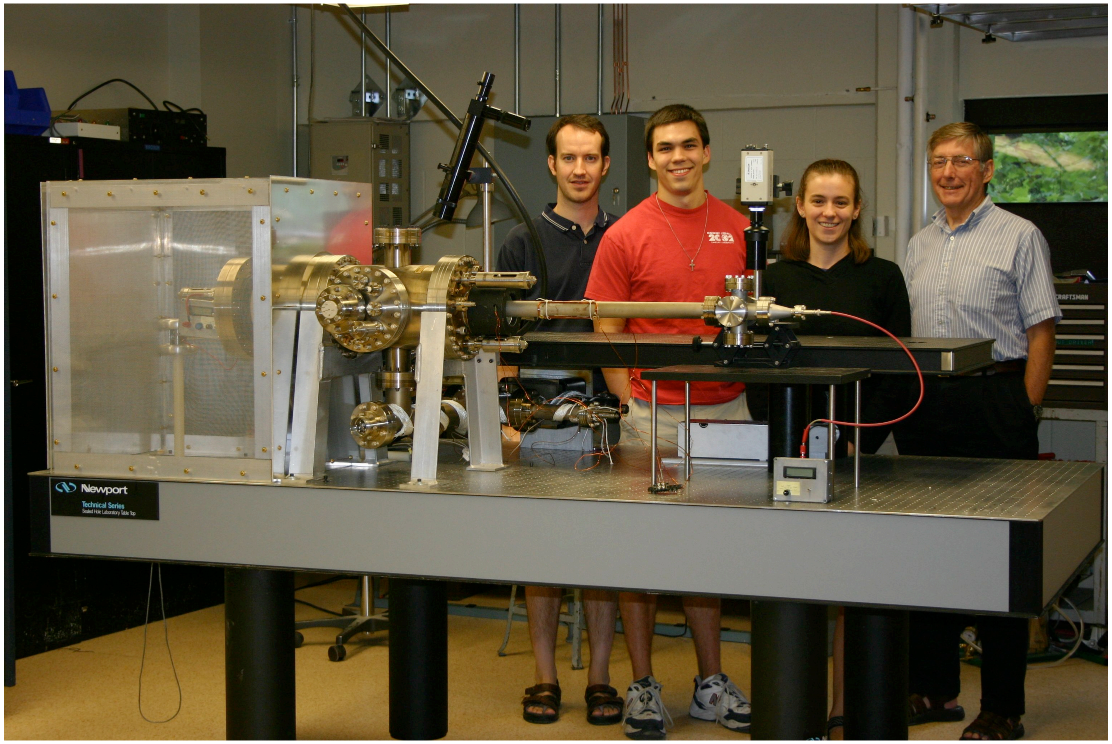
Needle cathodes for high-brightness beams



Chase Boulware

Jonathan Jarvis

Heather Andrews

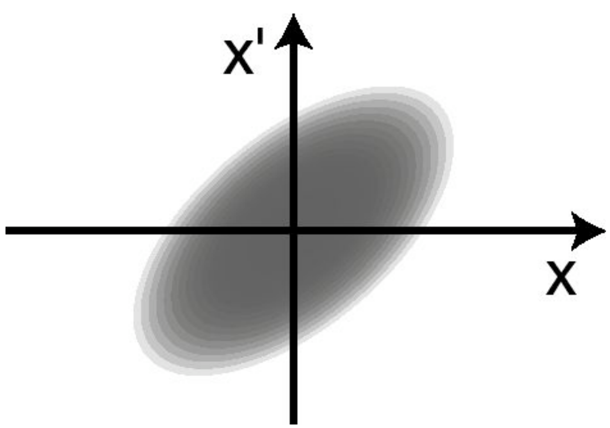
Charlie Brau

Outline of the talk

- What is brightness?
  - Definition
  - Sources
- Why is brightness important?
  - Light sources
  - FELs
- How do we get high brightness?
  - Photoemission
  - Field emission
  - Photofield emission

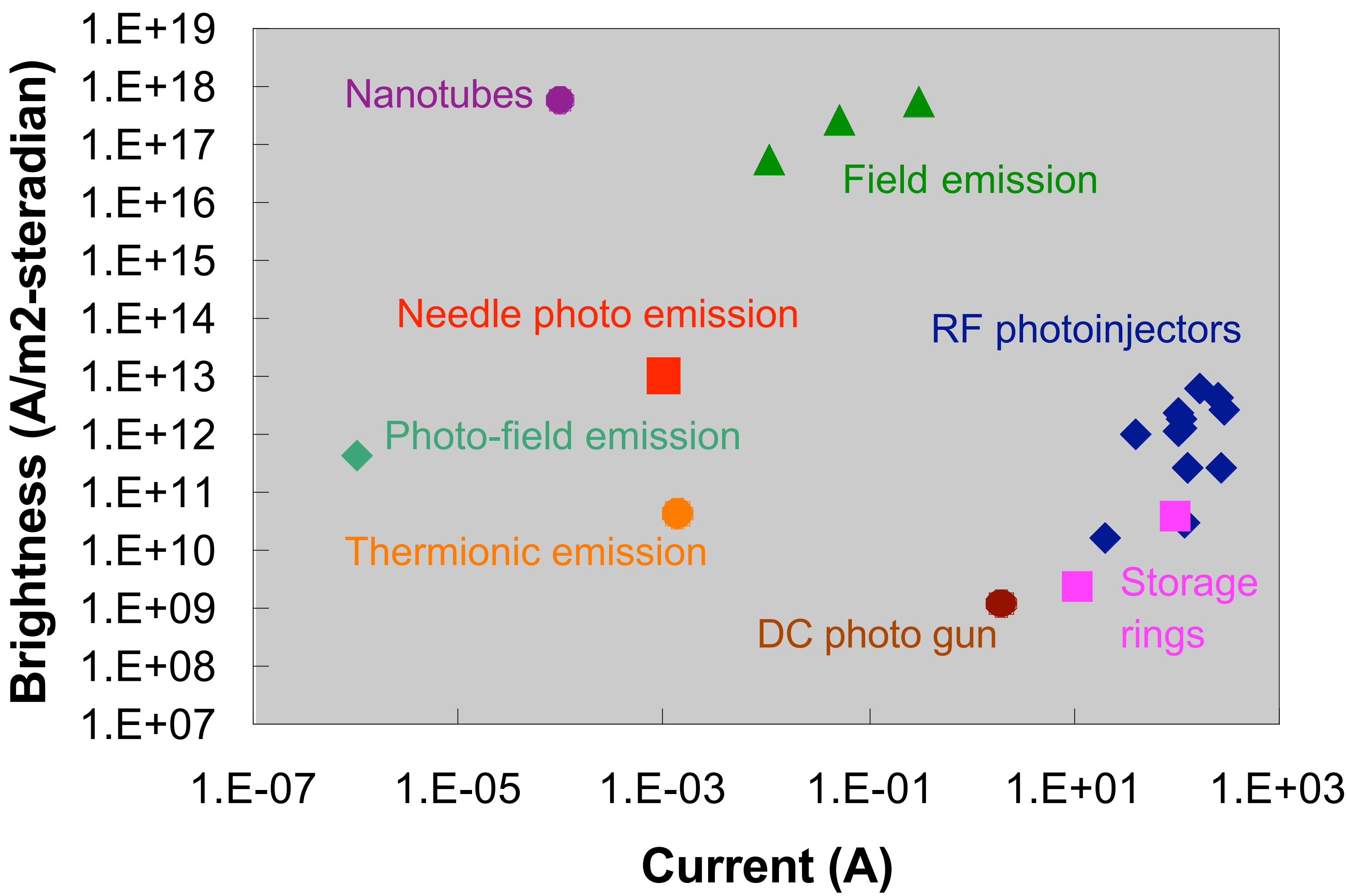
Definition of brightness

- Emittance is
  - π^{-1} x area in phase space (old definition)
  - Or, weighted average over beam (rms emittance)



- Brightness is
  - Density in transverse phase space
  - Local property of beam

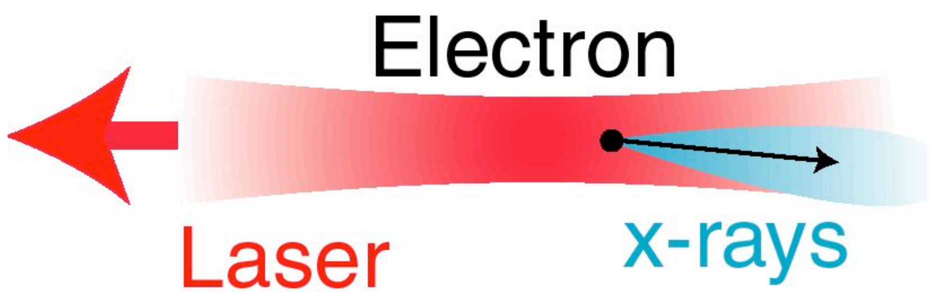
Electron sources span many orders of magnitude in brightness and current



Why brightness is more important than current

- Brightness is a useful figure of merit
  - Normalized brightness is roughly invariant with respect to beam current, electron energy
  - Can be used to compare different devices
- Often it's the most important parameter
  - When brightness is the most important parameter, lower current may be possible
  - Lower current reduces other problems, including radiation, halo, CSR, space charge

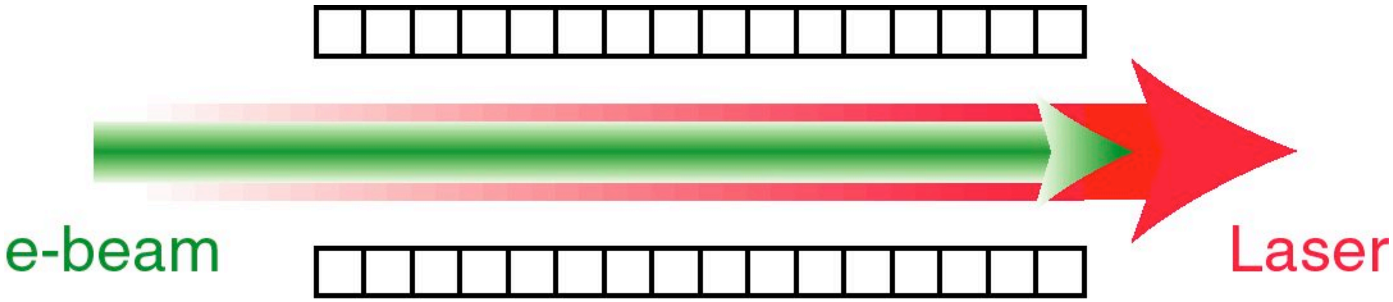
Spectral brilliance of Compton x-rays depends on brightness, not current



- For small emittance

  spectral brilliance is

Gain of Thompson FEL depends on brightness, not current



In strong optical guiding regime

power gain is independent of current

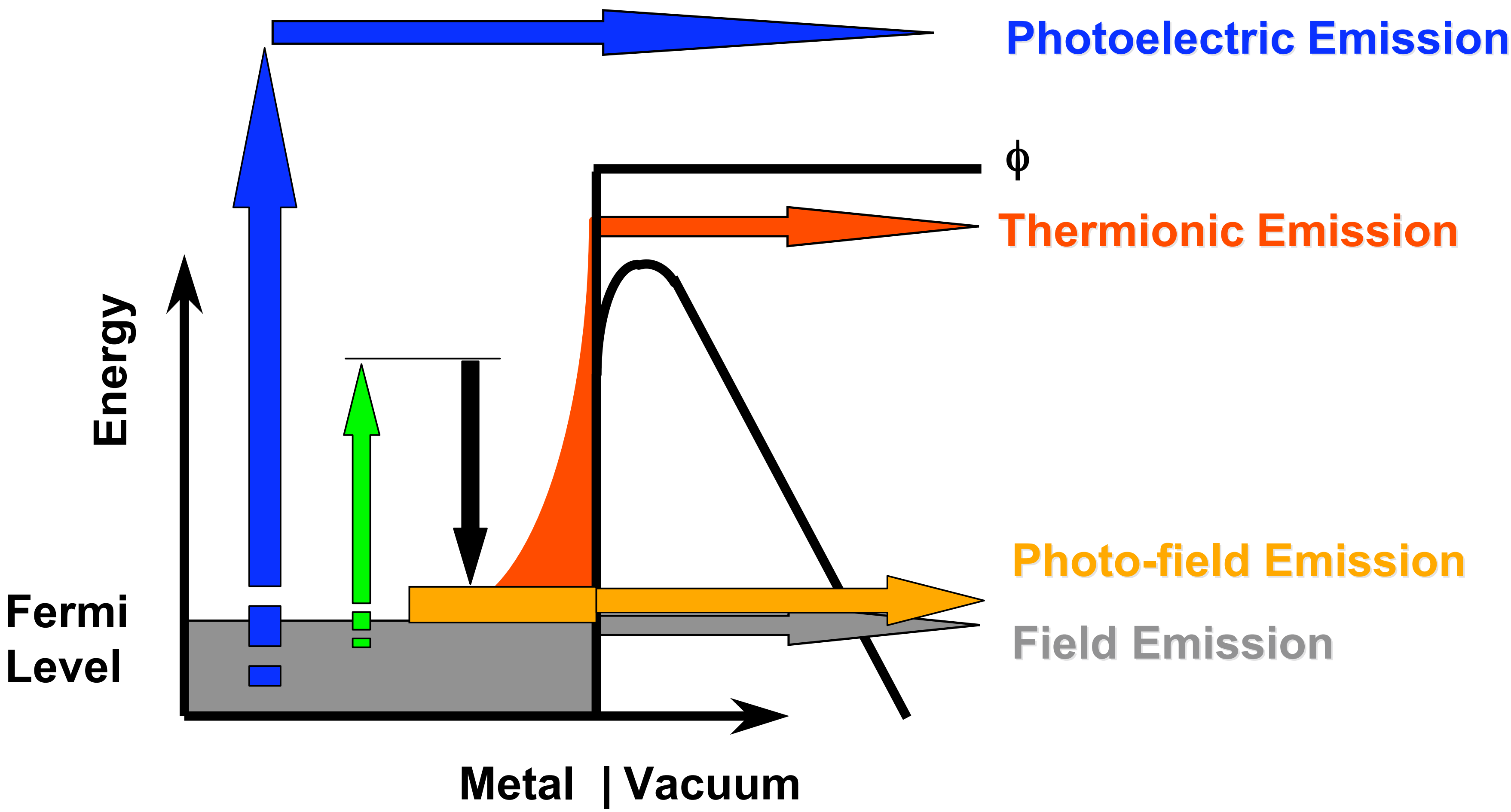
Claudio's microwave-undulator x-ray FEL (FEL 2005)

- Parameters
  $\lambda_W = 1.45$ cm
  $a_W = 0.4$
  $\gamma = 2150$
  $\lambda_L = 2$ nm
- M. Xie formulas
  $I_e = 2000$ A
  $B_N = 2.5 \times 10^{13}$ A/m^2-sr
  $\mu = 0.7$ /m
- Gain in strong-guiding regime (my formula)
  $\mu = 0.8$ /m
- Minimum current for strong guiding
  $I_e > 400$ A
- Beam diameter
  $d = 70$ μm

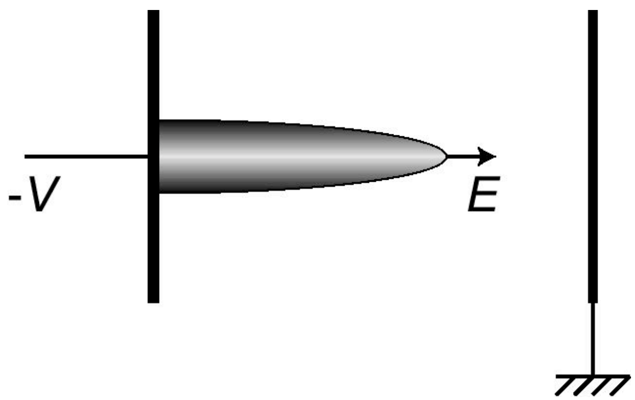
High electric fields at the surface enhance cathode performance

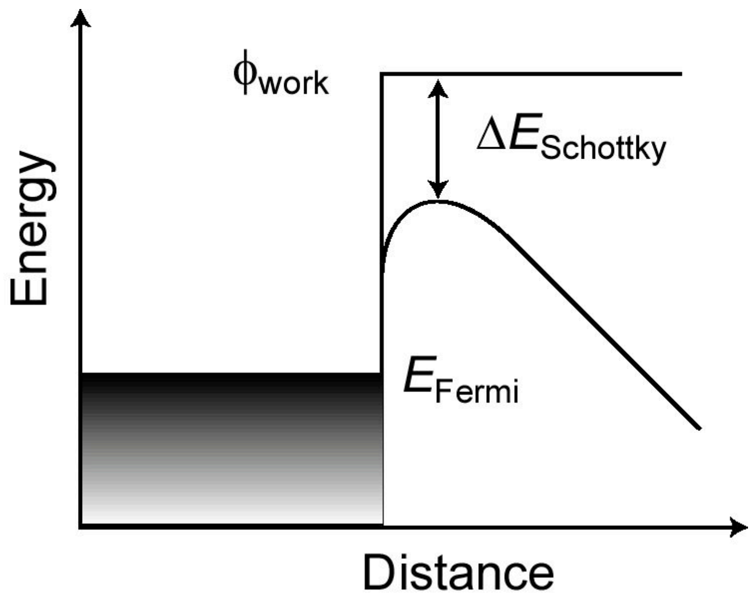
- High electric fields:
  - Conventional DC guns ~ 10^6 V/m
  - Conventional RF guns ~ 10^7 - 10^8 V/m
  - Needle cathodes ~ 10^9 – 10^{10} V/m
- Enhanced performance due to
  - Schottky effect on photoemission
  - Field emission
  - Photo-field emission
  - Reduced space-charge effects

Electron emission at the surface of a metal in vacuum occurs by four mechanisms



Schottky effect reduces surface barrier at high electric field

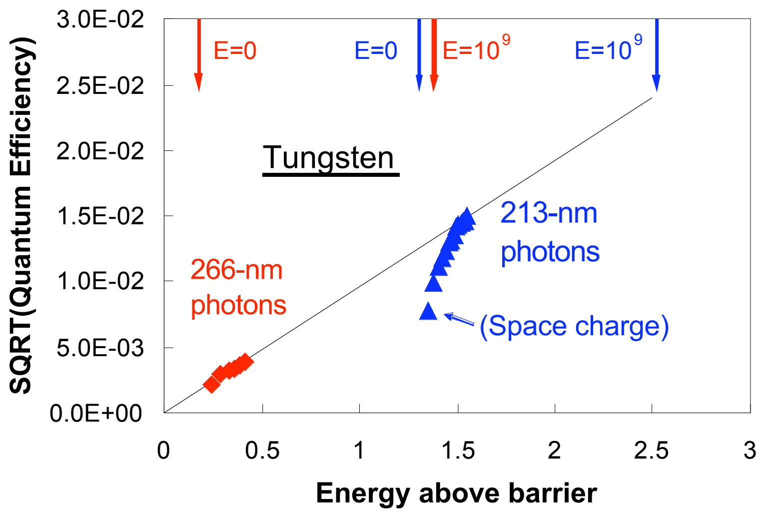


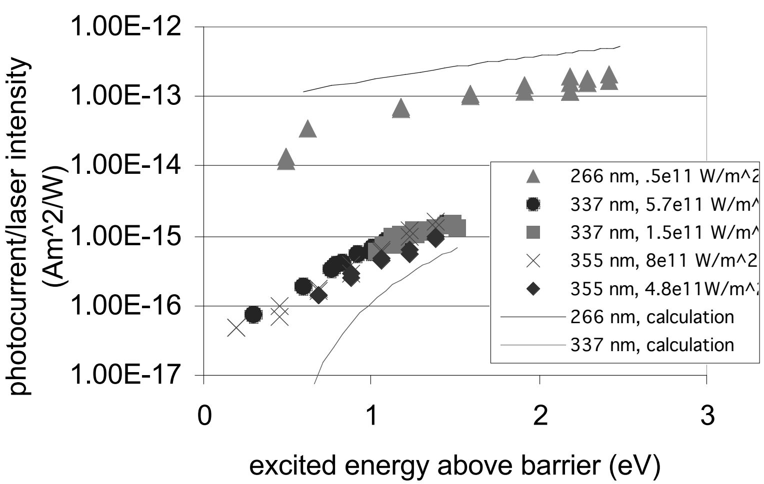


- Field is enhanced at tip of needle

- Schottky effect lowers barrier at surface

Schottky effect enhances quantum efficiency of needle cathodes





- Threshold law for quantum efficiency
- Holds over wide range
- Increases QE by orders of magnitude

Laser damage to cathode limits achievable photocurrent density

- Figure of merit for cathodes is η_{QE} x P_{damage}
- Tungsten cathodes
  - P_{damage} ~ 10^{12} W/m^2 for 5-ns pulses
  - P_{damage} ~ 10^{14} W/m^2 for 1-ps pulses
- Limiting current density for QE ~ 10^{-4}
  - J_{max} ~ 10^7 A/m^2 for 5-ns pulses
  - J_{max} ~ 10^9 A/m^2 for 1-ps pulses
- Highest current densities will be space-charge limited

Space-charge limits current density

- Planar geometry

- Spherical geometry*

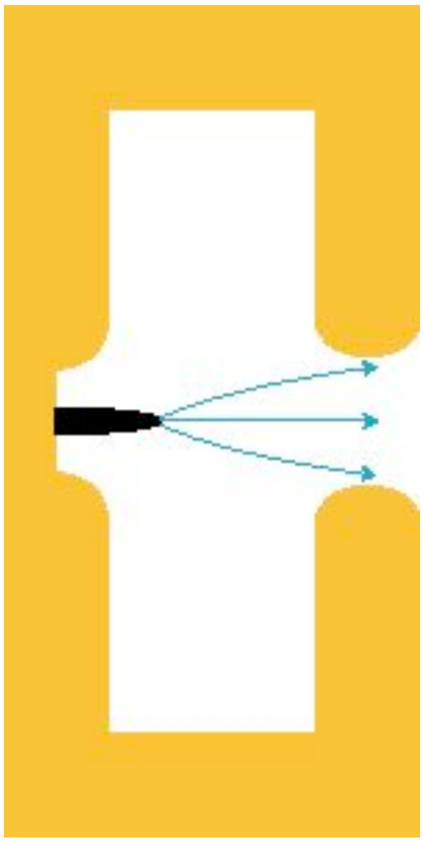
- For small spot size (<< tip radius)**

- For E_{tip} ~ 10^9 V/m, r_{tip} ~ 1 mm, J ~10^8 A/m^2

* a^2 = O(5 -10)

**Y. Y. Lau

Needle cathodes produce high brightness in RF guns*

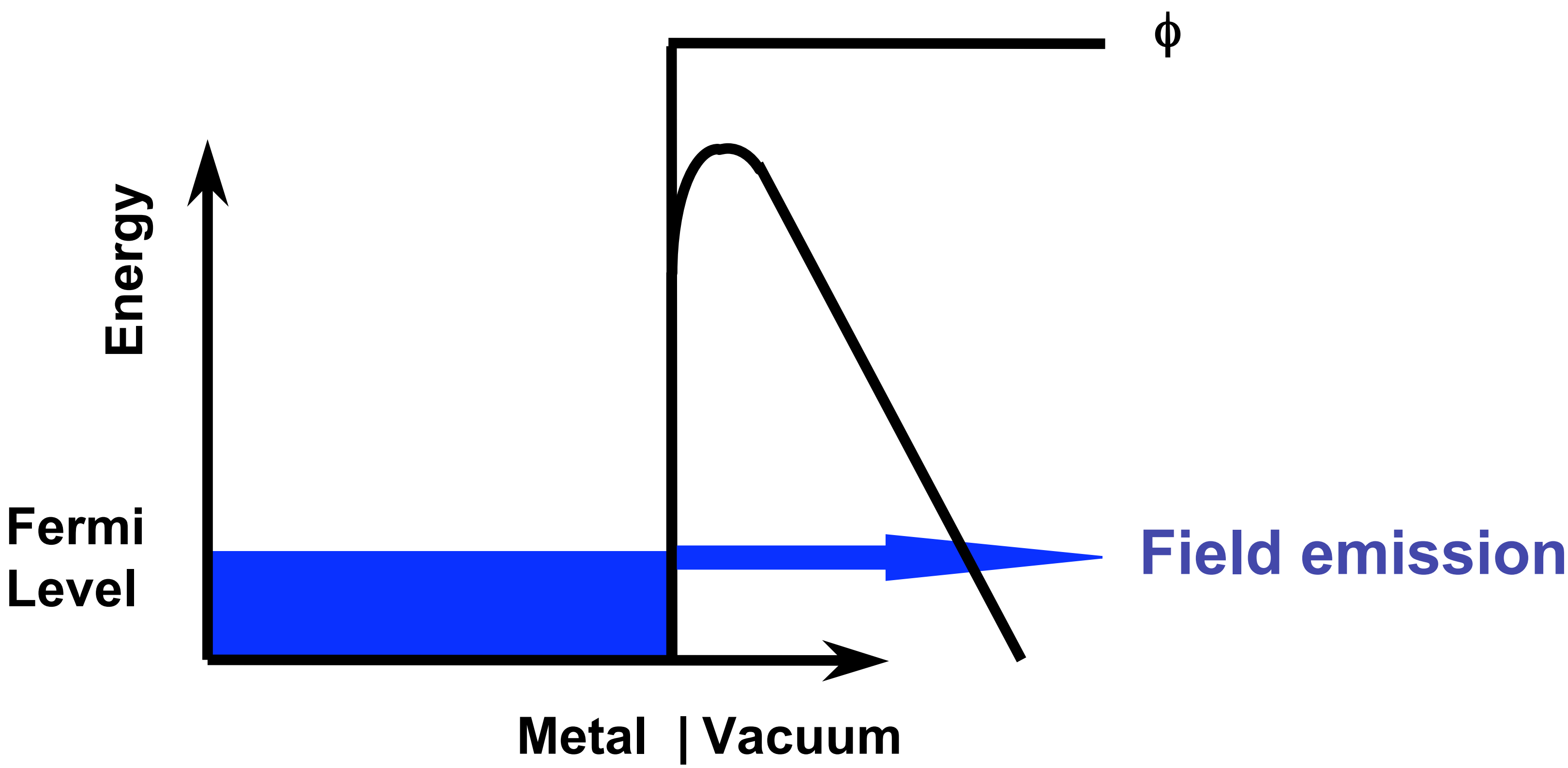


- Field at cathode enhanced by
- Example:
  - 1 mm diameter, 1 cm long
  - E_0 = 50 MV/m
  - E_{tip} = *O*(500 MV/m)
- Space-charge limit ~ 10^8 A/m^2
- Brightness ~ 10^{13} A/m^2-str
  - *before pulse compression!*

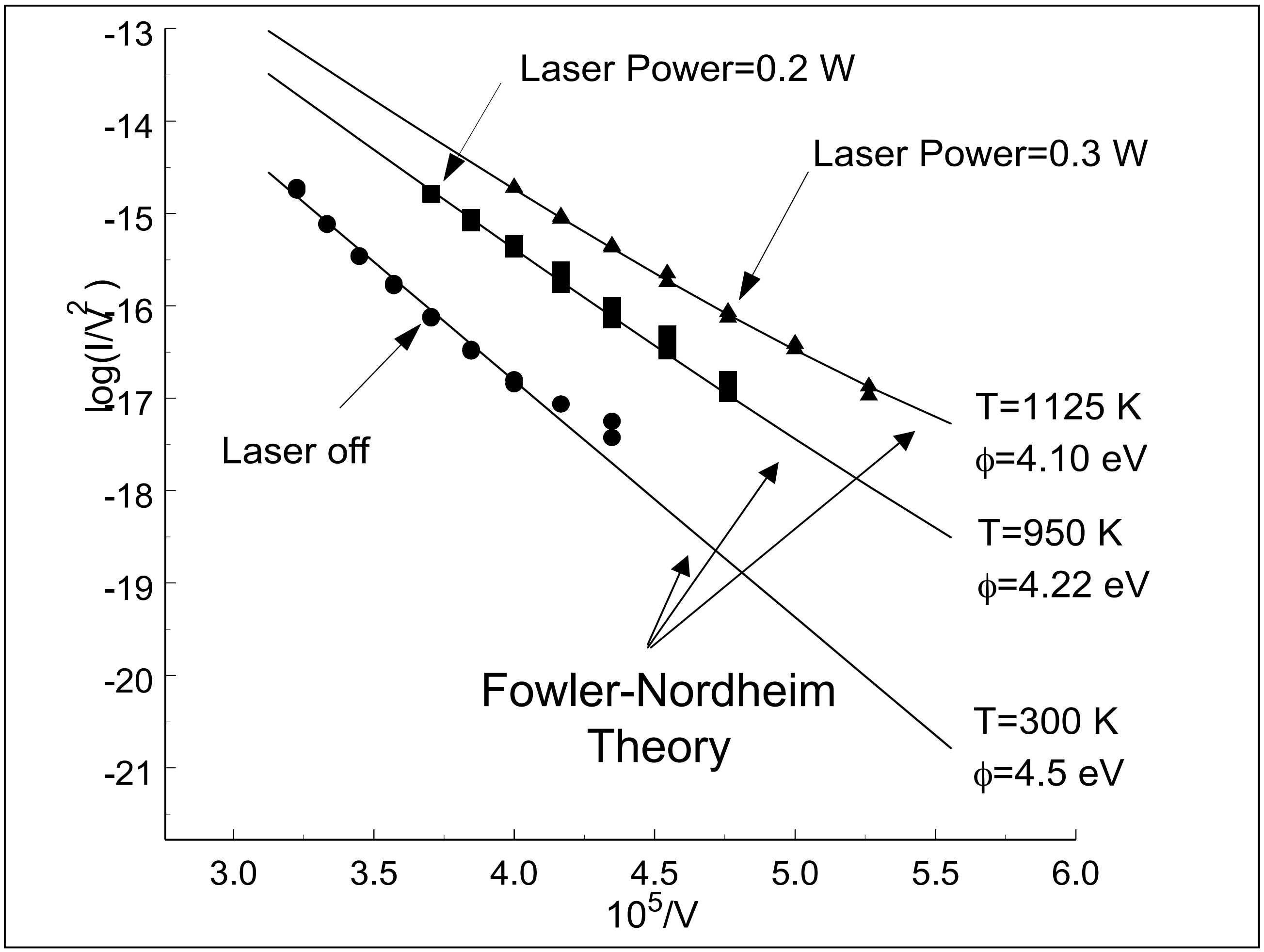
* Lewellen, Sardegna

Field emission involves electrons in levels near the Fermi level

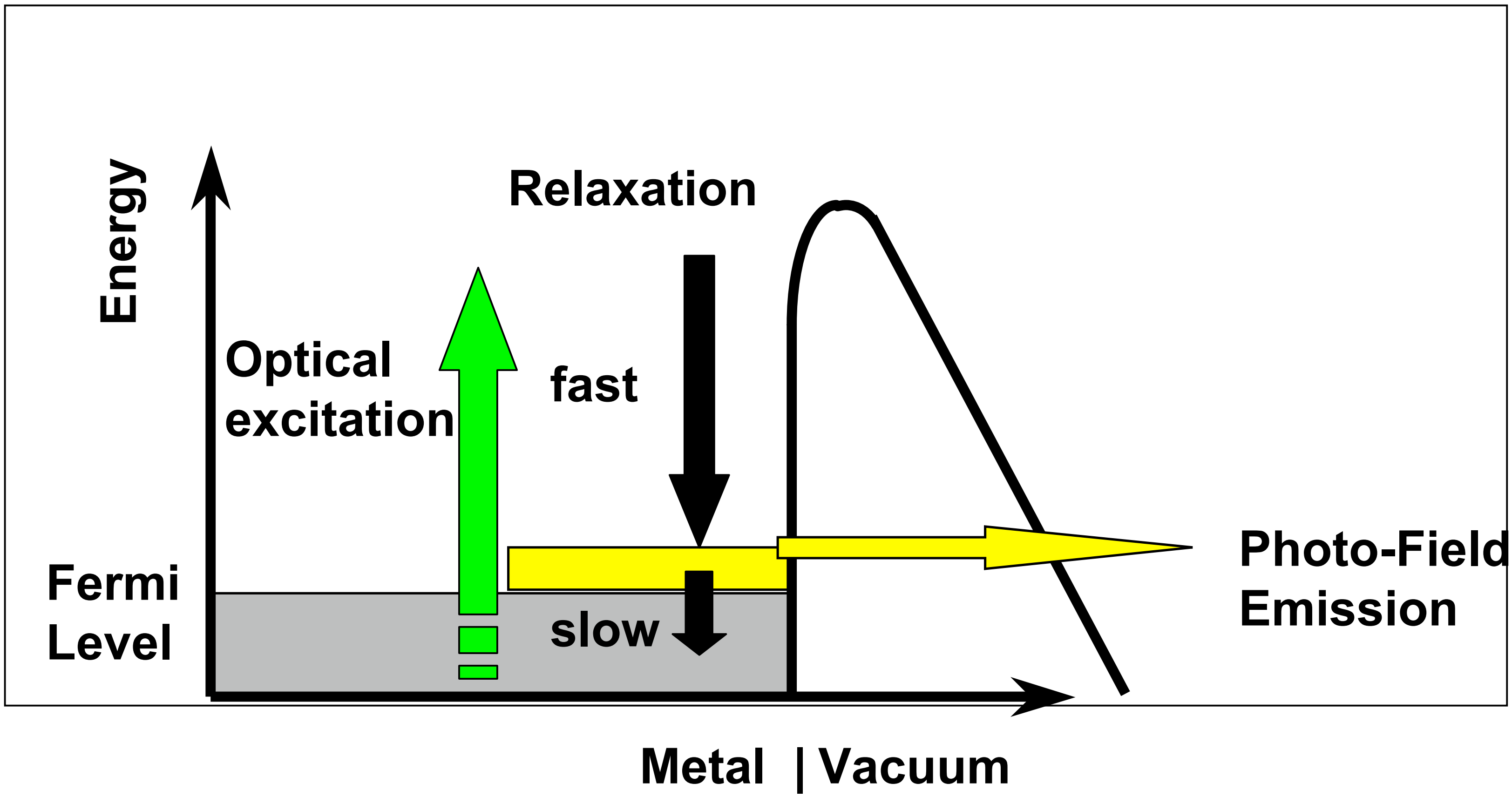
- Tunneling through barrier causes characteristic steep voltage dependence (Fowler-Nordheim)



The characteristic steep voltage dependence of photo-field emission at 514 nm strongly indicates tunneling from just above the Fermi level



Photoelectrons excited from d-conduction band into s-conduction band where they reside just above Fermi level for ~ microsecond



- No effect observed in ZrC (only one conduction band)

Conclusions

- High brightness is often more important than high current
- Needle cathodes operate at high electric fields (10^9 – 10^{10} V/m)
  - Enhanced emission from cathode
  - Reduced space-charge effects
- Interesting physical effects are found at high electric fields
  - Field-enhanced photoemission (Schottky)
  - Photo-enhanced field emission (tunneling)