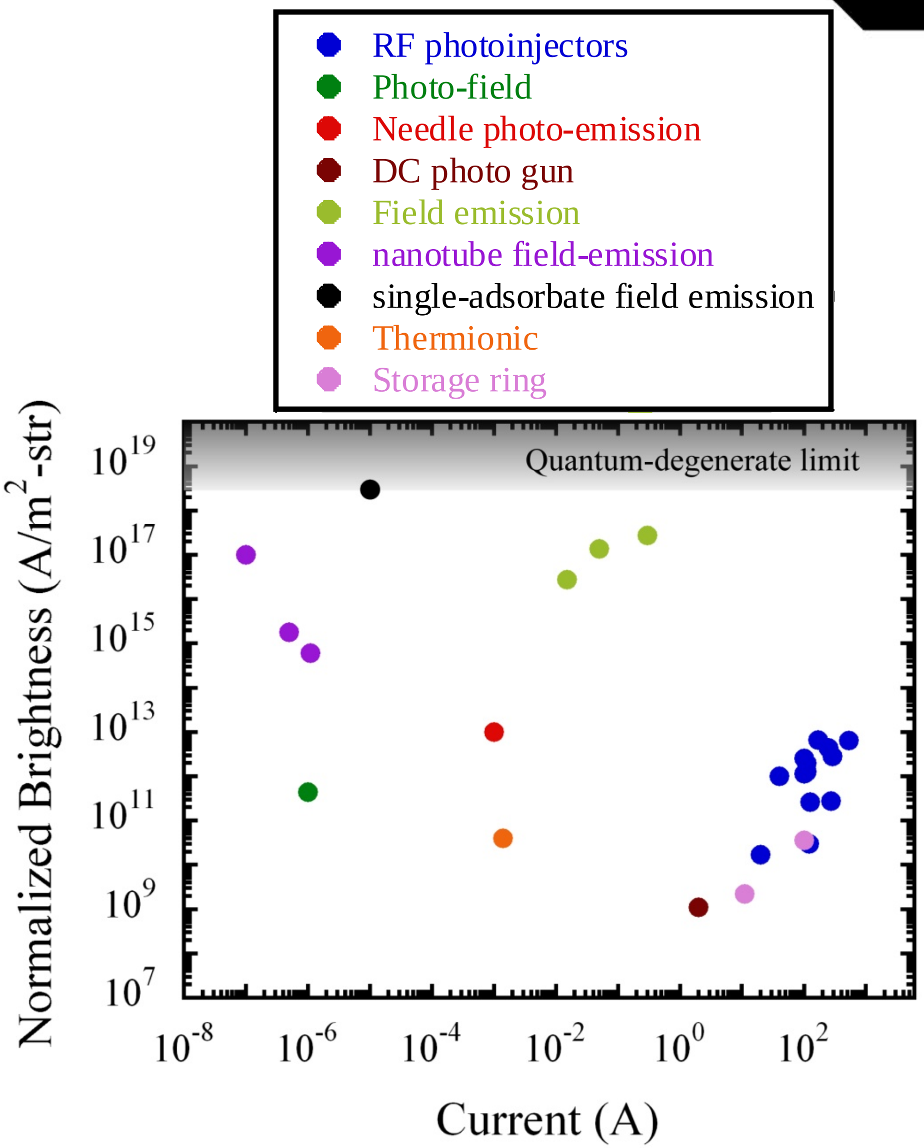


Electron source brightness spans nine orders of magnitude:

- Three primary emission mechanisms:
    - Thermionic emission
    - Photo emission
    - Field emission

- Field emission provides brightest beams but typically low current

- The brightness for certain field emitters approaches the universal limit set by QM effects



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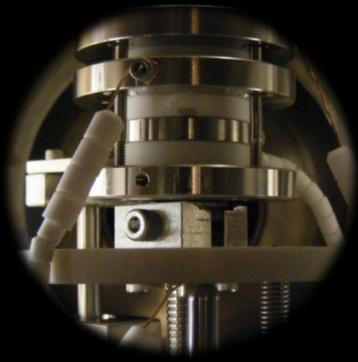
For a large 6-D brightness the anti-symmetry of electrons is important:

- The uncertainty principle and Pauli exclusion set a maximum phase-space number density of $2/h^3$ for fermions.

- A quantum-degenerate beam would have special properties such as suppressed e-e scattering (similar to electrons in a metal)

- Beams with high degeneracy should exhibit antibunching

$$\delta = \frac{h^3 d^6 N_e}{2 dx dp_x dy dp_y dE dt}$$



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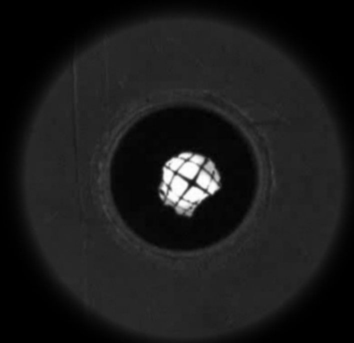

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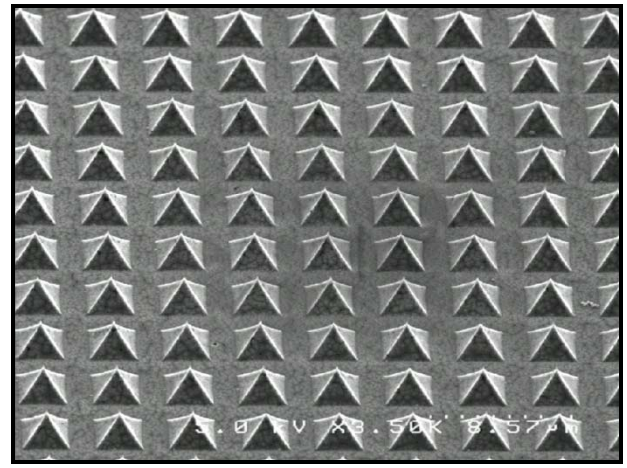
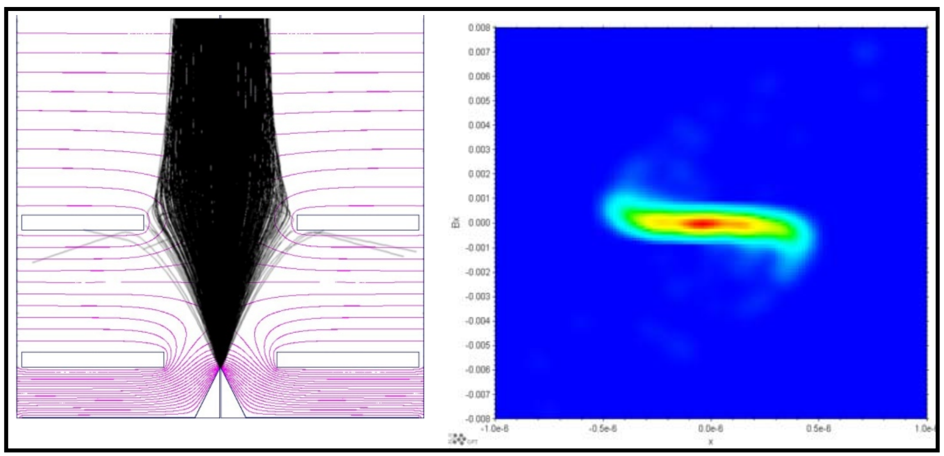
FEAs are microfabricated arrays of individual field emitters:

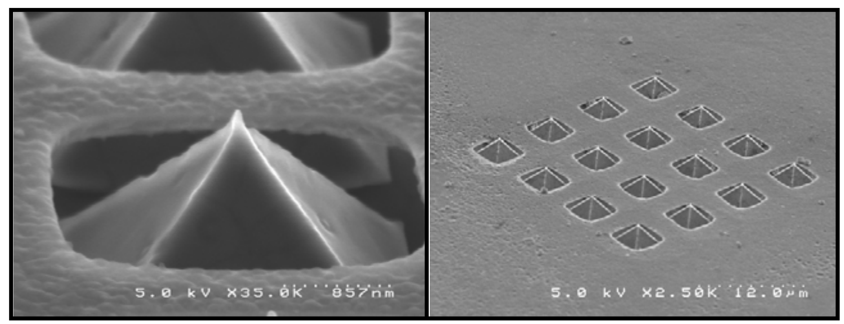
- Can be made with and without gate electrodes
- Emission can be time gated using various techniques
- Additional self-aligned electrodes may be included for beam collimation
- Many varieties, including Spindt type, CNT, Diamond (DFEA) etc..



ungated DFEA



w/ collimation *x-p_x phase space*



Gated DFEA

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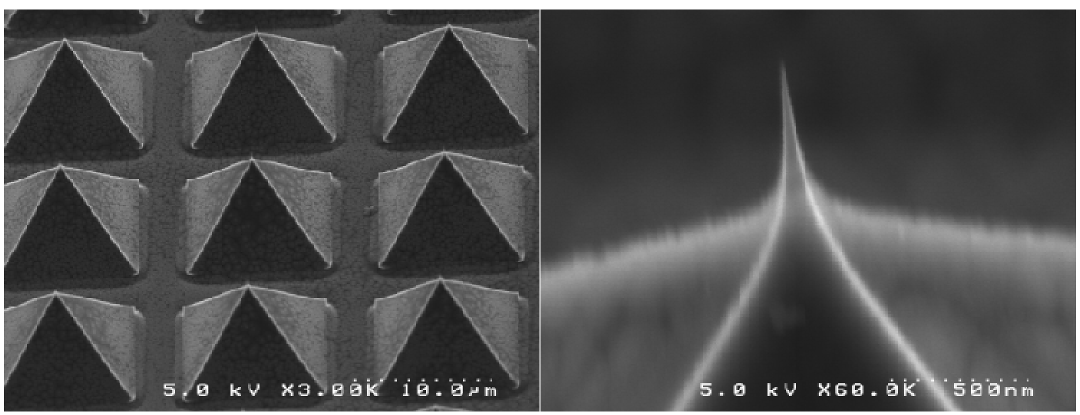
Diamond field-emitter arrays are a promising new beam source:

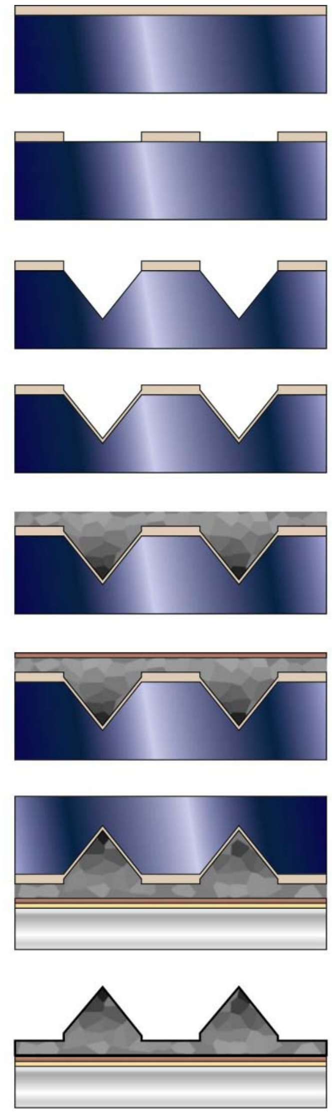
•Developed at Vanderbilt by Davidson et al.

•Fabricated with an inverse mold transfer technique

•CVD diamond w/ boron and nitrogen

•Can be customized with multiple nanotips





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Gated DFEAs are now becoming operational:

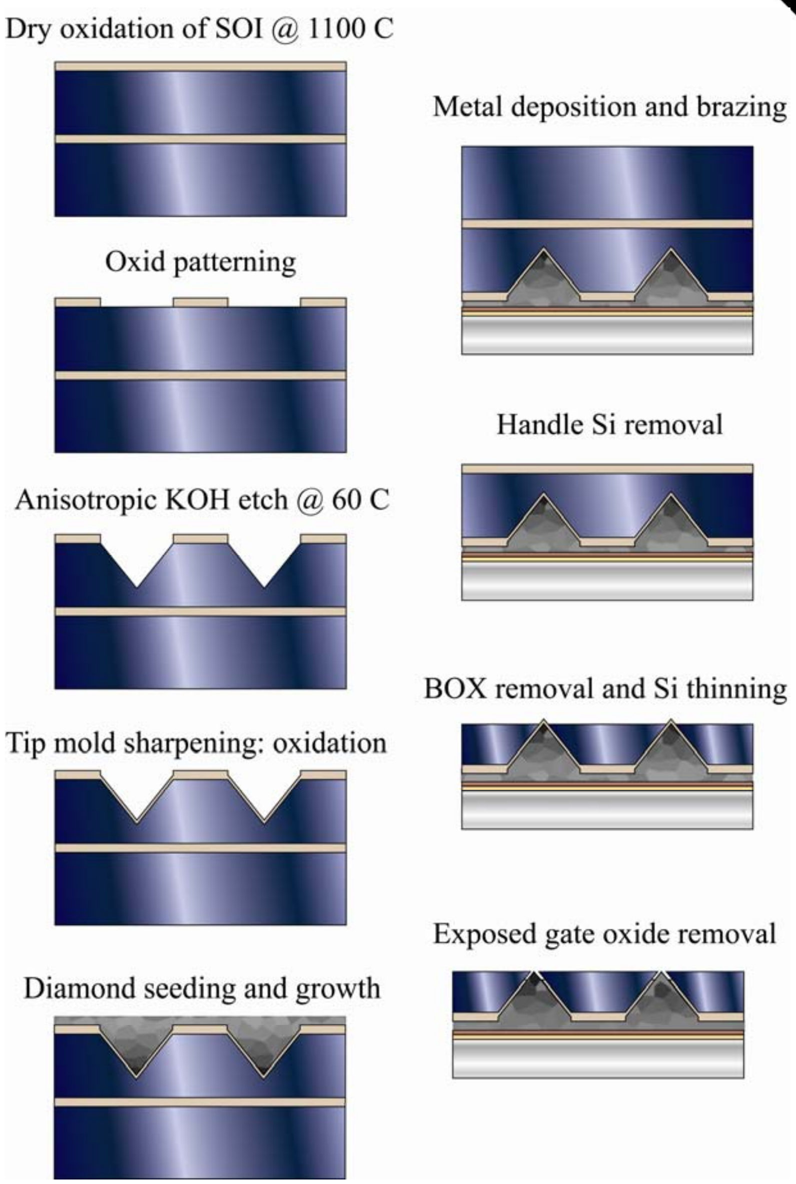
•Gated DFEAs can be produced using either SOI or volcano processes

•Turn-on voltages of < 30 V (gate to cathode)

•Currently addressing issues with gate-oxide-surface contamination

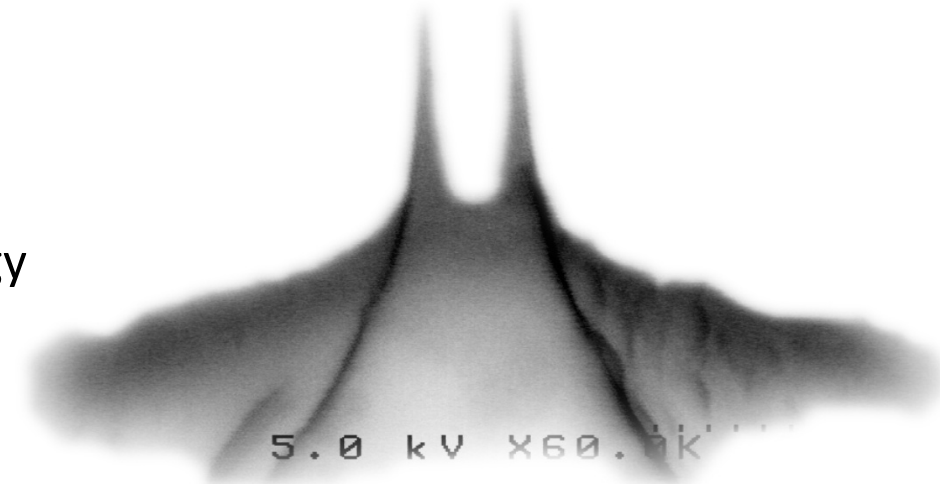
•High-frequency response has not yet been measured or simulated

•Process flow for double-gated devices has yet to be determined



DFEAs have several advantages over photocathodes:

- Rugged: high thermal conductivity and chemically inert
- Tolerate poor vacuum operation, 10^{-5} Torr, transport in air
- Can be conditioned for highly uniform emission
- Degrade gracefully (ungated)
- No drive laser required
- Compatible with NCRF/SRF technology
  - No heat generated
  - No laser window required
- Photocathode survival in Ampere-class injectors is uncertain



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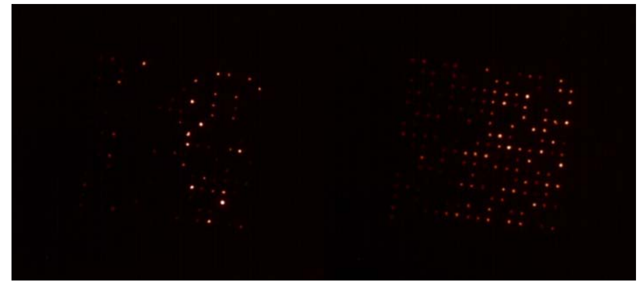
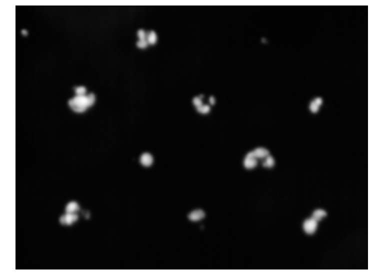
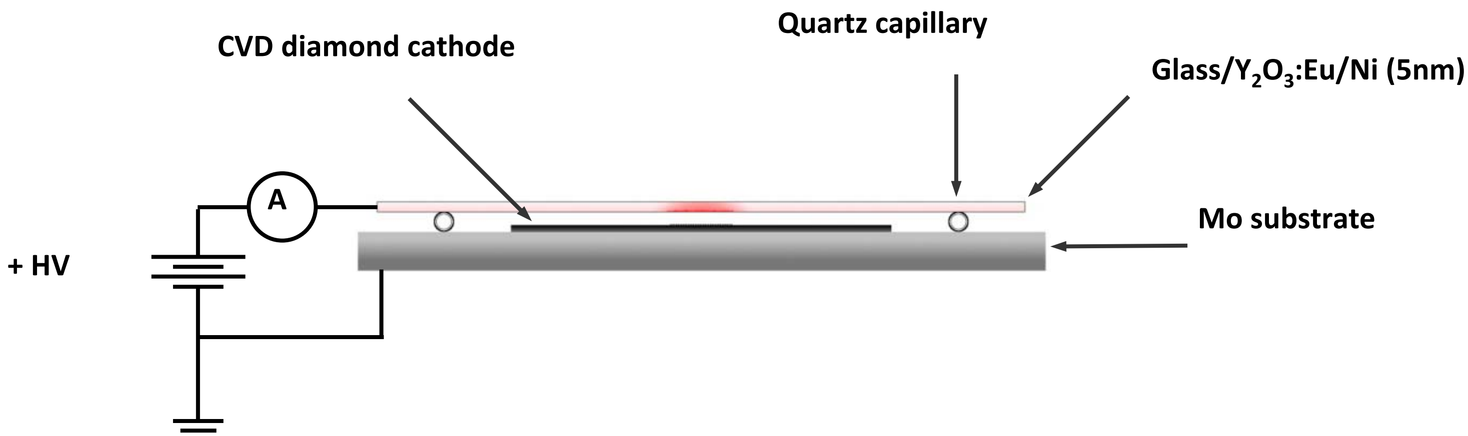
DFEAs can be conditioned for highly uniform emission:





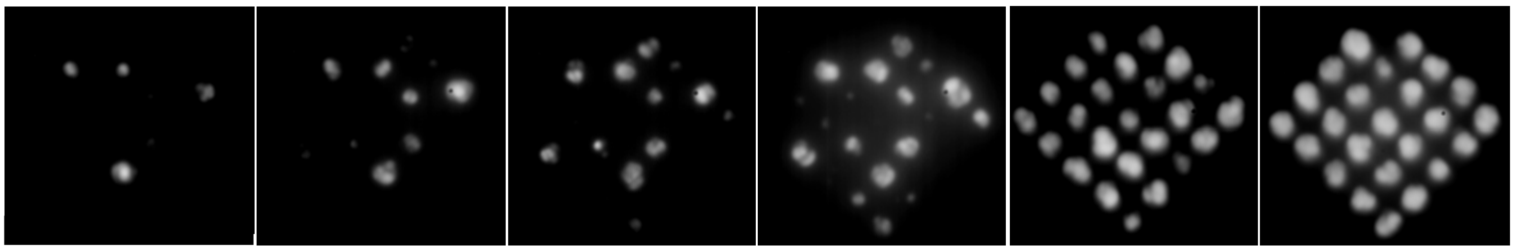
Investigated several conditioning methods:

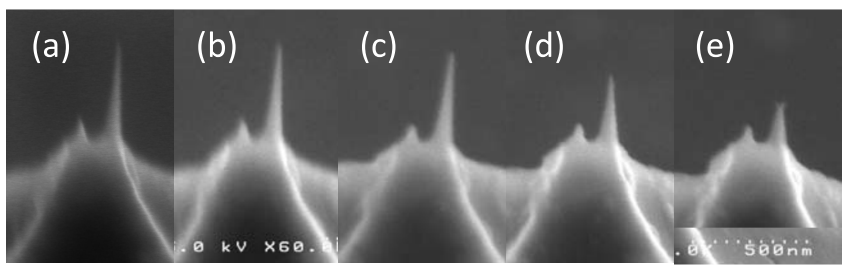
1. Selective gas exposure
   - no improvement thus far
2. Thermal conditioning
   - High-field annealing of tightly adsorbed species
   - Greatly improved temporal stability
3. Moderate/high current operation
   - Morphology changes by thermal-assisted field evaporation

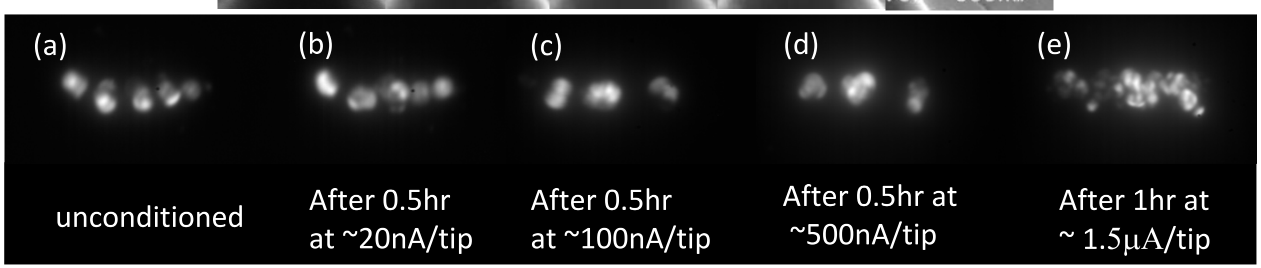


High-current conditioning is the most successful thus far:

- Evaporation of nanotips is self limiting, leading to highly uniform emission.
- Similar to pulsed conditioning of Spindt cathodes.
- DC Studies limited by anode destruction (maximum per-tip current thus far : 15 μA)







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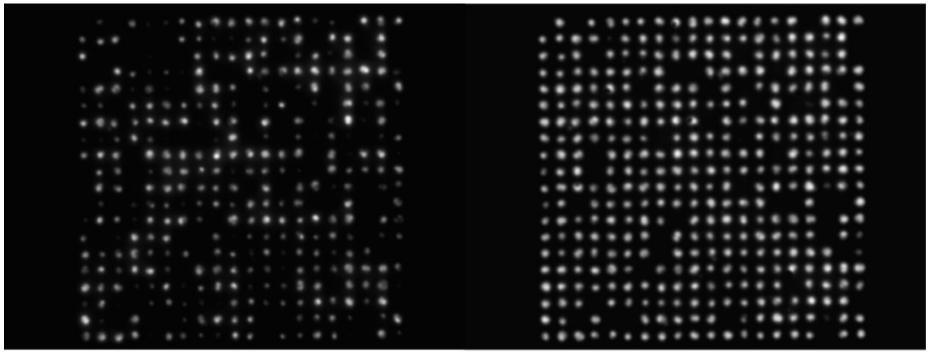
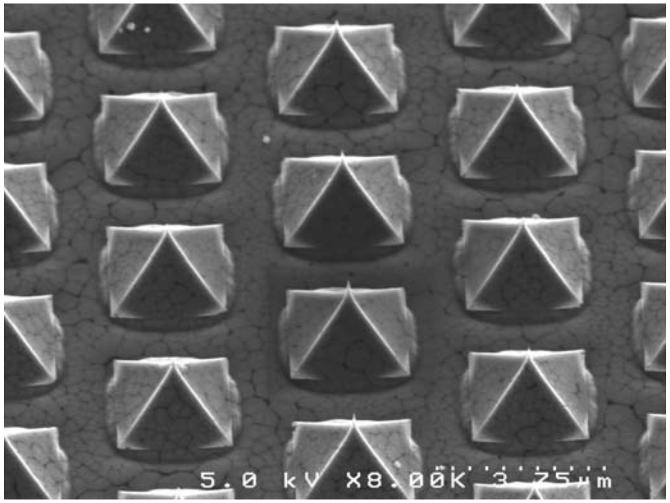
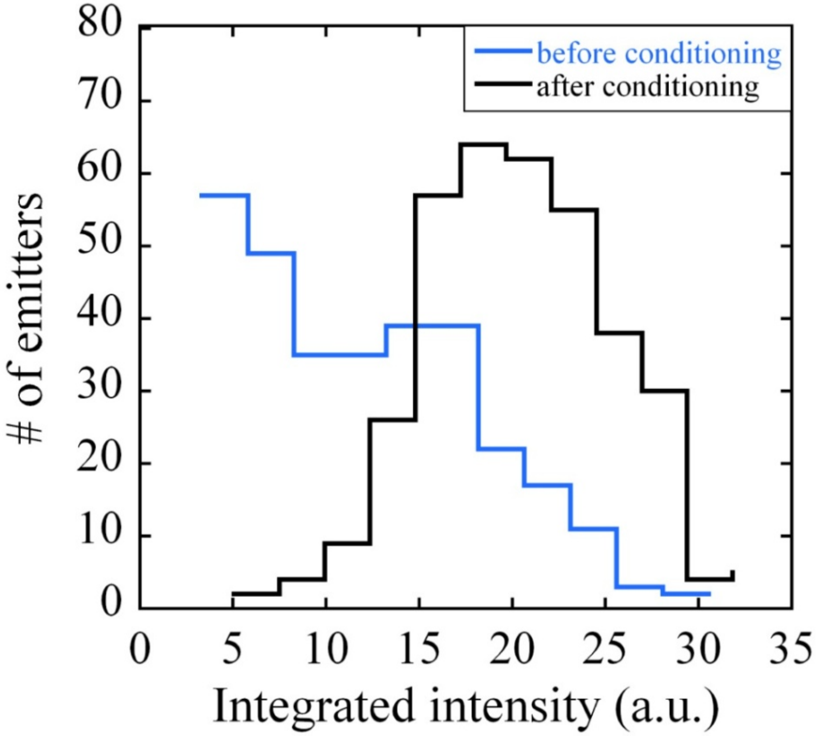
Close-diode DC conditioning is only possible for large-pitch arrays:

- Anode destruction prevents DC conditioning of dense arrays

- For 4 μm pitch array, 15 μA/tip, and 1.5 kV beam energy, the power density at anode is 100 kW/cm^2

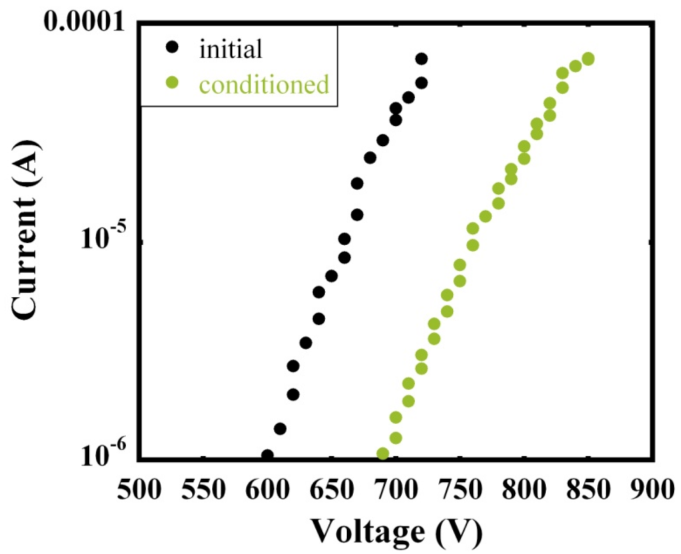


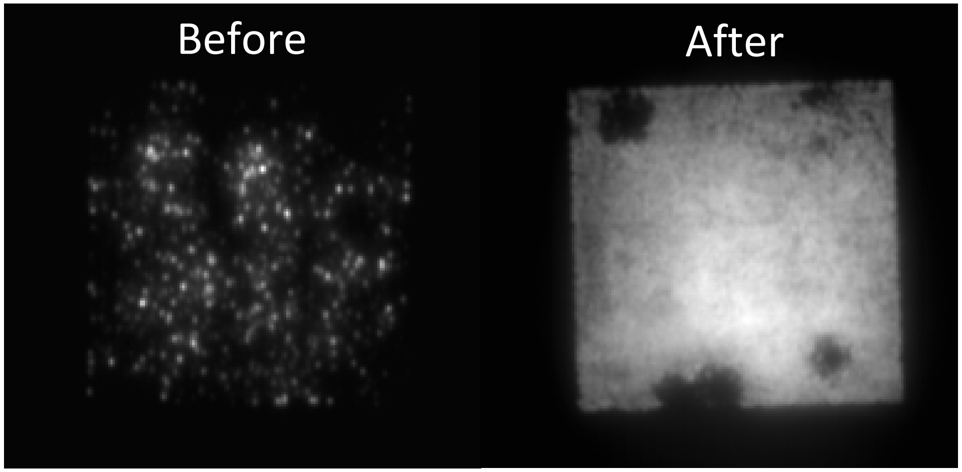




Pulsed operation at microsecond time scales allows conditioning of dense arrays:

•Microsecond pulsing limits anode temperature rise to a few hundred °C

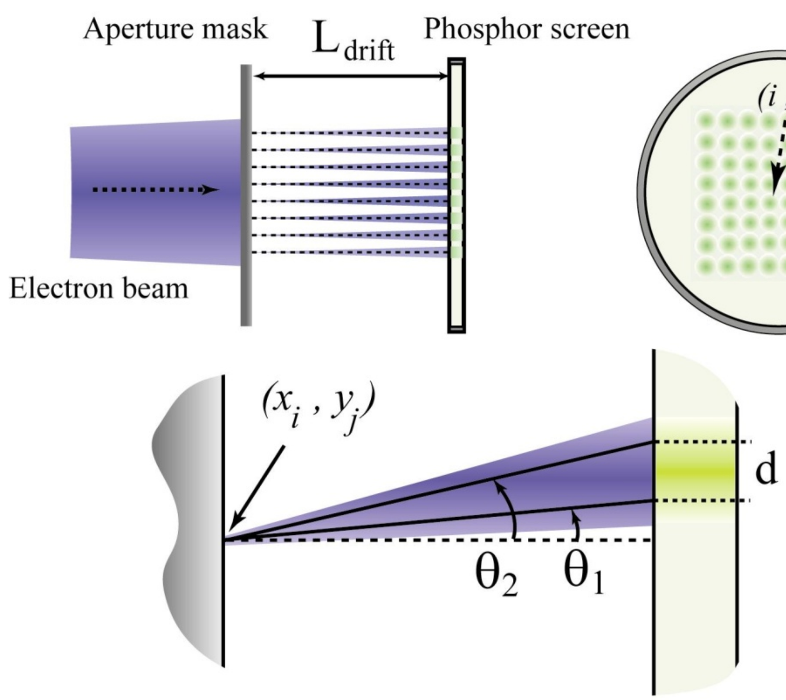


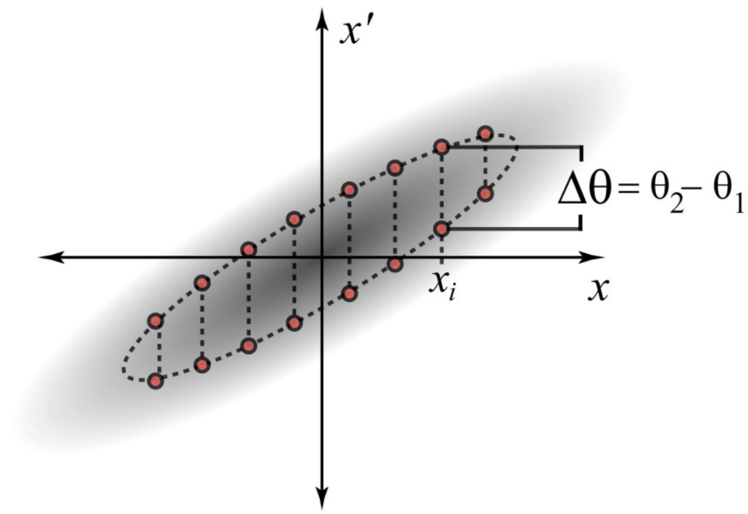


•Pulsed operation of a 4 μm pitch array recently achieved ~30 A/cm^2 (~5μA/tip), limited by power supply.

The emittance can be measured with a pepperpot technique:

- Aperture array inserted into the beam samples the divergence for various transverse positions
- This allows the beam's "transverse trace space" to be determined





$$\epsilon_{N_x} = \beta\gamma\sigma_x\sigma_{x'}$$

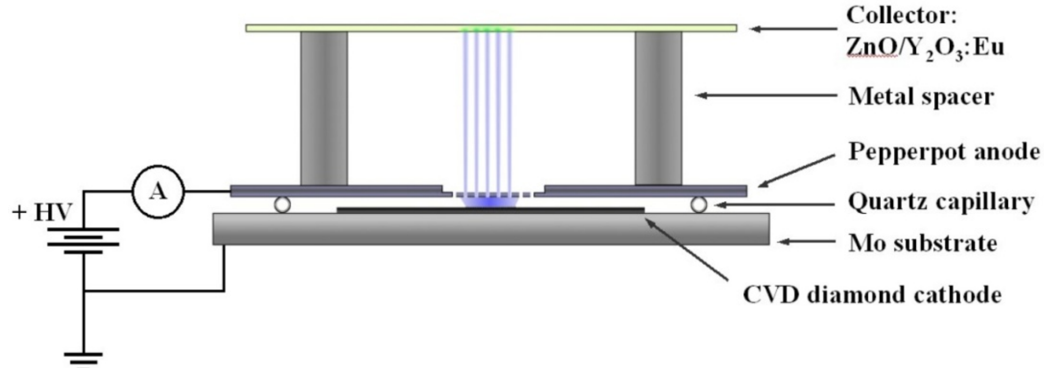
Emittance for ungated arrays has been successfully measured:

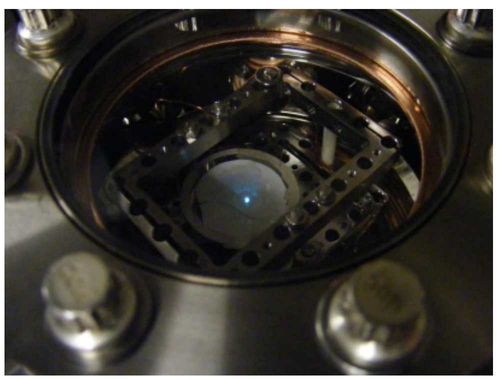
•For uniform emission, we may measure the expansion of a single beamlet

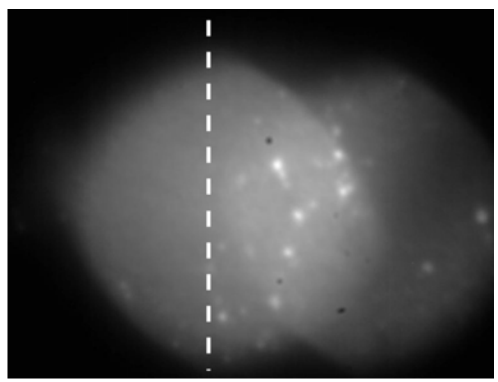
•Estimated rms divergence of ~38 mrad

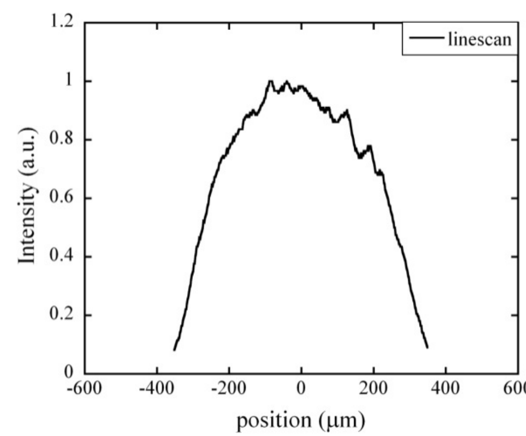
•For 2 kV beam and a 1 mm cathode, normalized x-emittance is:

$$\epsilon_{N_x} \approx 1 \text{ mm-mrad}$$





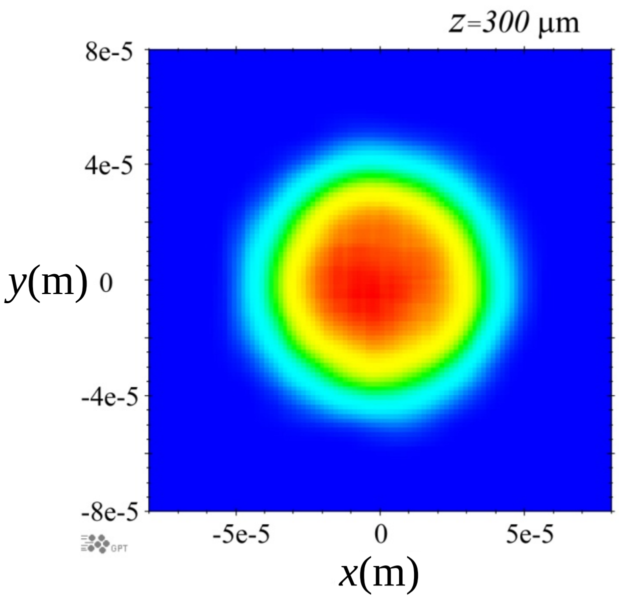


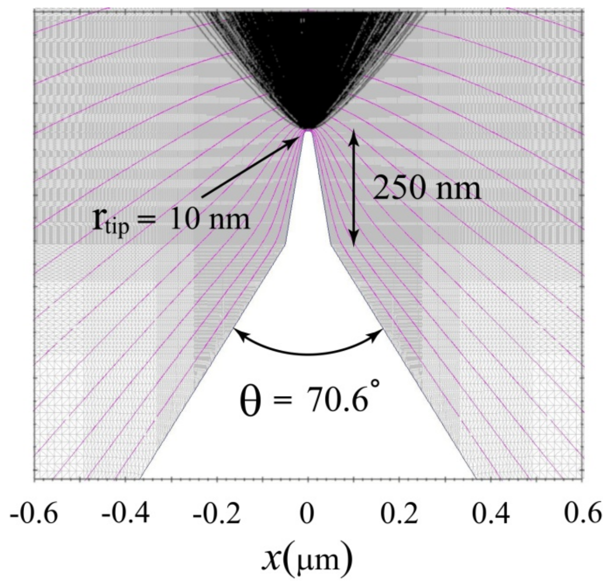


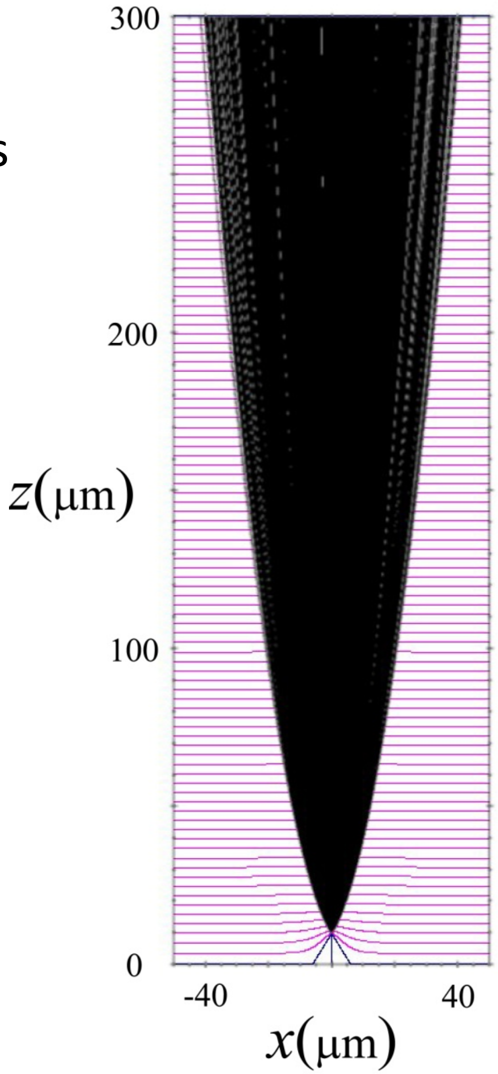
Simulated single tip divergence agrees well with experiment:

- Simulations performed in POISSON/GPT

- For the same conditions, the simulated rms divergence is ~40 mrad

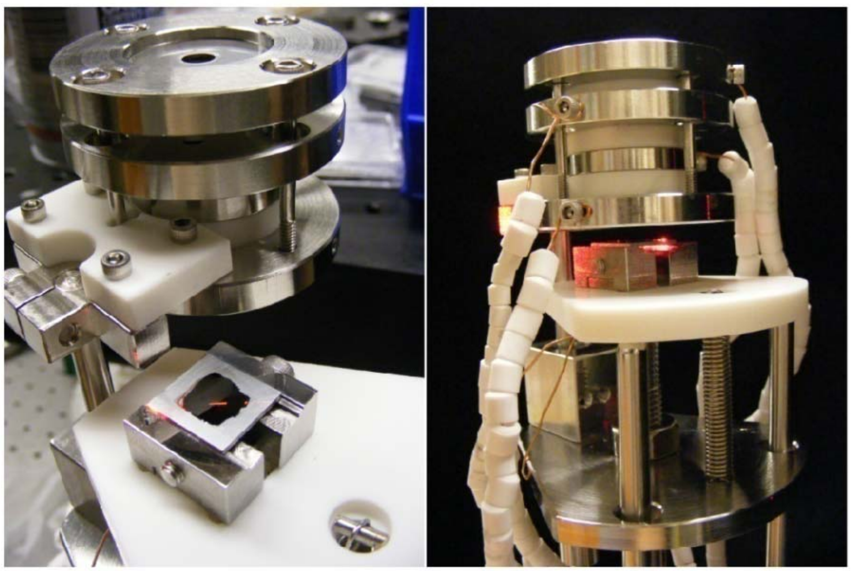


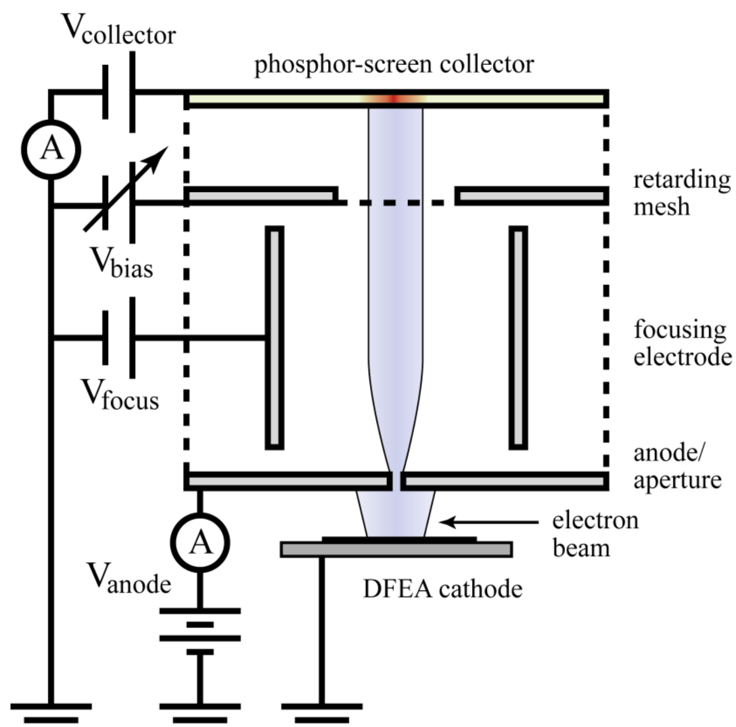




High-resolution energy analyzer built for examining spectrum from DFEAs:

- Based on University of Maryland (UMER) design
- Focusing electrode improves resolution by several orders of magnitude
- Integrated into DC teststand capable of anode-cathode planarity and gap adjustment during high-voltage operation



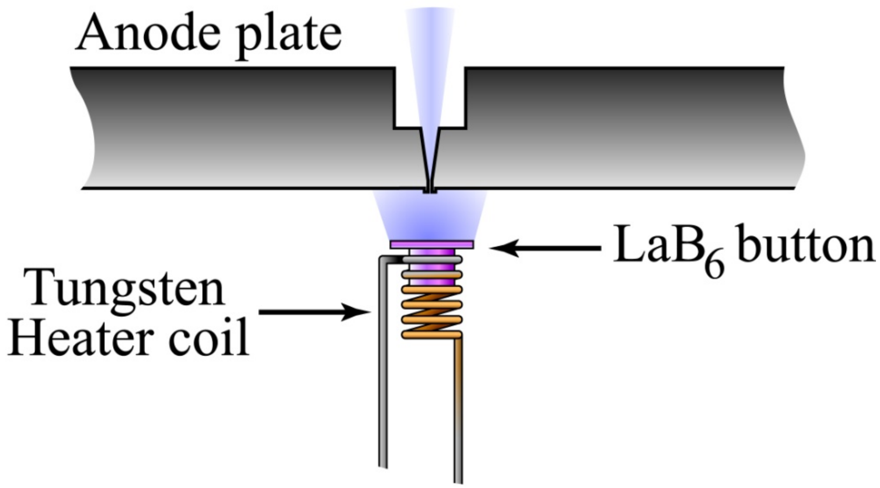


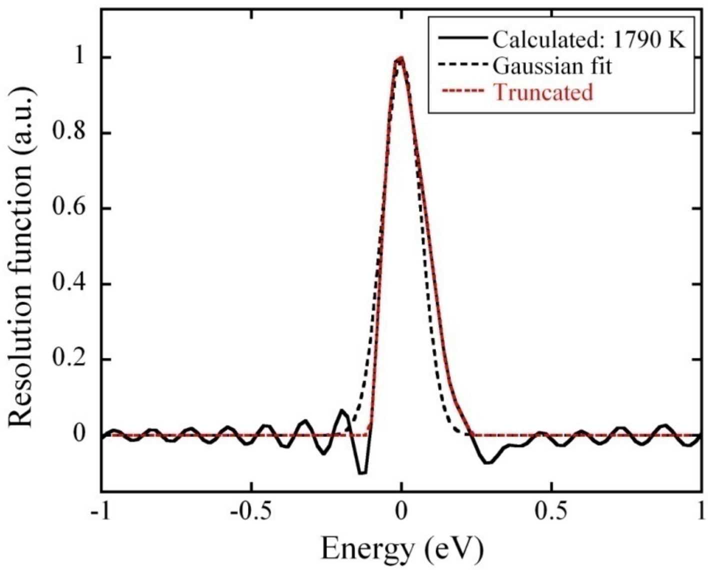
Instrumental broadening by analyzer was determined with a thermionic source:

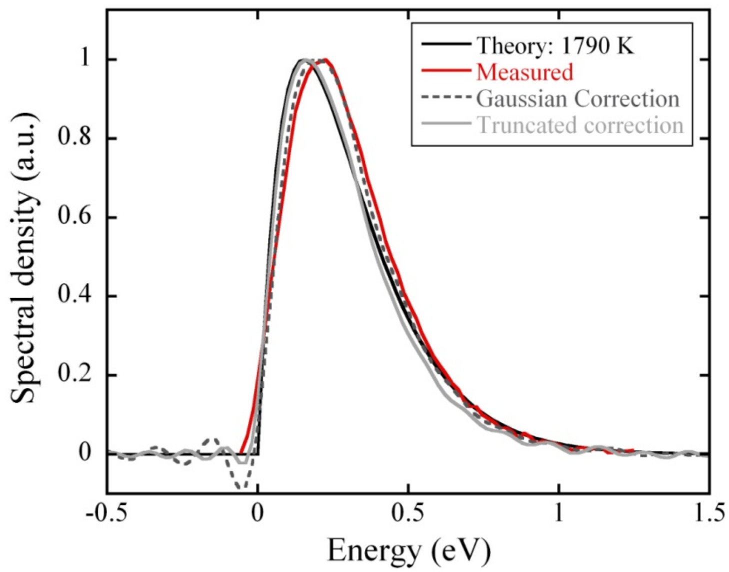
•Known thermionic distribution is used to extract the analyzer's resolution function; FWHM = 0.15 eV

•Measured distribution agrees well with theory

•DFEA spectra can be measured with confidence







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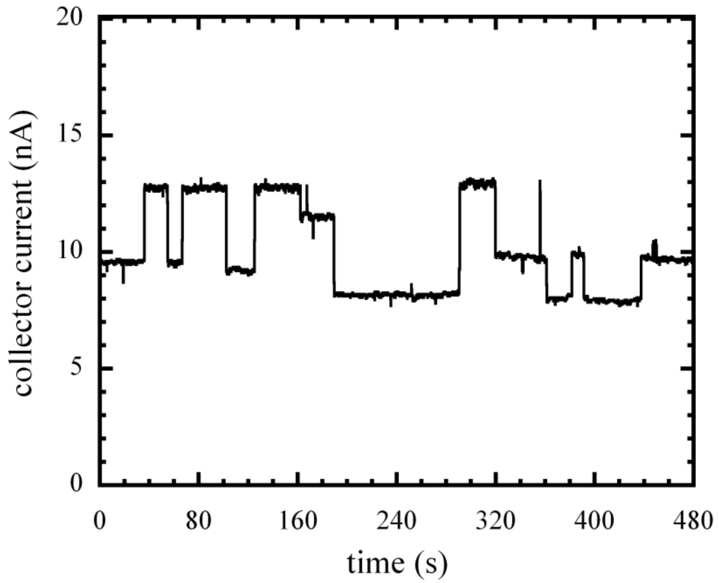
From previous experiments, emission is expected to be adsorbate dominated:

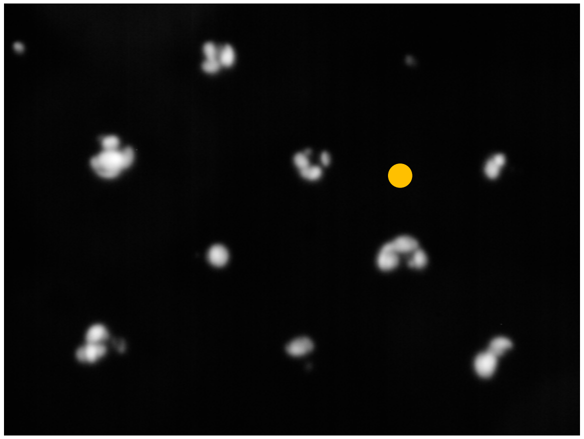
•Adsorbates are known to modify the intensity and spectrum of field-emission

•Resonant tunneling effects greatly enhance the tunneling probability at certain energies

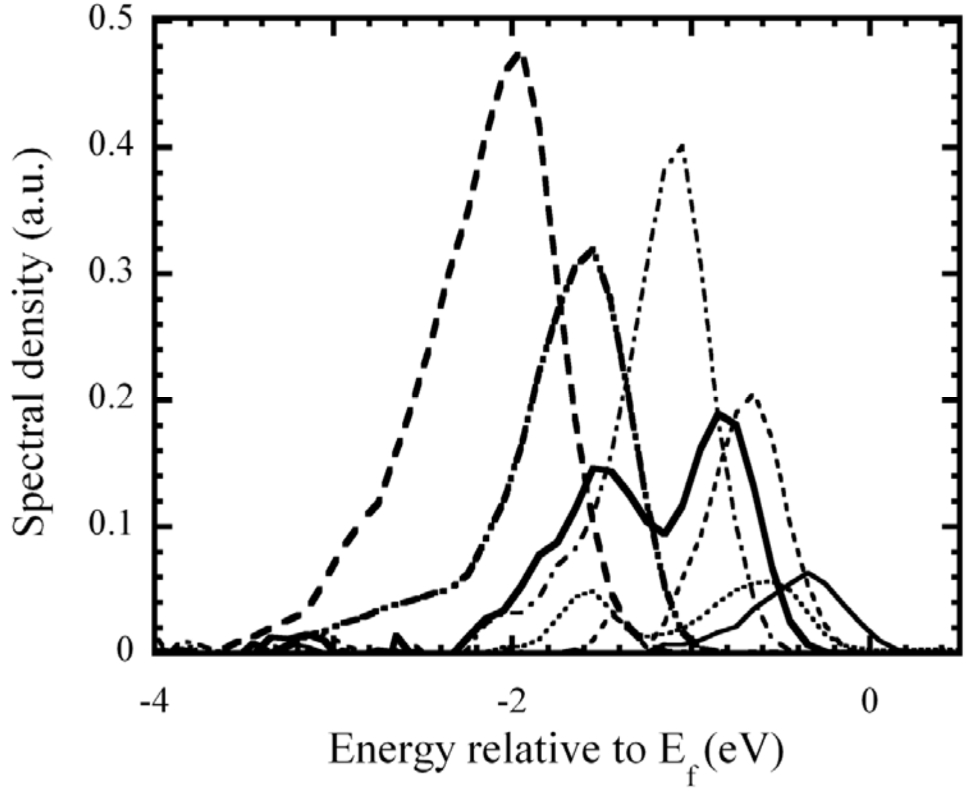
•Typically, adsorbates remain stable for many seconds (long enough to acquire spectra)

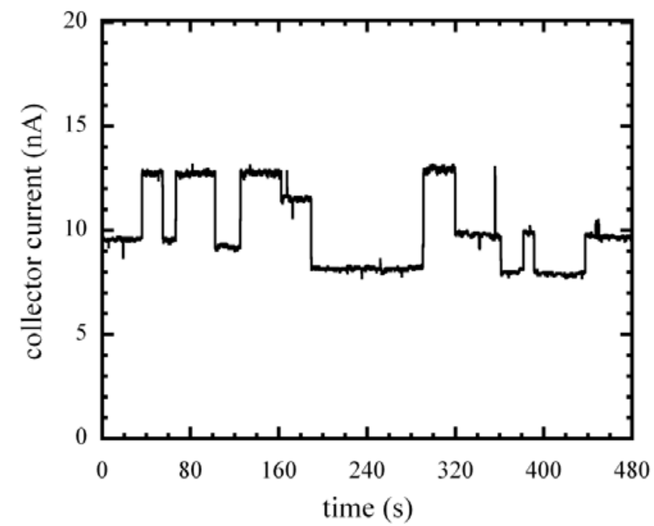
•Analyzer aperture examines current from a single tip at a time





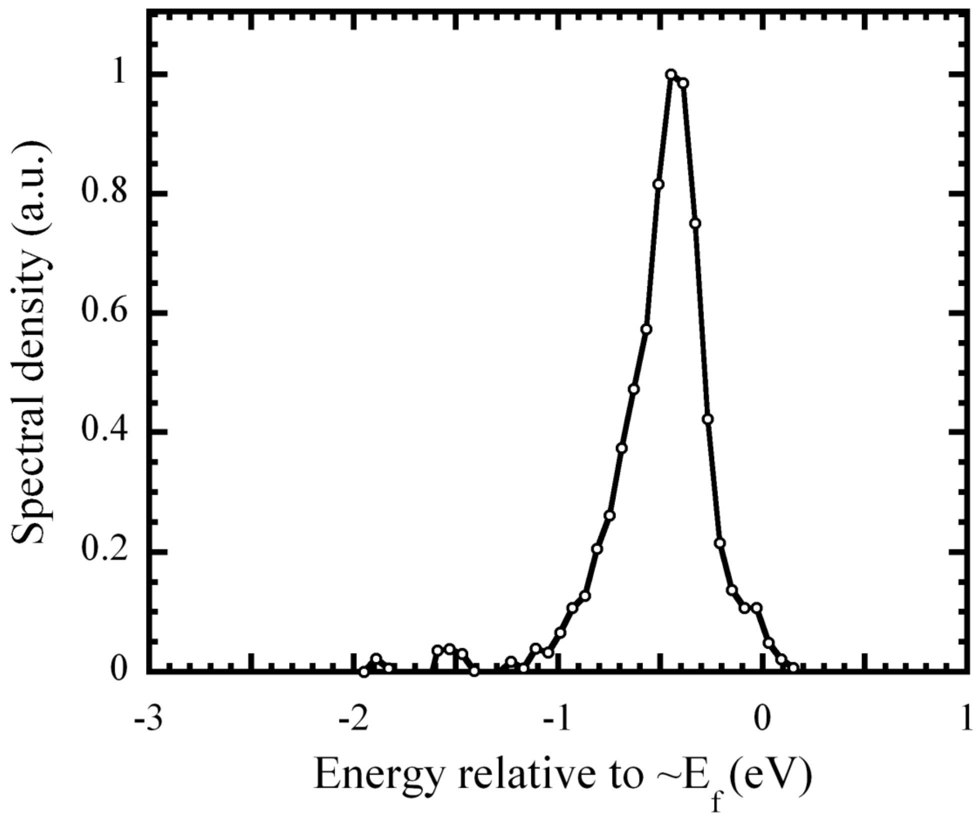
Adsorbates significantly modify the energy spectrum of a clean emitter:





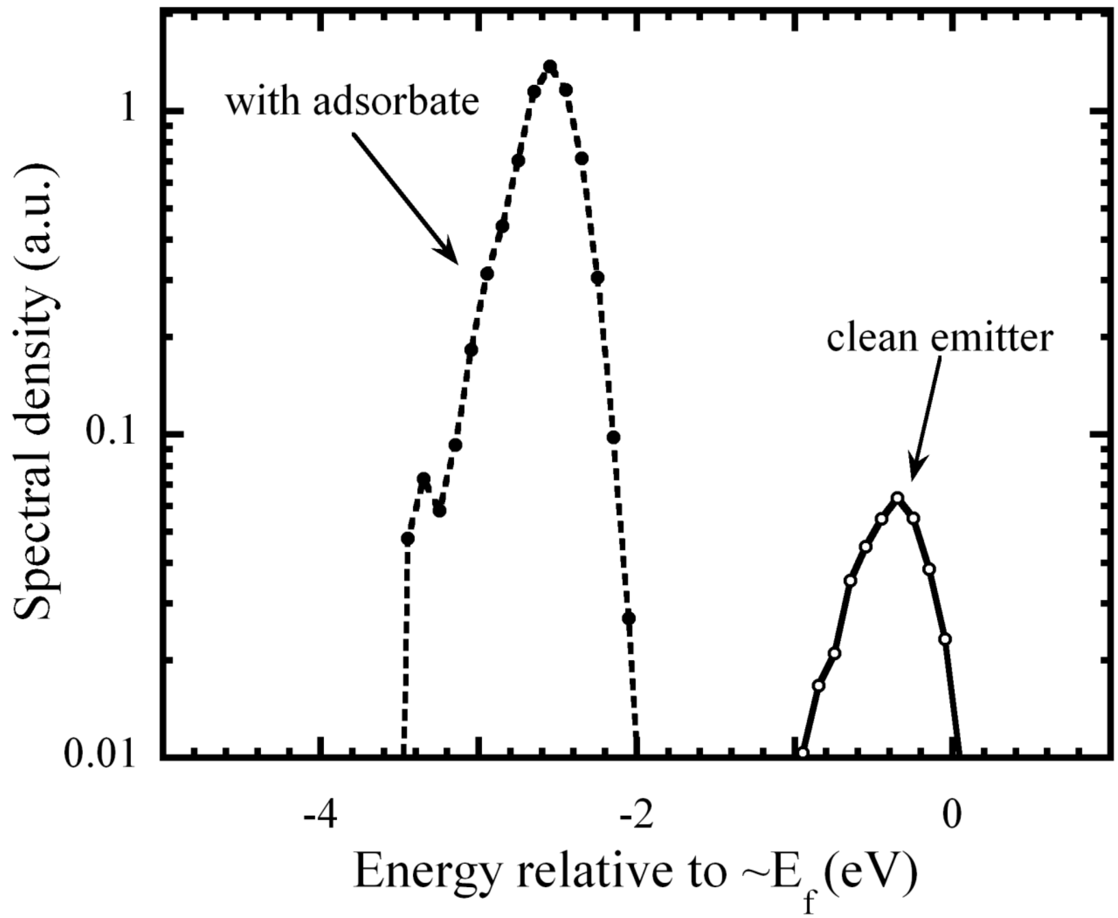
- Each spectrum taken for identical experimental conditions during various periods of stable emisison
- Transitions between spectra are concurrent with emission current fluctuations

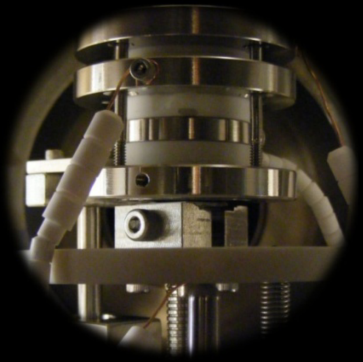
Spectrum from a clean emitter (purported) is similar to that of metals:



- Expect "clean" spectra to occur at low intensity and near the Fermi energy
- FWHM of ~0.3 eV, narrowest spectrum observed
- The effects of varying sp^2, sp^3, boron, and nitrogen unknown

Observe order-of-magnitude current enhancements without spectral broadening:





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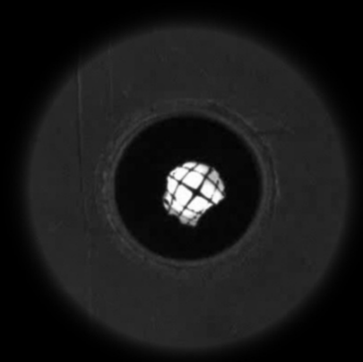

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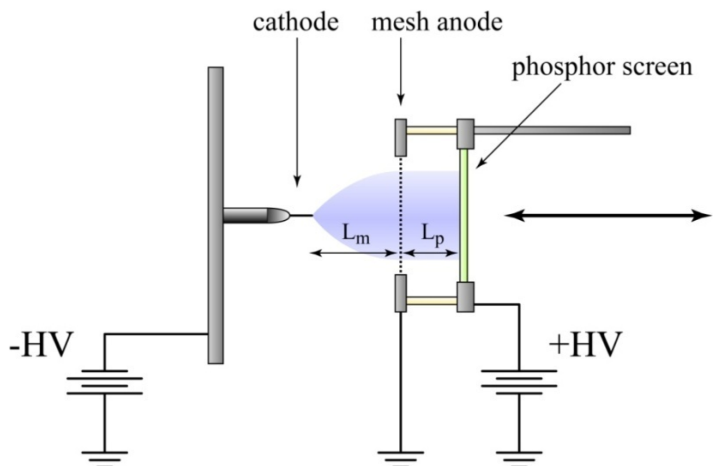
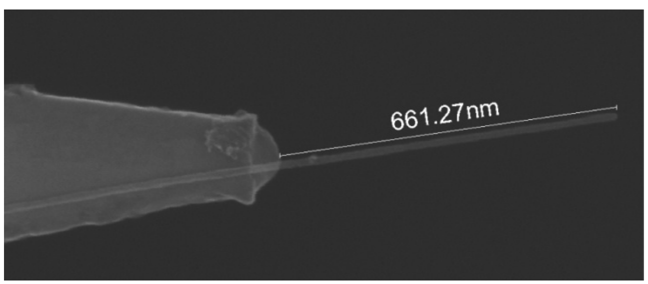
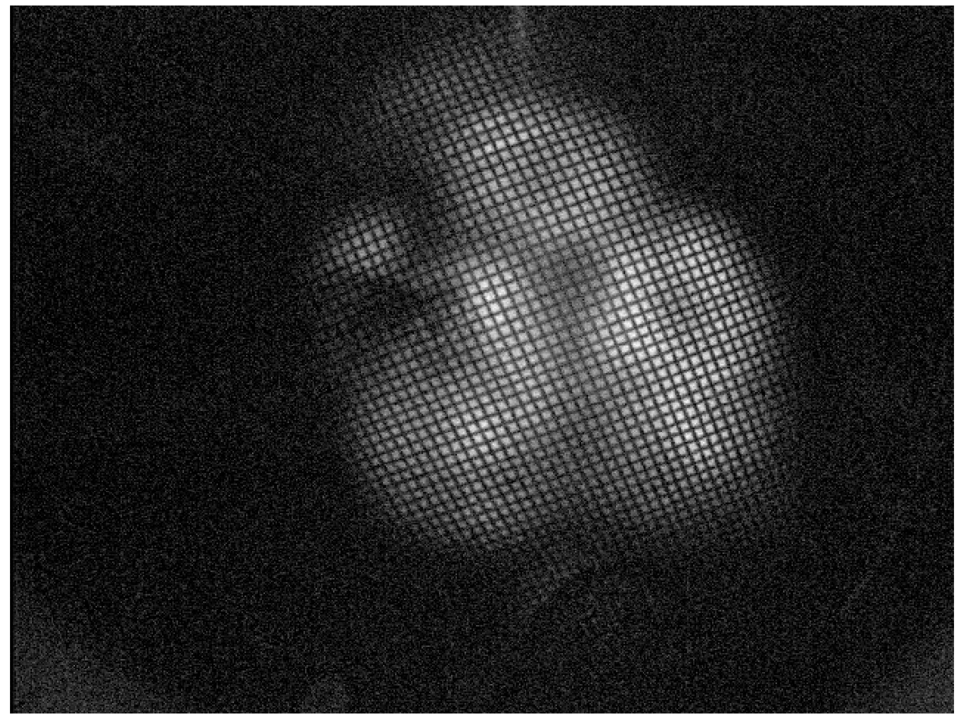
A field-emission microscope was built for studying CNT field emisison:

•Large fields at the emitter surface "freeze" in an image of the emission area







•Pentagonal rings, indicative of a clean nanotube cap, are clearly visible

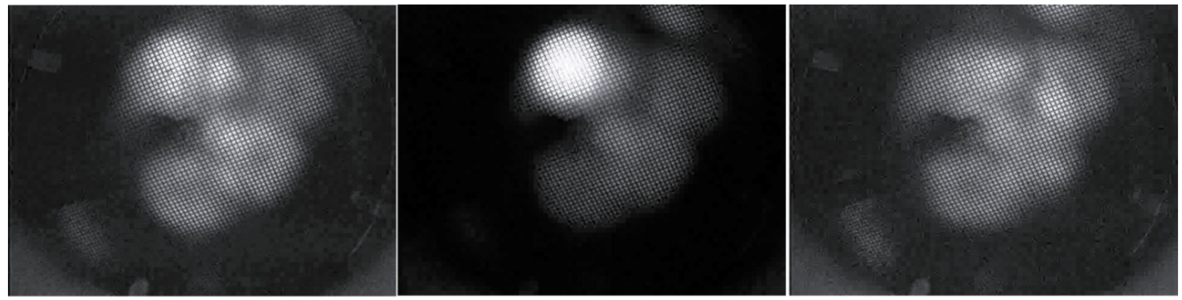
•Adsorbate migration and large, localized current enhancements are seen

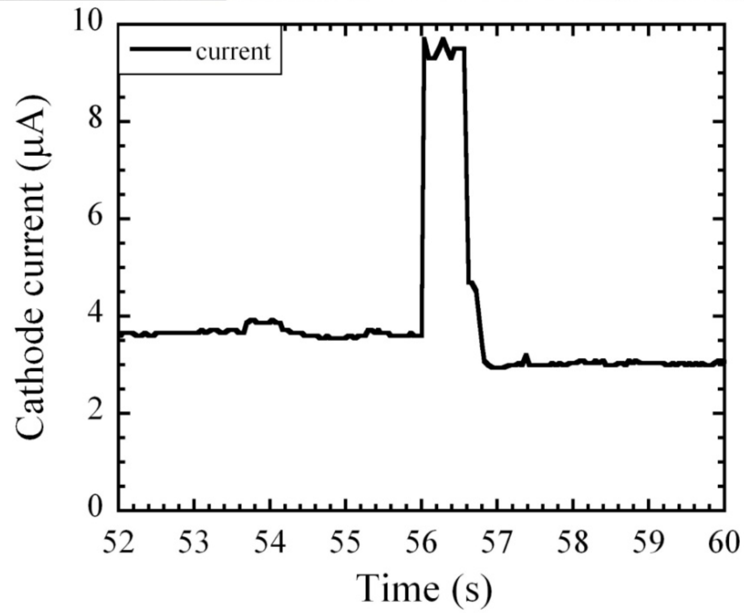
An adsorbate on a carbon nanotube field emitter may produce a QDEB:

- A single adsorbate more than doubled the total emitted current (+6 μA)

- Transient event, only lasting a fraction of a second

- If the adsorbate is presumed to be a single, small molecule, then the brightness is estimated to be quantum degenerate
(assuming dE ~ 0.3 eV)





"Designer" metal adsorbates on CNTs may provide stable QDEB sources:

- Binding energies for residual gases on CNTs are typically fractions of an eV, even with induced polarization from field gradient at tip

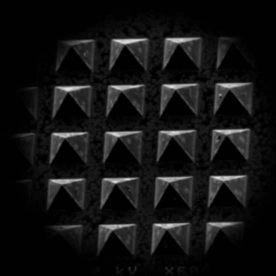
- DFT calculations demonstrate a range of different zero-field binding energies for metals atoms on CNTs

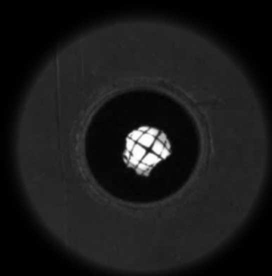
- The goal is to locate a metal adsorbate that significantly enhances local emission, and is stable at the currents required for high degeneracy

- Because of the close parallels between CNTs and DFEA tips, these specialized adsorbates might also be used to enhance DFEA emission properties

Conclusions:

- There is a quantum-degenerate limit to electron beam brightness
- DFEAs can tolerate poor operating conditions, be conditioned for highly uniform emission, be produced in an arbitrary footprint
- While gated arrays are now becoming operational, ungated arrays have demonstrated 30 A/cm^2 in μs-pulsed operation and should easily scale past the 100 A/cm^2 mark. Much higher per-tip currents might be achievable in ps pulses.
- DFEAs are slated for testing in several RF guns (ANL, NPS, LANL)
- The importance of adsorbed species in field emission from DFEA tips has been established
- The use of specialized metal adsorbates on CNTs may provide a 10 μA level QDEB source
- DFEA performance might be improved in the same manner





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