Superconducting niobium nanotip electron field emitter

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Motivation: New cold electron field emitter for microscopy and QIS

General motivation:

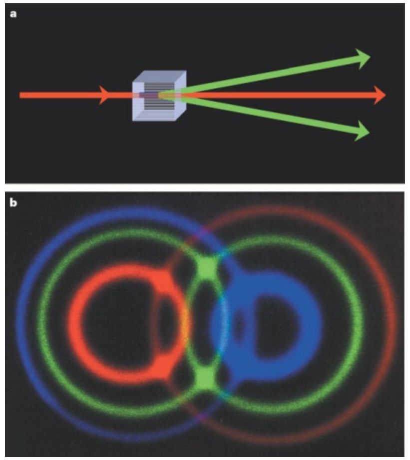
Using electron quantum features such as
- Superconductivity
- Coherence
- Entanglement

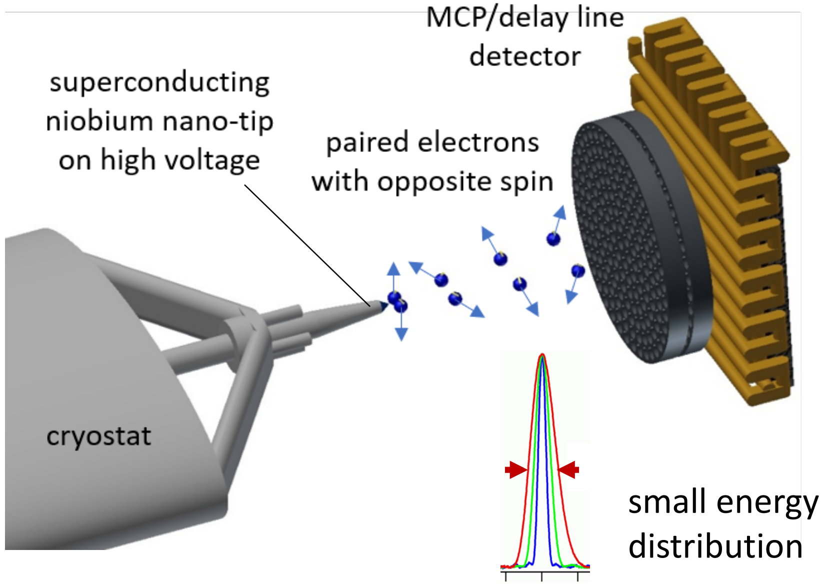
For:
- Microscopy/Spectroscopy
- Quantum communication
- Sensor applications

Specific motivations:

1) Development of a coherent, intensive electron source with ultra-low energy distribution (SBIR with Electron Optica)
2) Development of an entangled two-electron field emitter (DOE QIS project “QUINTESSENCE”)

In analogy to quantum information science (QIS) with entangled two-photon source

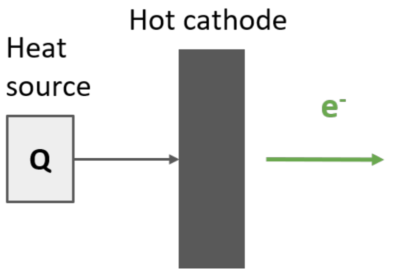


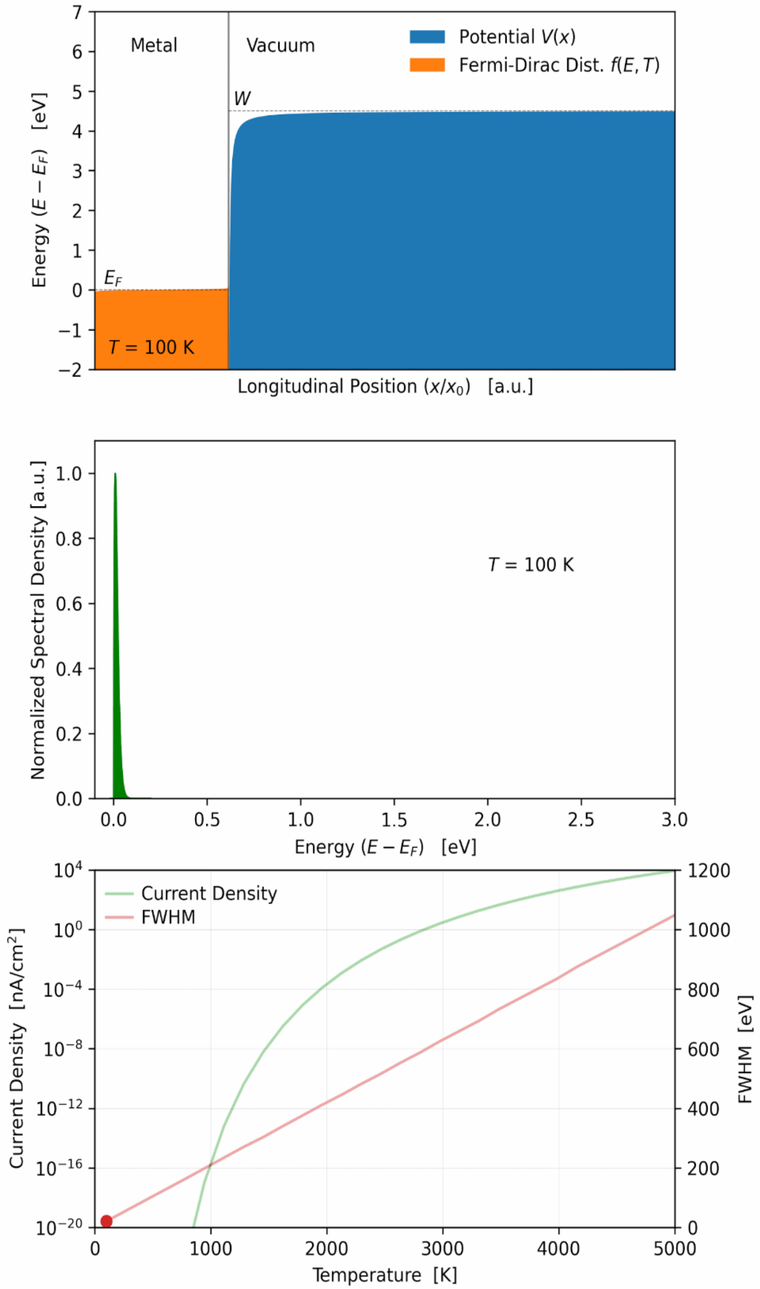


Will allow unique tools:
- ⇒ Ultra-low energy distribution electron beams
- ⇒ Decreasing aberration effects in microscopy
- ⇒ Ultra-high resolution electron spectroscopy
- ⇒ QIS with entangled electrons
- ⇒ Non-interactive soft surface analysis
- ⇒ Two-electron interferometry
- ⇒ Decoherence studies for quantum materials

Introduction: Electron beam emitter types

Thermal emission:





Heating a metallic cathode:

⟹ Population in the electron density of states above the Fermi energy E_F

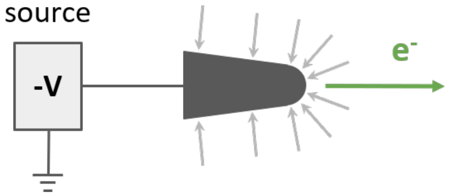
⟹ According to the Fermi-Dirac distribution

⟹ Electrons above the work function W are emitted into vacuum

⟹ Thermionic emission

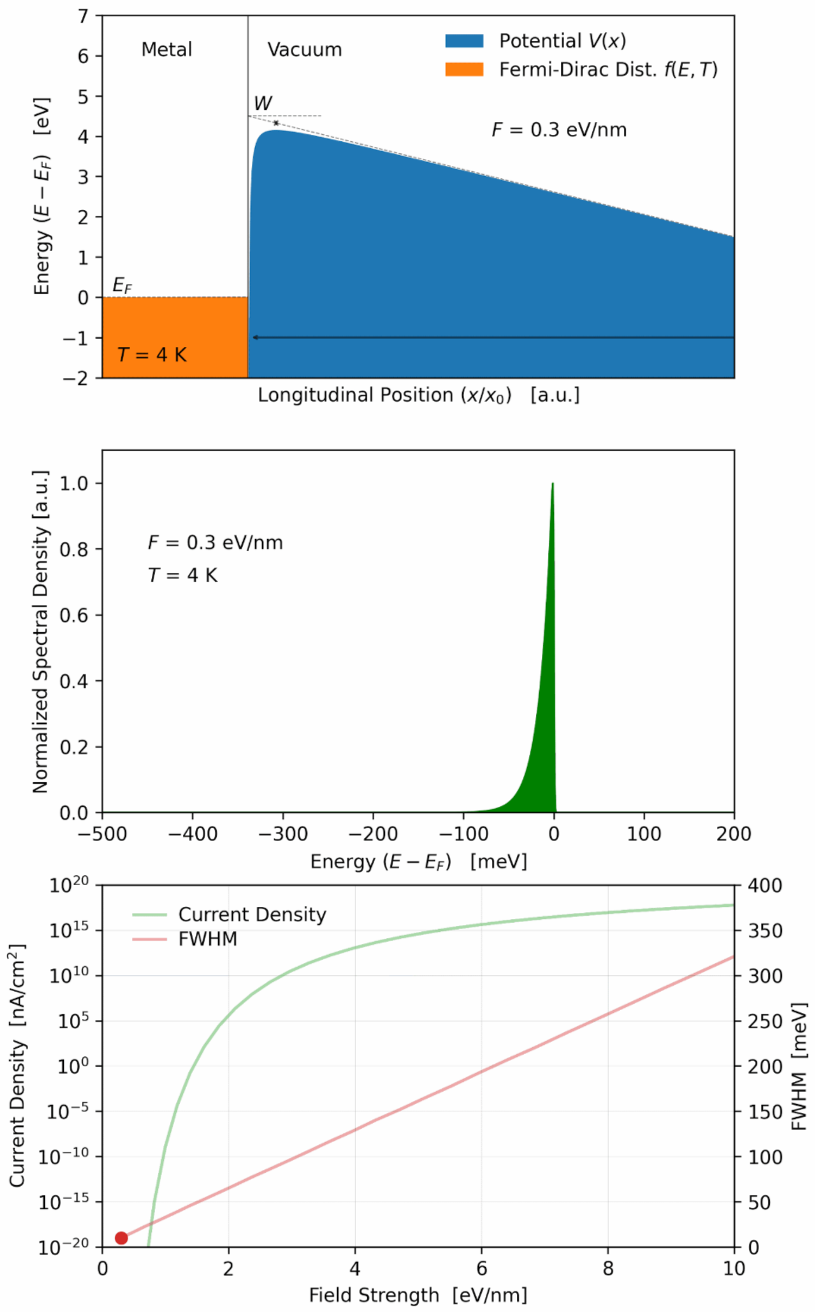
⟹ Broad energy distribution

Fowler-Nordheim field emission:



Field enhanced by tip geometry

$$F = \beta V$$



Cold field emission:

⟹ Lowering Coulomb barrier by field voltage

⟹ Enables tunneling Fermi energy E_F

⟹ Described by Fowler-Nordheim distribution

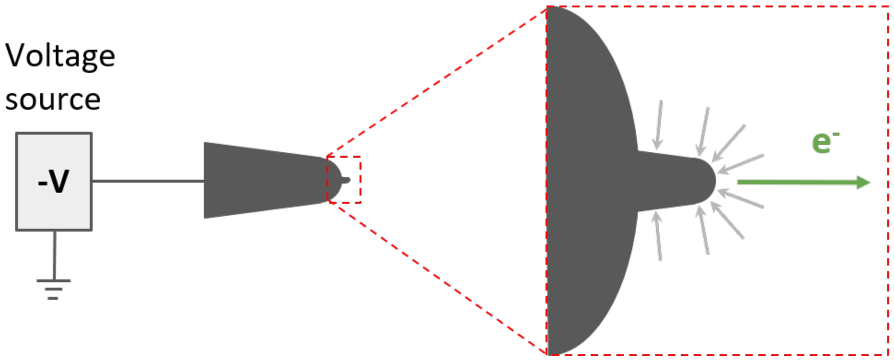
⟹ Narrow energy distribution

Resonant tunneling field emission

⇒ High aspect ratio nanoprotrusion on a nanotip

⇒ Discrete localized surface states supplied by bulk Fermi sea electrons

⇒ Allows ultra-narrow energy distribution when state is close to E_F



Total energy distribution

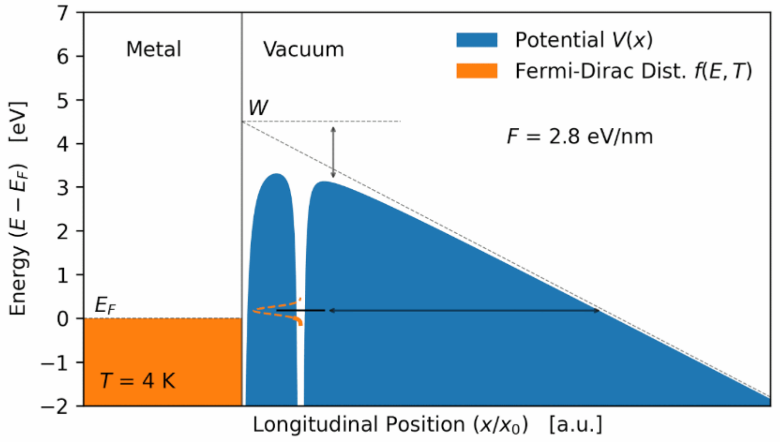
$$g(E,T) = g_{FE}(E,T)\sum_j g_j(E,T)$$

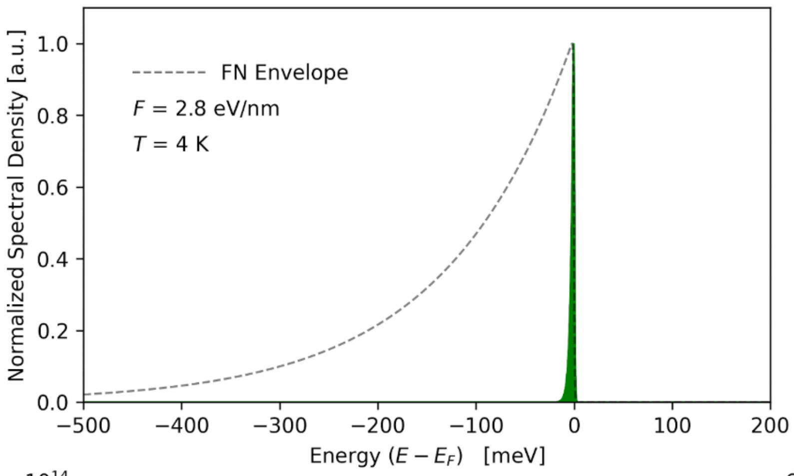
Energy distribution from tip field emission

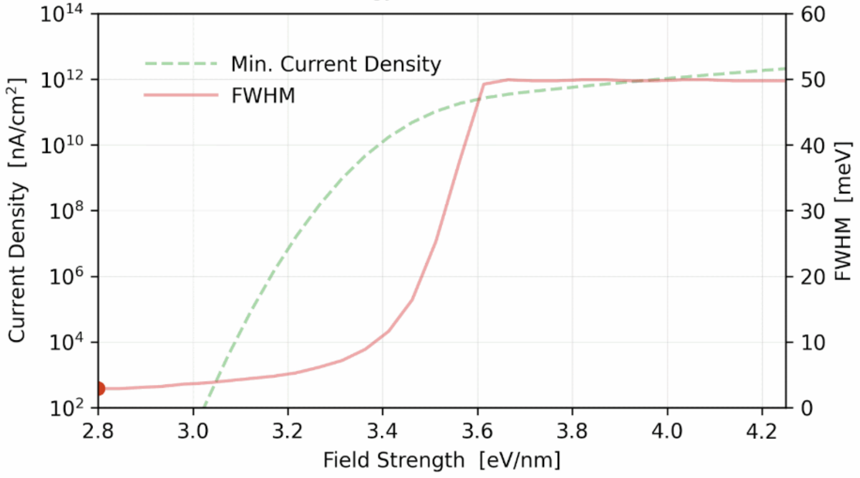
Local density of states for each discrete state (surface energy bands)

Additional due to geometry:

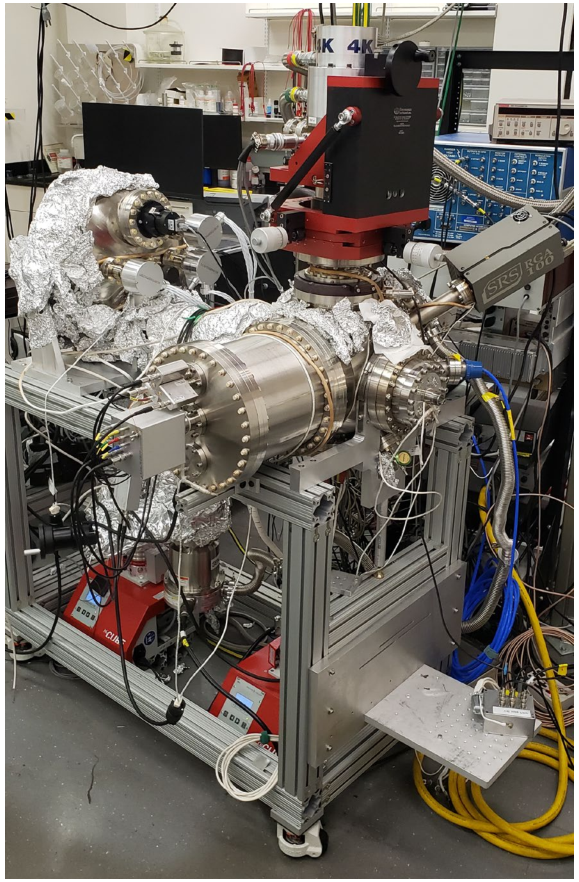
⇒ Field enhancement and self-focusing: low emission angle

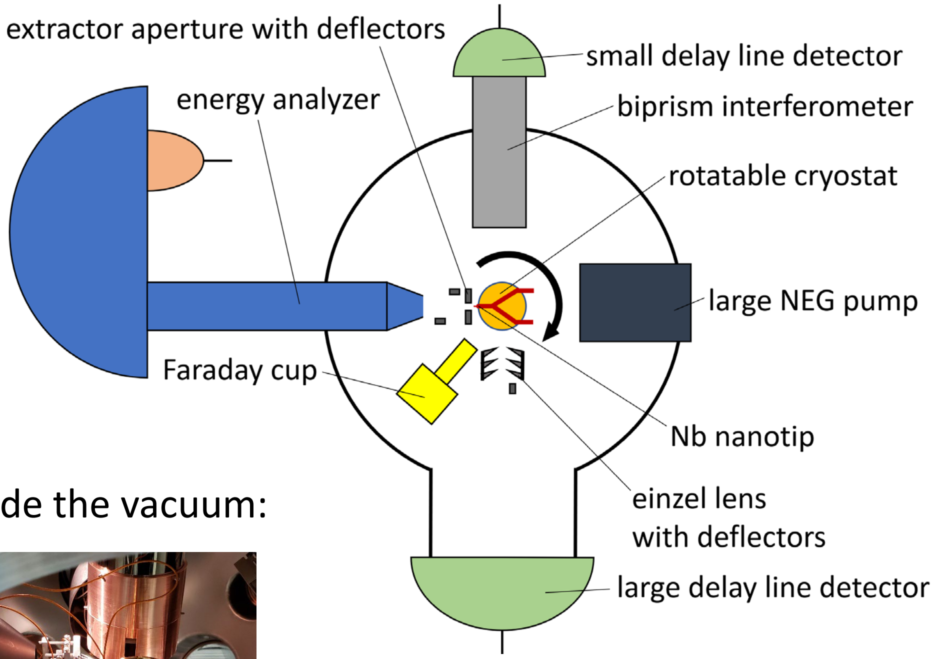




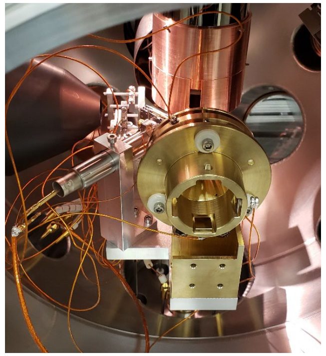


Field emitter test and characterization vacuum setup established in the Quantum Lab 1201 at the Berkeley Lab Molecular Foundry:





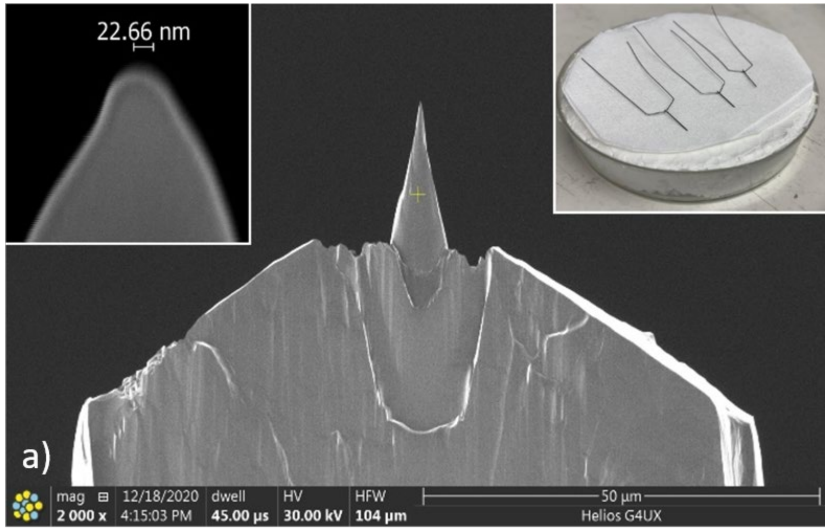
Inside the vacuum:



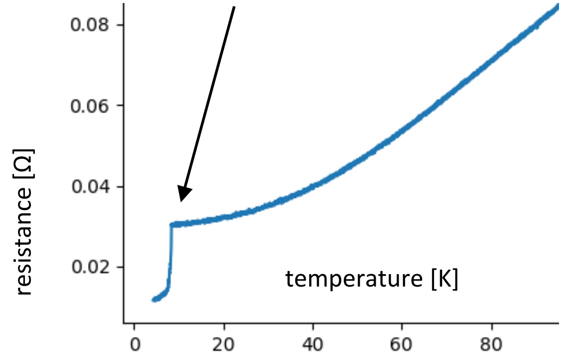
Our approach:

⇒ Fabricate monocrystalline superconducting Nb nanotip
⇒ Measuring electron energy spectrum in analyzer
⇒ Determining pair-correlations with delay line detector

Monocrystalline Nb tip spot welded on Nb bar and fabricated by electro-chemical etching and FIB ion milling (r < 23 nm):



Superconducting transition of our monocrystalline Nb tip at 9.3 K



Nb nanotip emission at 4K: Observation of surface states with ultralow energy distribution

- At tip voltage of -650 V best full-width-half-maximum (FWHM) value: 19 meV
- Subtracting instrument noise/resolution: FWHM = 16 meV
- About one order of magnitude lower than conventional cold field emitter!

Related to annealing process:

- 3 classes of field emission observed

Unpublished data, visible in the live presentation

Nb nanotip at 4K: field emission characterization

Unpublished data, visible in the live presentation

Do we really have surface band structures?

Can be checked by changing the local field on the tip:

⇒ Applied -604 V on tip: Measured peak E_1

⇒ Applied extractor lens voltage of +170 V

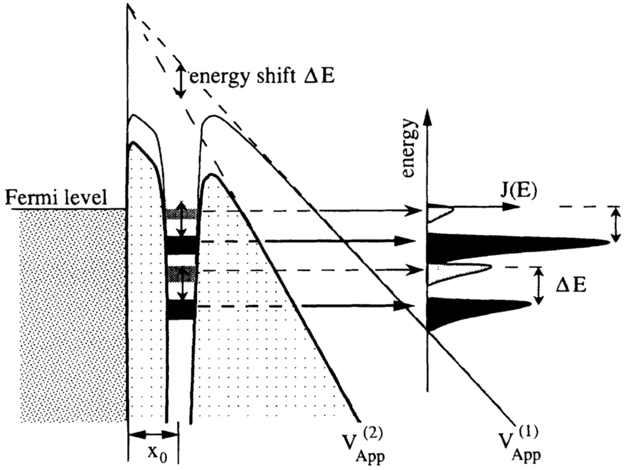
⇒ Emitted current went up (to 1 nA) and peak shifts down to E_2

⇒ Both distributions visible: Fowler-Nordheim and surface state

⇒ Comparable to data in literature

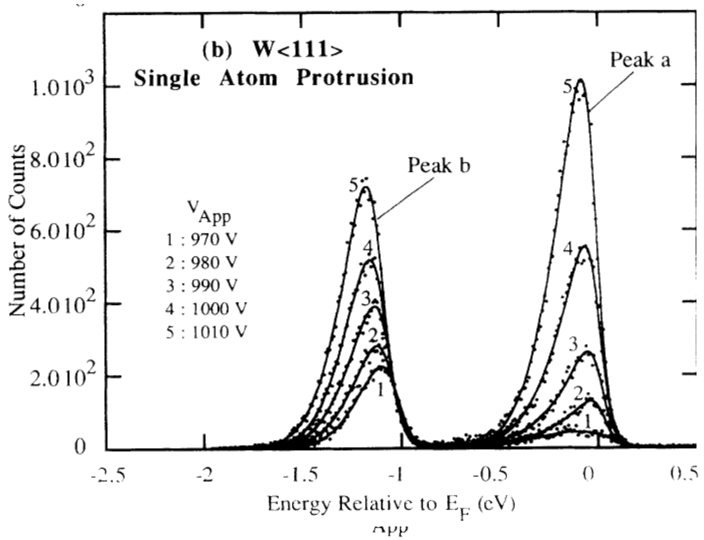
Data comparison:

➢ W-tip surface band structure field emission by Binh et al.:



V.T. Binh et al., PRL 69, 2527 (1992)

Peak positions shift as function of voltage:



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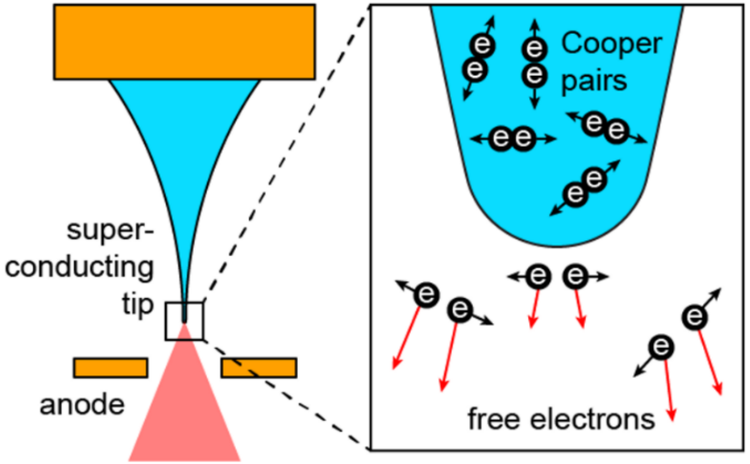
Correlated 2-Electron field emission from Nb tip in superconducting state possible?



- Idea based on experiment by Nagaoka et al. with Nb tip cooled well below T_c (9.2 K)
  - 10-fold increase in intensity (rel. to 25 K)
  - 10-fold smaller energy distribution
  - Claim to be a BCS quantum effect
- Theory suggest (Yuasa et al.:): pairwise, entangled emission
- Solid state measurements and Josephson junctions support that assumption

Our observation:

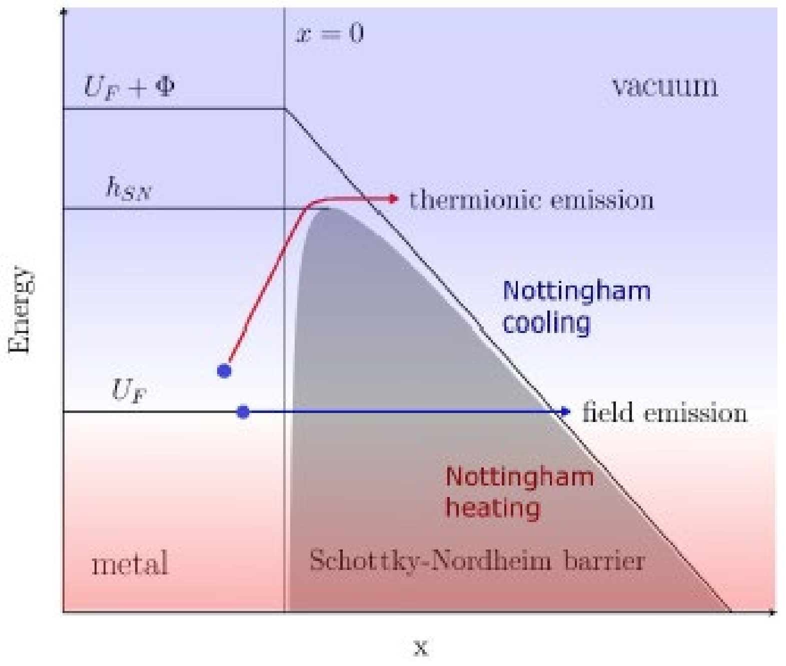
- Energy spectra did not change around T_c
- We made rigorous correlation measurements with delay line detector
- However, no evidence found for correlated electron pairs yet!

K. Nagaoka, T. Yamashita, S. Uchiyama et al., Nature **396**, 557 (1998)
K. Yuasa, P. Facchi, R. Fazio, H. Nakazato, I. Ohba, S. Pascazio and S. Tasaki, Phys. Rev. B **79**, 180503R (2009)
L. Hofstetter, S. Csonka, J. Nygard and C. Schönenberger, Nature **461**, 960 (2009)

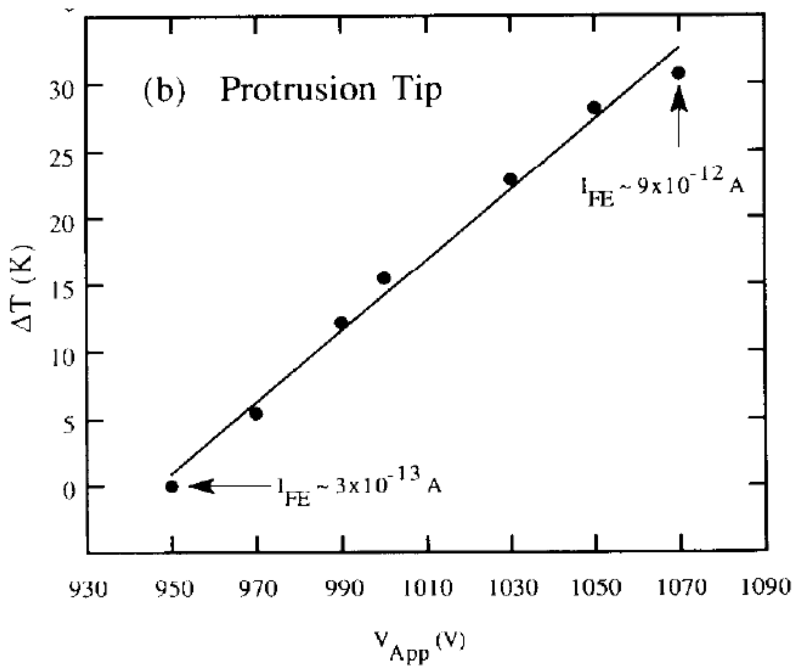
Possible reason for missing two-electron emission: The Nottingham effect

Emitted electrons locally heat the tip:

- The Nottingham effect is characterized by the average energy difference from Fermi energy of the emitted electrons
- Since at low temp. most electrons are below E_F: local heating of electron exit region
- Assumption: Local tip heating above T_c



Taken from lecture by V. Zadin, University of Tartu



*V.T. Binh et al., Surface Science Letters **279** L197 (1992)*

Path to overcome Nottingham heating: Nottingham cooling!

Shown in literature for tungsten with nano-protrusion:

⇒ Peaks from the surface band structure can move above E_F at low voltages

⇒ Nottingham heating turns to Nottingham cooling!

⇒ However, only few electrons left at 4K above E_F

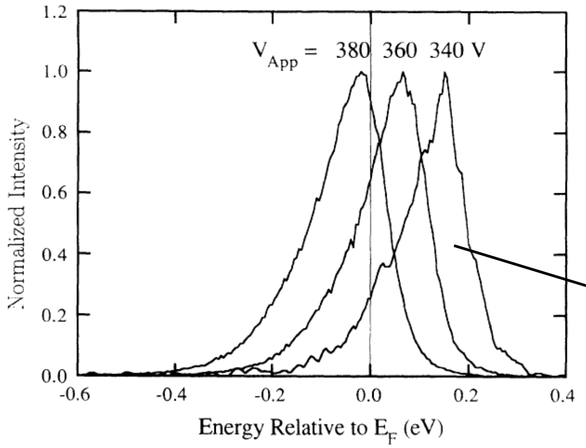
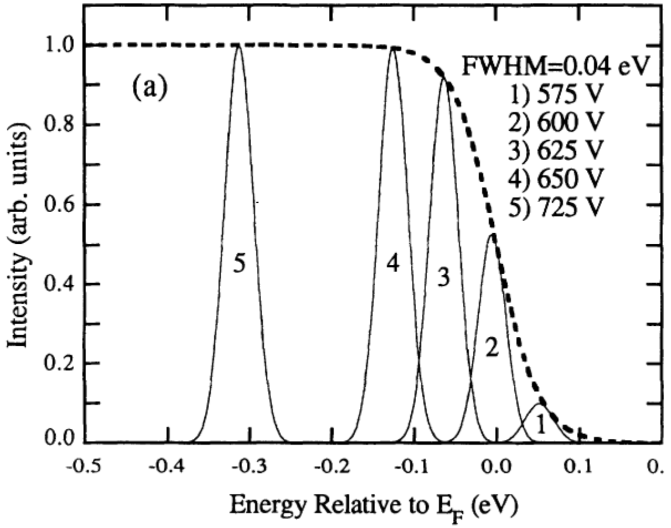


FIG. 6. FEES spectra as a function of applied field from a high clean nanometric protrusion formed on a W field emitter. For the lower voltages the peak shifts to above E_F.

Normalized peak heights

Shifting peak position with voltage (for tungsten):



*S. T. Purcell et al., PRB **49**, 17259 (1994)*

Possible way to cool the tip by emission and get correlated e-pairs:

⇒ High nano-protrusions on sharp tip

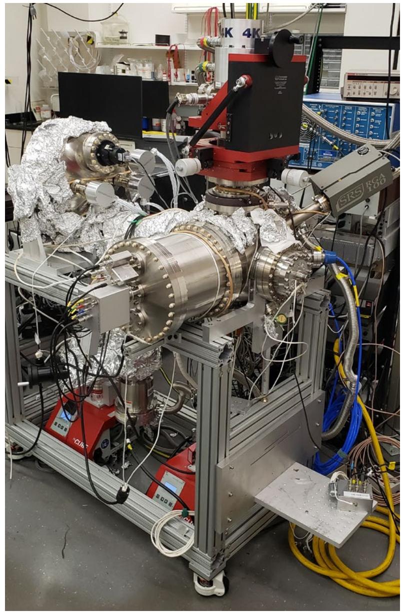
⇒ Low voltage

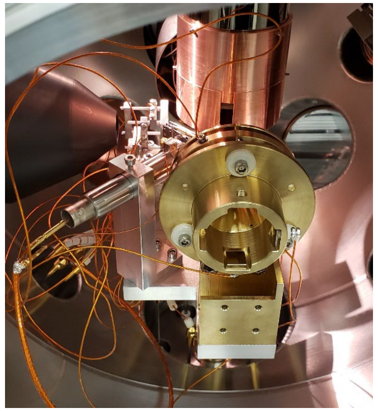
⇒ Low emission current

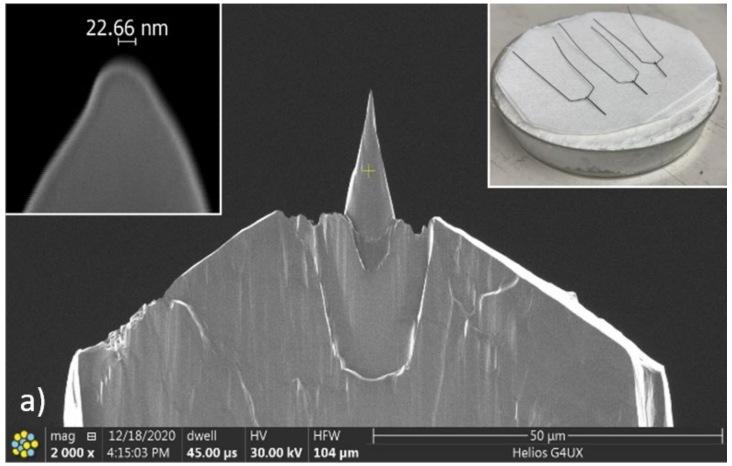
Probably helpful: Superconducting electron pairs at E_F

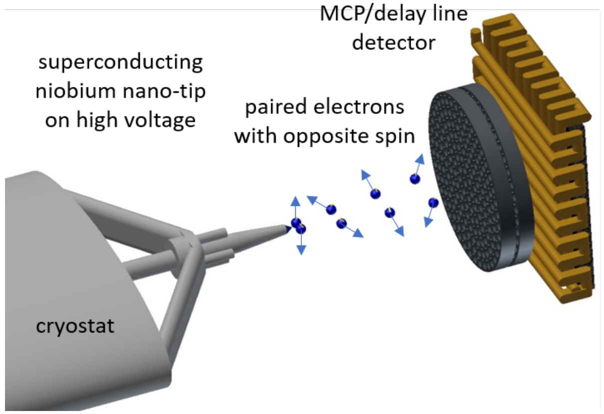
Summary

- Development of coherent superconducting electron field emitters for QIS and microscopy
- Realized a field emitter measurement and characterization setup and fabricated a monocrystalline Nb nanotip
- Observed Nb surface state field emission at 4K with extremely narrow energy distribution FWHM of 16 meV
- Stable, bright emission in ~6 deg. angle
- Increasing beam current with xenon gas coverage by two orders of magnitude
- Efforts towards entangled two-electron beam source, currently limited assumable by Nottingham heating
- Proposed solution: pushing surface states beyond E_F to initiate Nottingham cooling











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