Cathode Physics
Welcome and Electron Sources

Matt Poelker and John Smedley

Course Plan

	Monday	Tuesday	Wednesday	Thursday	Friday
9:00- 10:20	Welcome Electron sources (John)	Photocathode Theory (John)	PEA Semiconductors (John)	Lasers (John)	Practical Experience (Matt)
10:30- 12:00	Introduction (Photocathodes) (John)	Metal Photocathodes (John)	Materials science techniques (John)	Student presentations	Practical Experience (Matt)
13:00- 14:30	Motivation for Spin Polarization (Matt)	Guns (Matt)	Diamond Amplifier (John)	Student presentations	
14:40- 16:00	GaAs (Matt)	Guns (Matt)	Vacuum (Matt)	Student presentations	

Homework will be handed out each morning and collected the next morning. The course “grade” will be ½ homework and ½ presentation. We want and expect everyone to succeed!

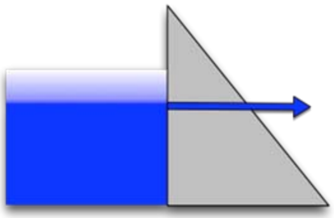
Student Presentations

- Each student will give a 15 min presentation on a cathode related topic
- It can be from your own work, or you can present and discuss a paper in the field
- If you need ideas, Matt and I will be happy to suggest some quintessential papers
- Please see one of us during a break or in the study session and let us know what you intend to talk about, so we can make up a schedule for Thursday.

What is a Cathode?

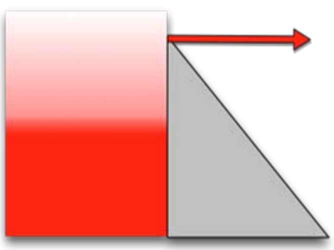
- For our purposes, it is anything that emits electrons into vacuum in a controllable way
- Electrons are bound to materials and we must add energy to get them to escape
  - For now, think of this as adding energy required to separate a charge from its image
- For solids, there are three main ways to do this:
  - Thermionic
  - Field emission or “tunneling”
  - Photoemission
- It is possible to use a gas/plasma as an electron source as well (*student topic?*)

The Canonical Emission Equations
(slide courtesy of Dr. K. Jensen, Naval Research Laboratory)



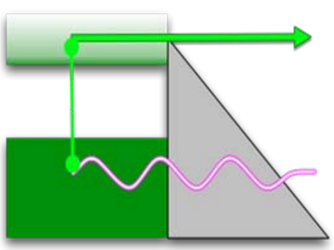
- **Field Emission**
  Fowler Nordheim
  E.L. Murphy, and R.H. Good,
  Physical Review 102, 1464 (1956).

$$J_{FN}(F) = A_{FN} F^2 \exp\left(-\frac{B\Phi^{3/2}}{F}\right)$$



- **Thermal Emission**
  Richardson-Laue-Dushman
  C. Herring, and M. Nichols,
  Reviews of Modern Physics 21, 185 (1949).

$$J_{RLD}(T) = A_{RLD} T^2 \exp\left(-\frac{\Phi}{k_B T}\right)$$



- **Photoemission**
  Fowler-Dubridge
  L.A. DuBridge
  Physical Review 43, 0727 (1933).

$$J_{MFD}(\lambda) = \frac{q}{\hbar\omega}(1-R)F_\lambda(\omega)\{\hbar\omega - \Phi\}^2 I_\lambda$$

Listed chronologically

Cathode Applications– Small Electron Guns

Thermionic guns with relatively low energy are common in a number commercial applications

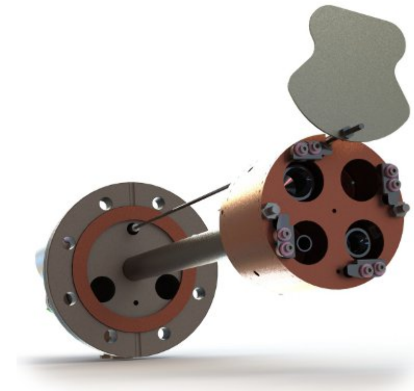
- Electron beam welding
- Electron beam heating
- Electron beam evaporation
  - These require 0.1 to 1 A, and generally operate at tens of kW
- Electron beam lithography
- Cathode ray tubes

Several research techniques:

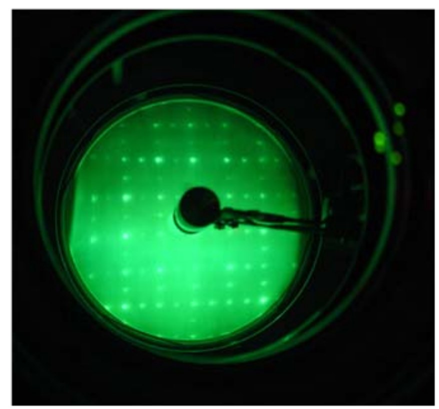
- Electron Diffraction (LEED and RHEED)
- Flood guns for charge neutralization
- Ionization of material for mass spectrometry

Cathode Ray Tube

Electron Gun



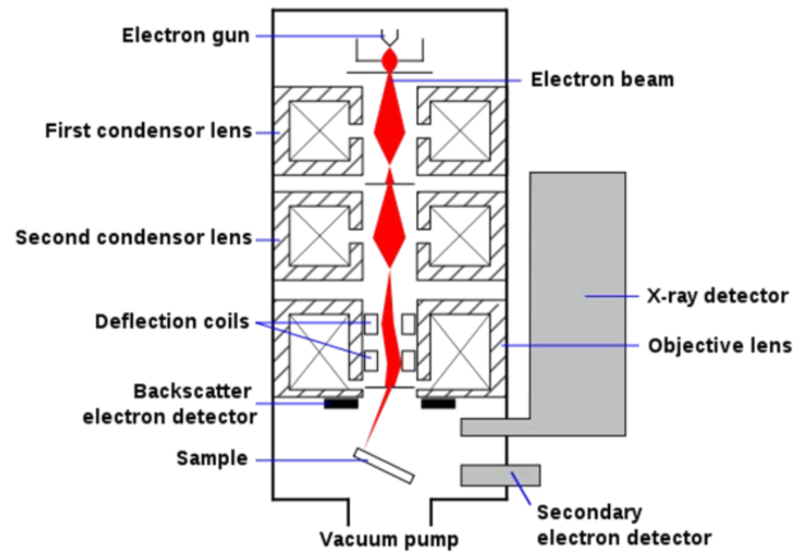
Electron Beam Evaporator

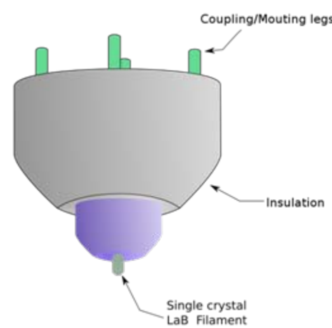


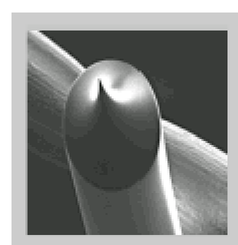
Low Energy Electron Diffraction on Si

Cathode Applications– Electron Microscopes

- Thermionic & Field Emission
  - Which provides better resolution?
- Typically few μA of DC current:
  - <50 keV in a Scanning Electron Microscope (SEM)
  - <300 keV for Transmission Electron Microscope (TEM)
- PEEMs (Photoemission Electron Microscopes) are a special breed, as the photocathode *is* the sample
- Electron microscopes can be fitted with a variety of tools:
  - Nano patterning
  - Electron diffraction imaging
  - X-ray fluorescence imaging
- HW problem – estimate the resolution of a 300 keV TEM







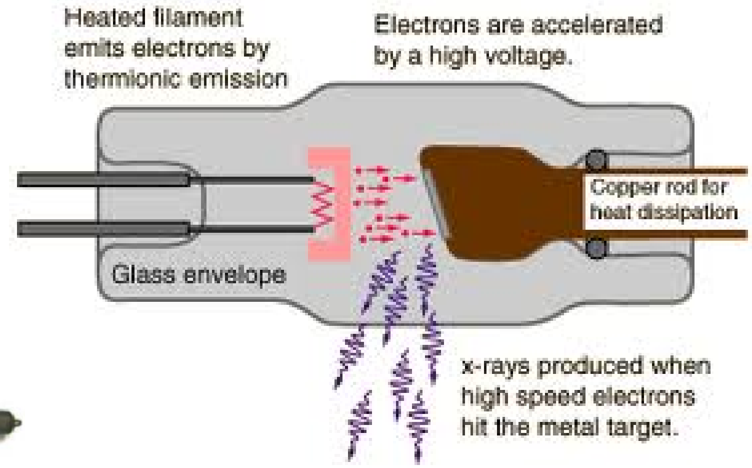
Cathode Applications– X-ray tubes

Used to make x-ray light….

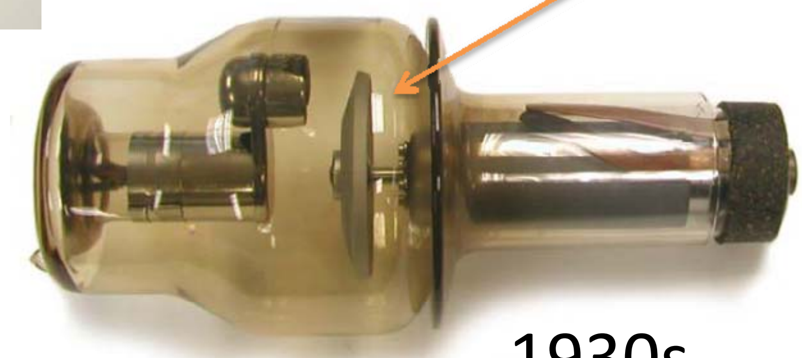
1880s

bias at high voltage

In 1913, William Coolidge invented an x-ray tube with high vacuum, a heated filament as electron source, and an x-ray producing anode. The tube, shown here, was produced in the 1920s by General Electric Corporation.
Photo: www.orau.org Oak Ridge Associated Universities



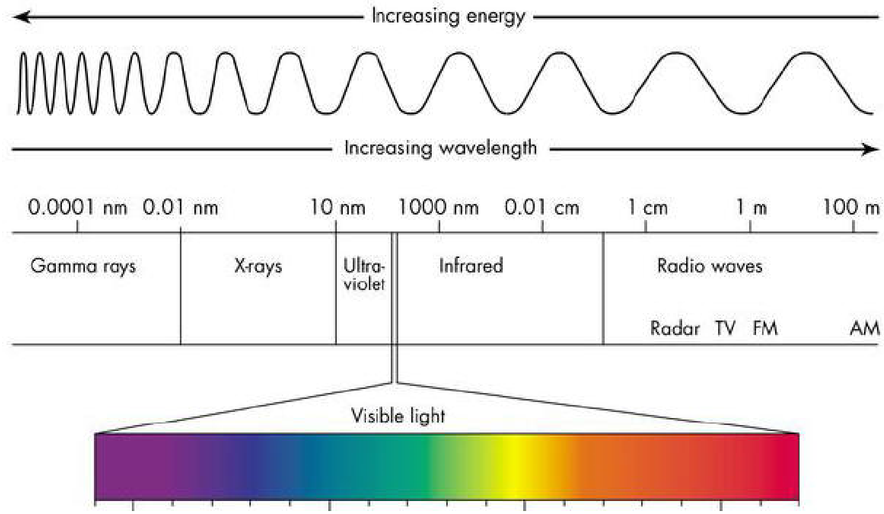
Rotating anode to distribute heat



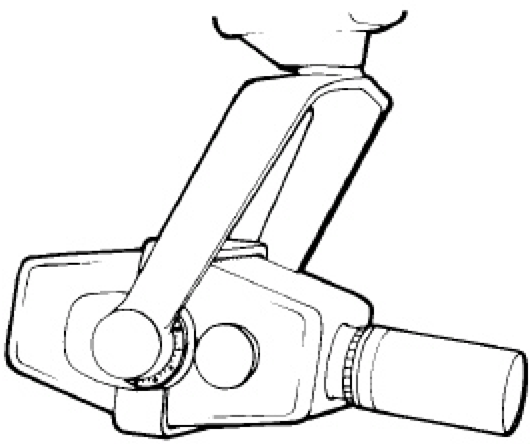
1930s

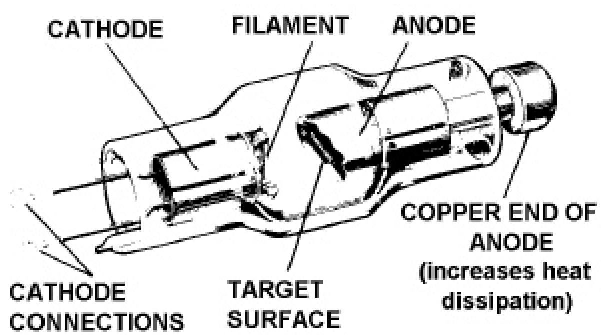
X-rays are generated when a DC electron beam, typically a few mA, strikes a tungsten target at 60-200 keV. e-Beam quality is not a big concern

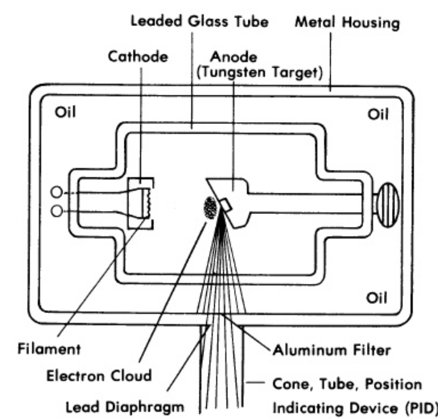
Modern X-Ray Sources



X-Ray energy depends on electron beam energy, i.e., bias voltage



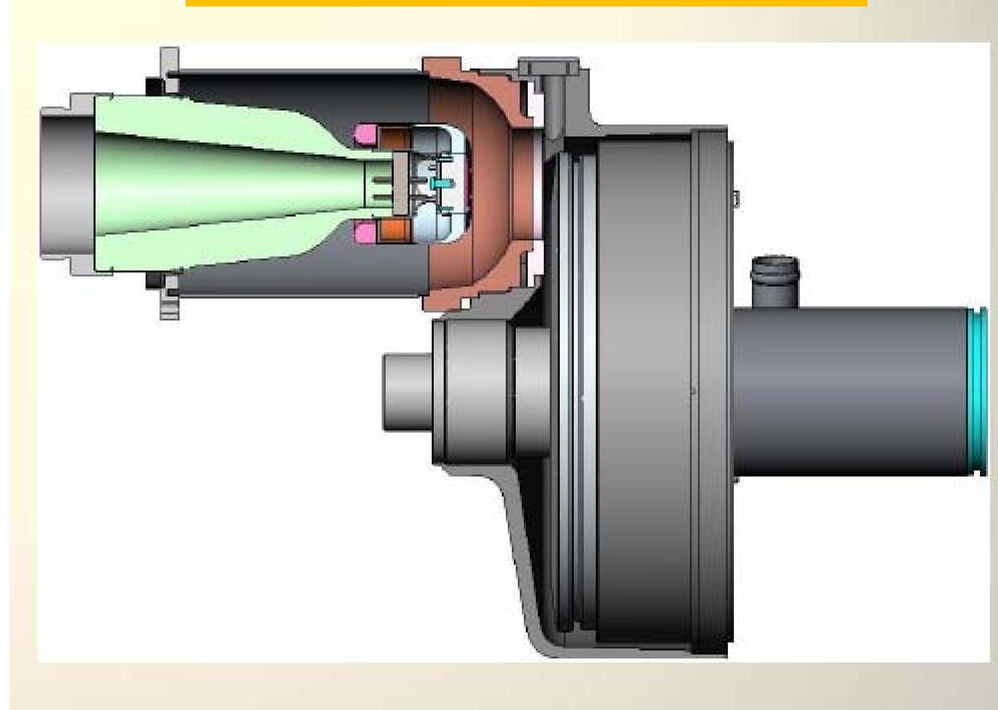




Modern X-Ray Sources

Higher e-beam current…..
Higher x-ray flux

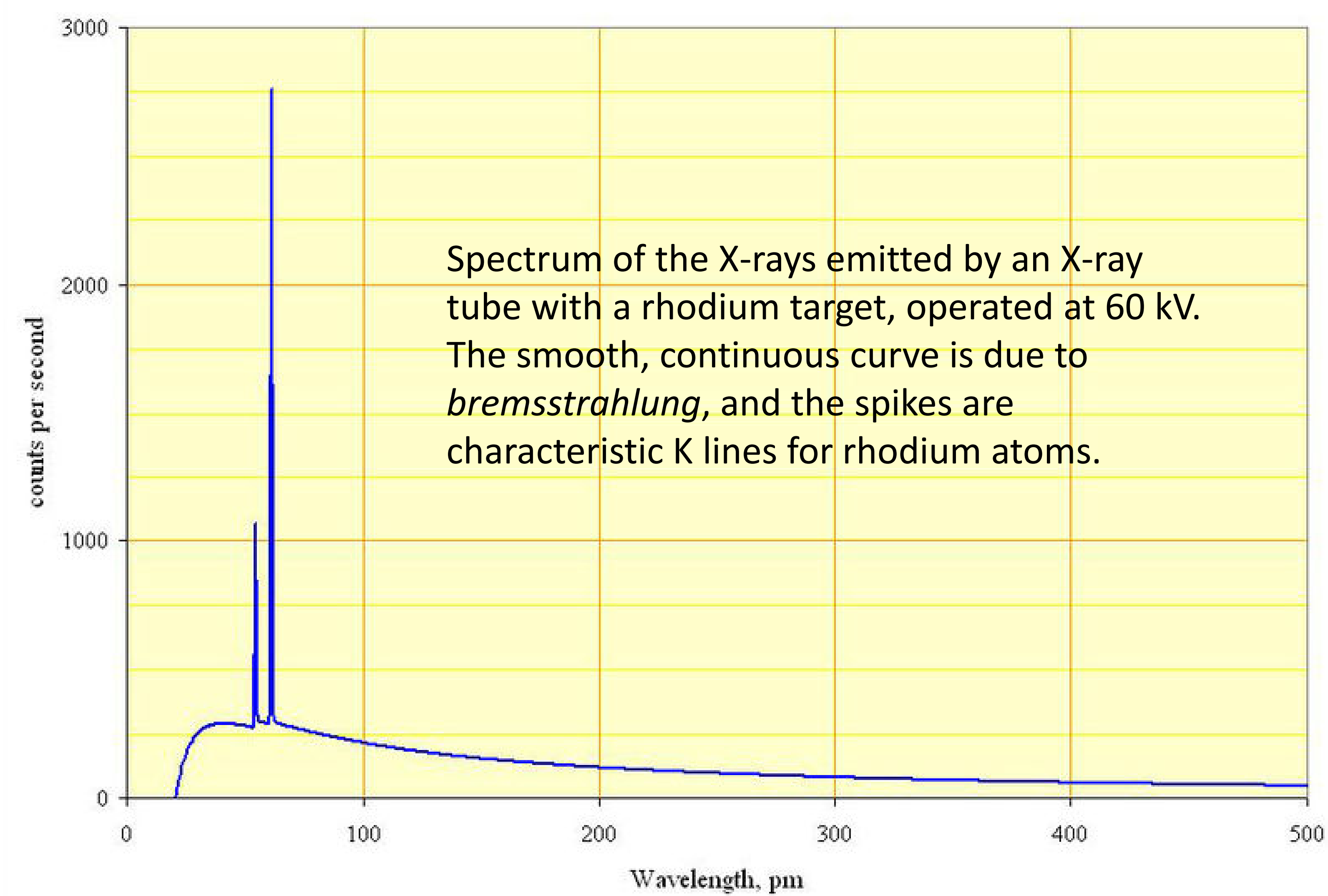
"inverted insulator"…more later



Higher Voltage….
More penetrating
x-ray beam

Courtesy Varian

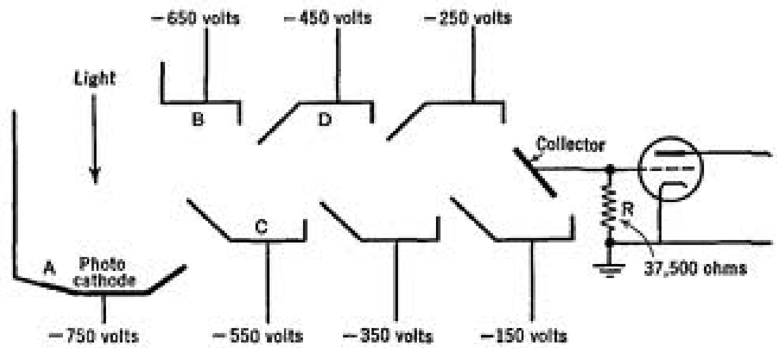
Bremsstrahlung and Characteristic X-rays

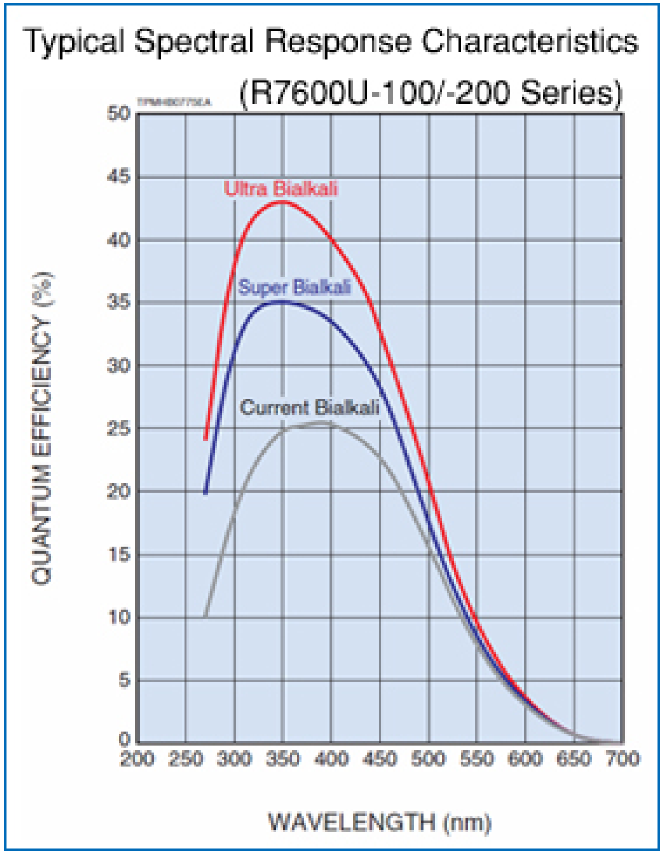


Spectrum of the X-rays emitted by an X-ray tube with a rhodium target, operated at 60 kV. The smooth, continuous curve is due to *bremsstrahlung*, and the spikes are characteristic K lines for rhodium atoms.

Photomultipliers and Photodetectors

- Photocathodes are used in photon detectors
  - Photomultiplier tubes for single photon counting
  - Photo tubes for pulse measurement
  - Streak cameras
- Tube manufacturers are a great source of information on cathode growth and performance



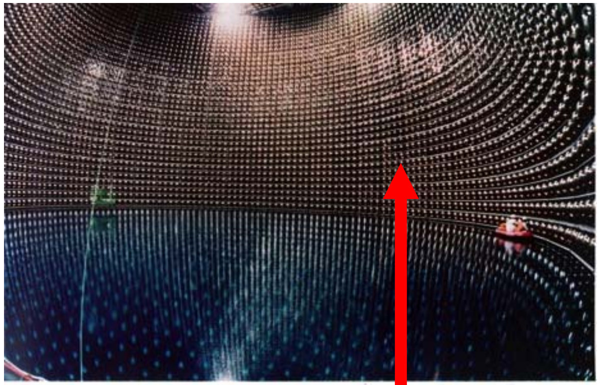


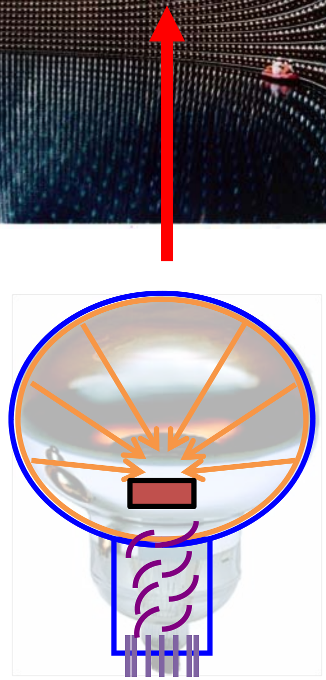
Learning from 60 Year History of Bialkali PMTs

K_2CsSb discovered by Sommer in 1950's

Bialkali PMTs:

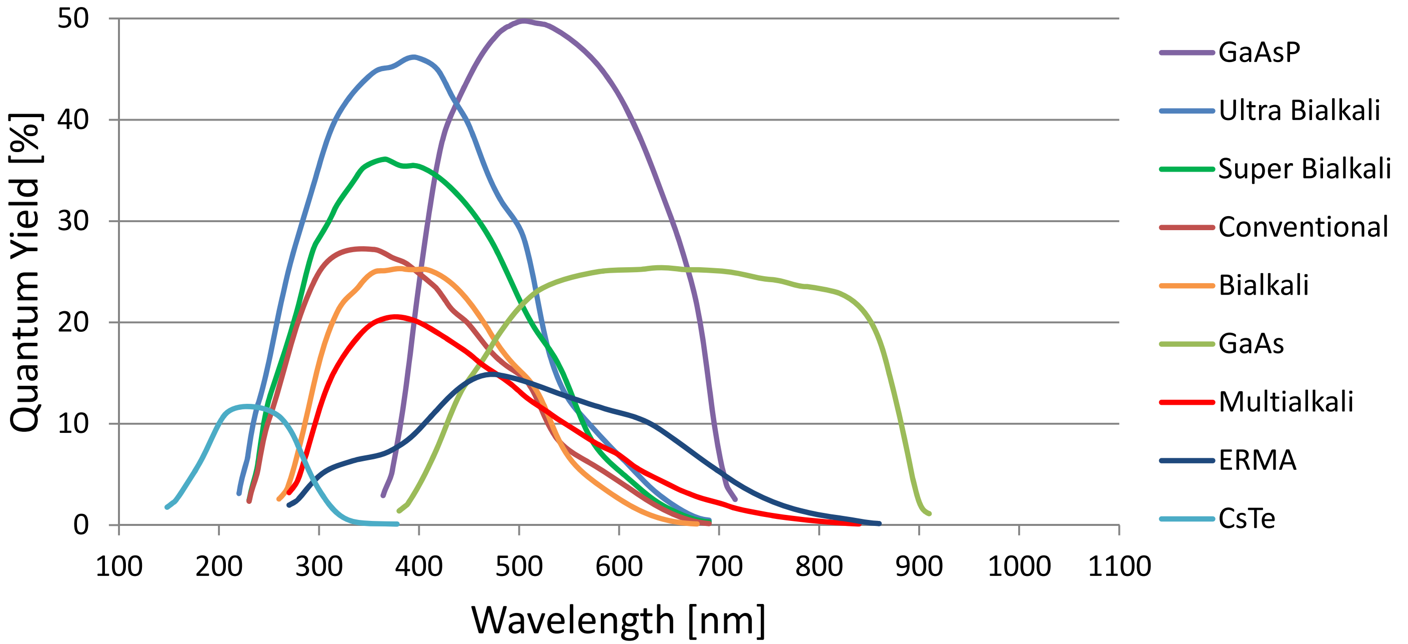
Old peak QE ~ 25–27% (+40 years ago)
New peak QE ~ 30–35%





Super-Kamiokande Neutrino Detector 11,200 20" K_2CsSb PMTs

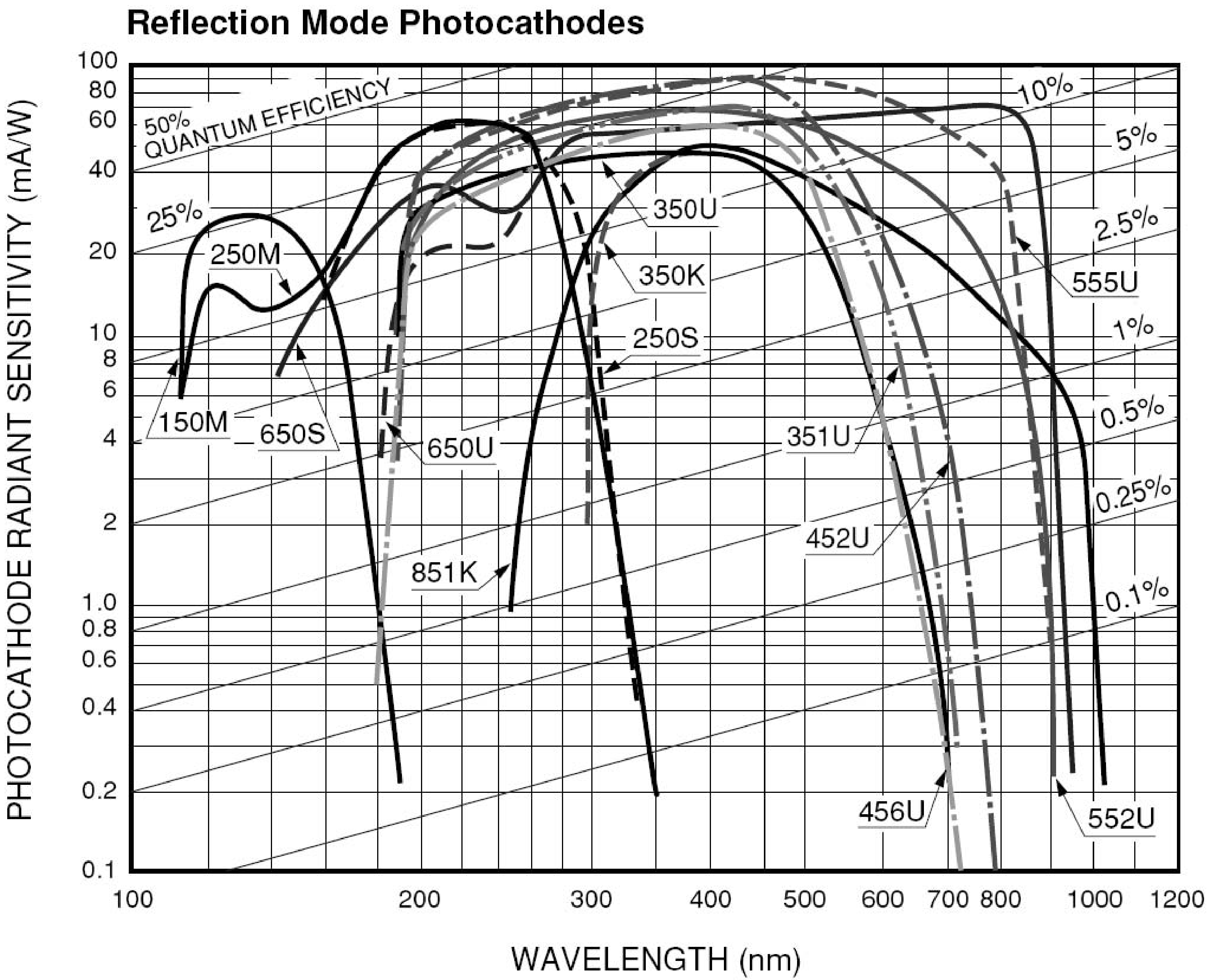
Spectral Response of Commercial Photocathodes



Source: Motohiro Suyama PoS(PD07)018 [Hamamatsu]

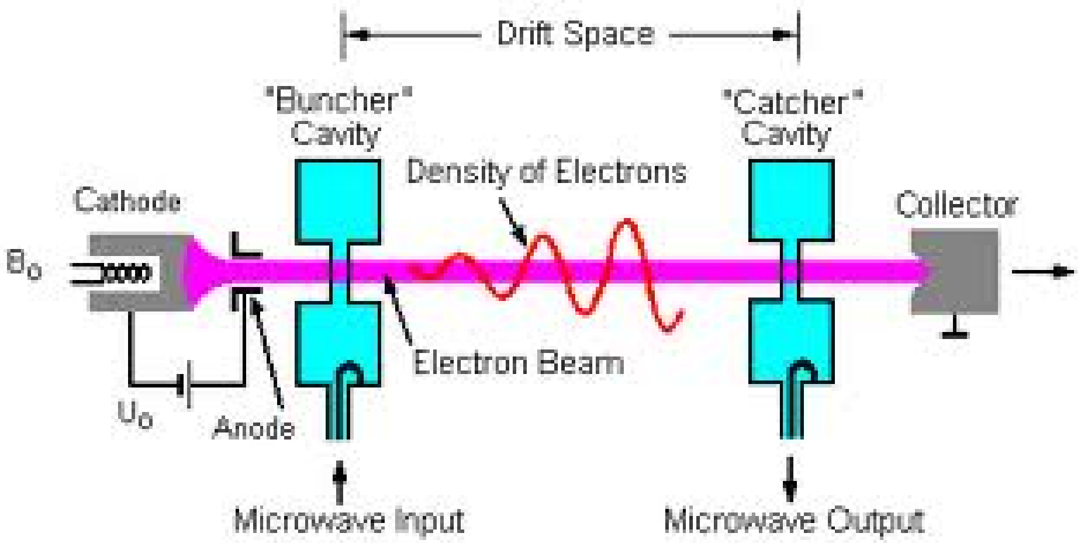
Theo Vecchione FEL '11

Hamamatsu Photocathodes



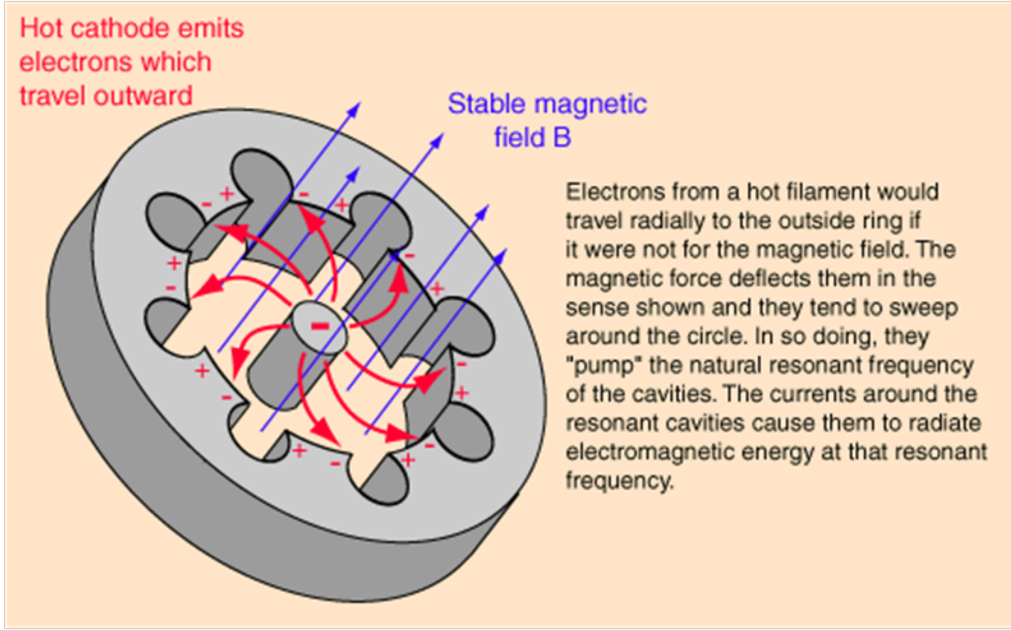
Klystrons — RF generators

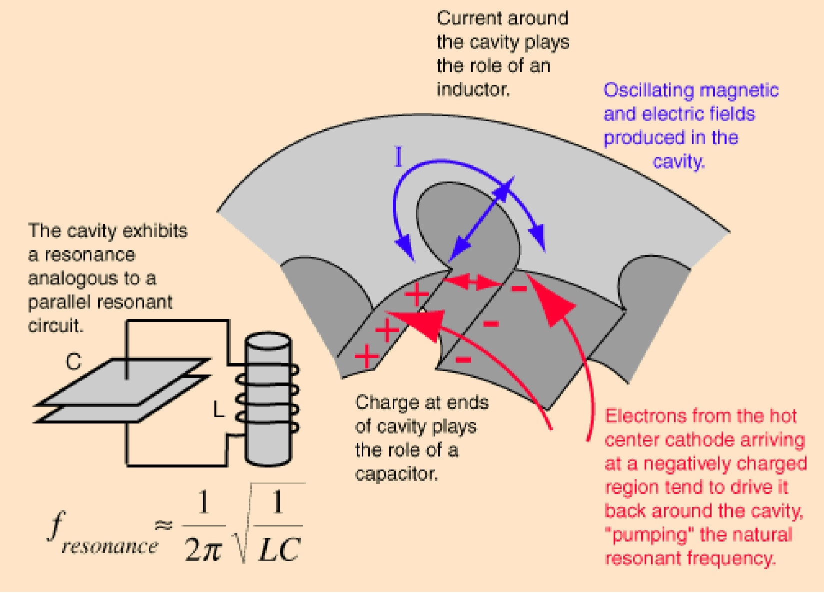
- Klystrons use a DC electron beam at a few mA to generate/amplify microwaves by velocity modulation.
- Klystrons use thermionic cathodes to generate the required electron beam.



Magnetrons – RF generators

- Invented in 1921 and developed for radar during WWII
- Electrons from a thermionic cathode travel in a circle in presence of strong magnetic field
- Resonances excited in tubes that line the anode

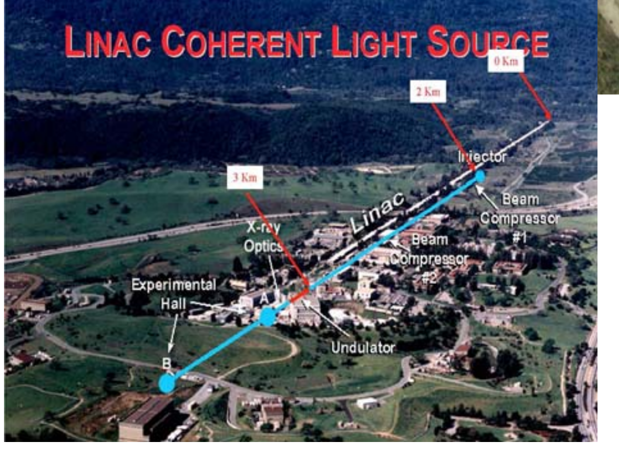




Cathode Applications– Accelerators

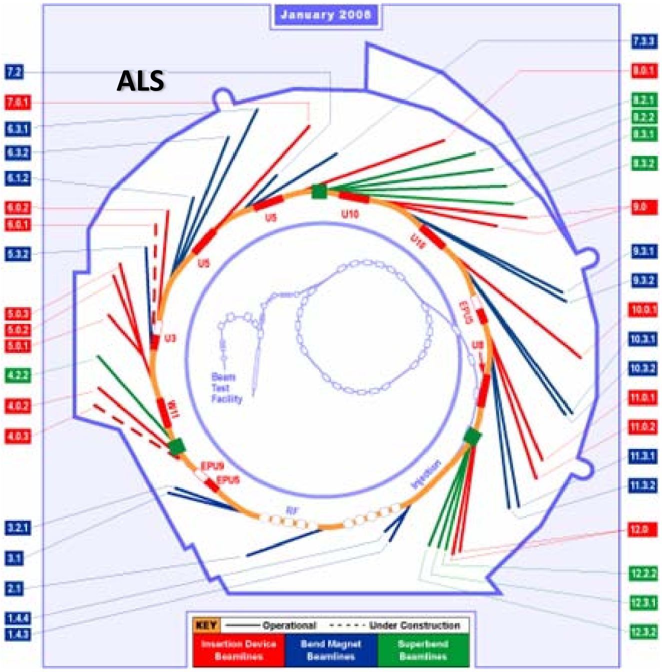
- Light sources typically use thermionic sources
  - Beam properties dominated by lattice, not cathode
  - This can be good and bad
- Electron machines for nuclear/particle physics (CEBAF, ILC, SLAC) typically require spin polarization and use special photocathodes
- Linacs (Flash, LCLS, ATF, Jlab FEL) typically use photocathodes – why?
- SCSS at Spring8 in Japan is a notable exception (*student topic?*)

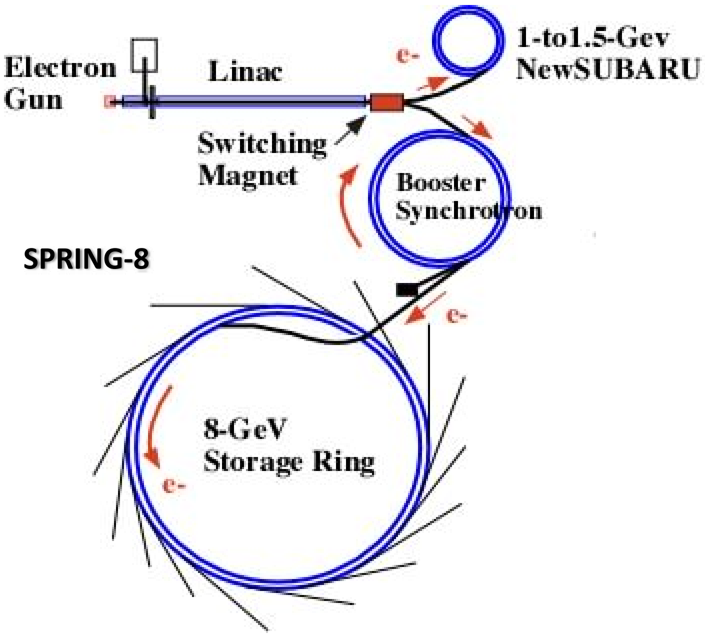
National Synchrotron Light Source II



The Role of the Electron Injector in Light Sources

In 1st, 2nd and 3rd generation light sources, electron sources are part of the injector chain that typically includes a small linac and a "booster" ring.
The beam generated by the electron gun goes through the linac and is then accelerated and stored in the booster for a time long enough that the 6D beam phase-space distribution is fully defined by the characteristics of the booster and not of the electron source.

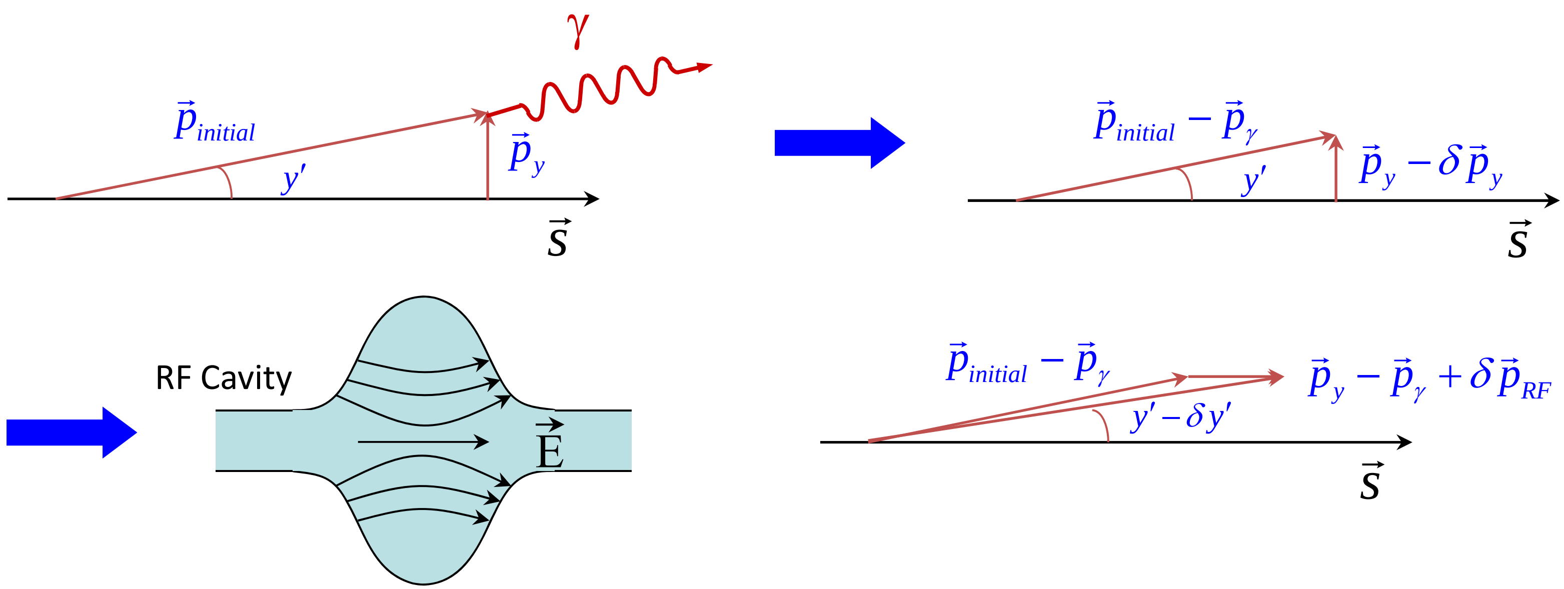




Synchrotron Radiation and Radiation Damping

From Mark Palmer's Lecture at the 3rd ILC school

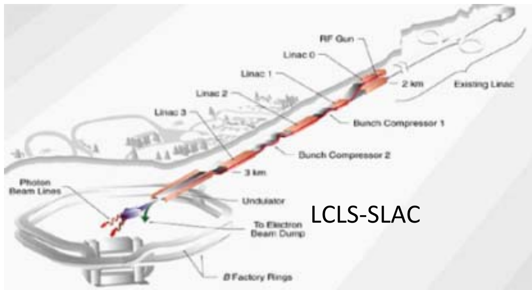
The energy lost by an electron beam on each revolution is replaced by radiofrequency (RF) accelerating cavities. Because the synchrotron radiation photons are emitted in a narrow cone (of half-angle $1/\gamma$) around the direction of motion of a relativistic electron while the RF cavities are designed to restore the energy by providing momentum kicks in the $\hat{s}$ direction, this results in a gradual loss of energy in the transverse directions. This effect is known as radiation damping.

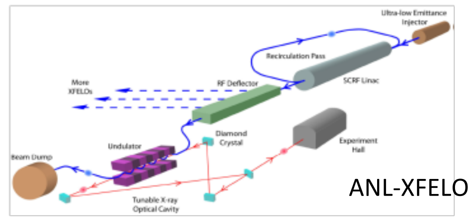


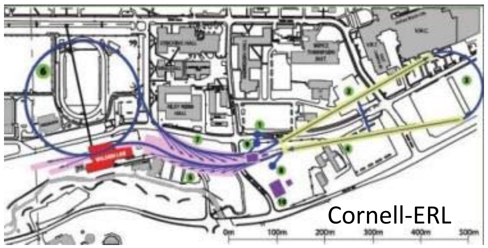
http://ilcagenda.linearcollider.org/conferenceOtherViews.py?view=standard&confId=2613

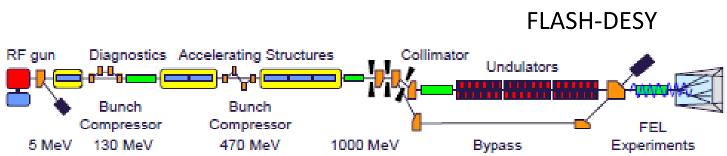
The Role of the Electron Injector in Light Sources

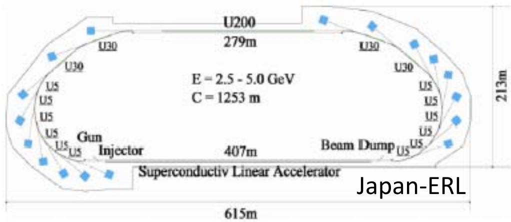
In linac based 4th generation light sources, such as free electron lasers (FELs) and energy recovery linacs (ERLs), the situation can be quite different. Indeed, in such a case, the final beam quality is set by the linac and ultimately by its injector and electron source.











In such facilities, the requirements for a large number of quasi-"monochromatic" electrons, concentrated in very short bunches, with small transverse size and divergence, translate into high particle density 6D phase-space, or in other words, in high brightness *B*:

$$B = \frac{N_e}{\varepsilon_{nx}\varepsilon_{ny}\varepsilon_{nz}}$$

with N_e the number of electrons per bunch and $\varepsilon_{nx,\,ny,\,nz}$ the normalized emittances for the planes x, y, and z

The brightness generated at the electron source represents the ultimate value for such a quantity, and cannot be improved but only spoiled along the downstream accelerator

Courtesy F. Sannibale

X-Ray 4th Generation Light Sources, the Most Challenging Electron Injector Case

- In FELs, the matching condition for transverse emittance drives towards small normalized emittances.

$$\varepsilon \approx \frac{\lambda}{4\pi} \quad \Rightarrow \quad \frac{\varepsilon_n}{\beta\gamma} \approx \frac{\lambda}{4\pi}$$

- The minimum obtainable value for ε_n defines the energy of the beam ($\gamma = E/mc^2$).

(with β the electron velocity in speed of light units, and assuming that an undulator with the proper period λ_u and undulator parameter K exist: $\lambda = \lambda_u / 2\gamma^2(1 + K^2/2)$)

- We will see later, that for the present electron gun technologies: $\varepsilon_n <\ \sim 1\ \mu m$ for the typical $<\ \sim 1$ nC charge/bunch.

For X-Ray machines ($\lambda <\ \sim 1$ nm) that implies GeV-class electron beam energy, presently obtainable by long and expensive linacs.

- Similar transverse emittance requirements apply also to ERLs.

- In X-Ray FELs the matching condition for the energy spread requires a fairly low energy spread as well

$$\frac{\sigma_E}{E} < \sim \rho_{Pierce} < \sim 10^{-3}$$

- Achieving the necessary FEL gain requires high peak current (~ 1 kA), and hence high charge/bunch and short bunches.

- In both ERLs and FELs, high-time resolution user-experiments require extremely short X-Ray pulses (down to sub-fs) imposing the need for small and linear longitudinal emittances to allow for the proper compression along the linac.

In summary, 4th generation X-Ray facilities challenge the performance of electron injectors.

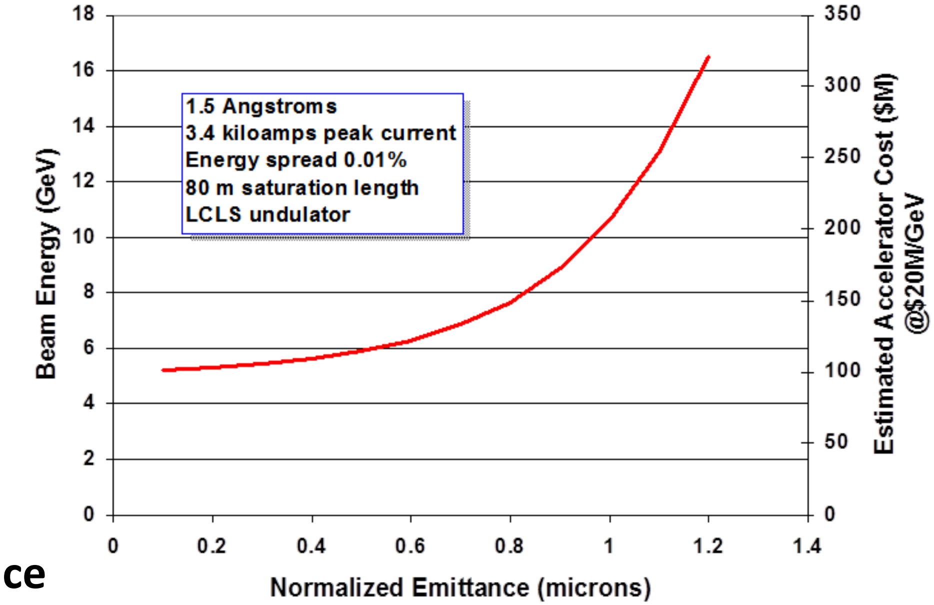
Courtesy F. Sannibale

Motivation for Brighter Electron Beams

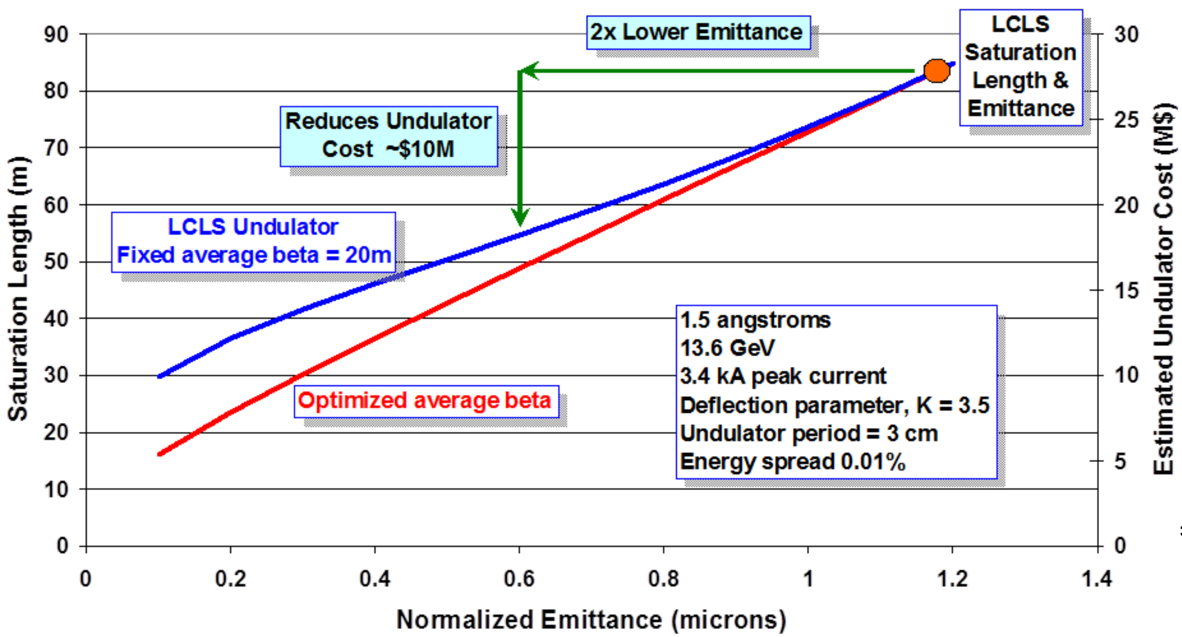
High energy electron beams are expensive

A poor beam can still laser at a high enough energy:

$$\frac{\epsilon_N}{\gamma} < \frac{\lambda_{FEL}}{4\pi}$$



Gain length and undulator cost vs. emittance



A poor beam increases the gain length which in turn increases to the undulator cost

*Doesn't include cost of infrastructure

The (obviously) most important Photocathode properties

- **Quantum efficiency**
  - High QE at the longest possible wavelength
  - Fast response time: <100 ps
  - Uniform emission
    - Non-uniform emission seeds emittance growth due to transverse, space charge expansion
  - Easy to fabricate, reliable, reproducible
  - Low dark current, field emission.

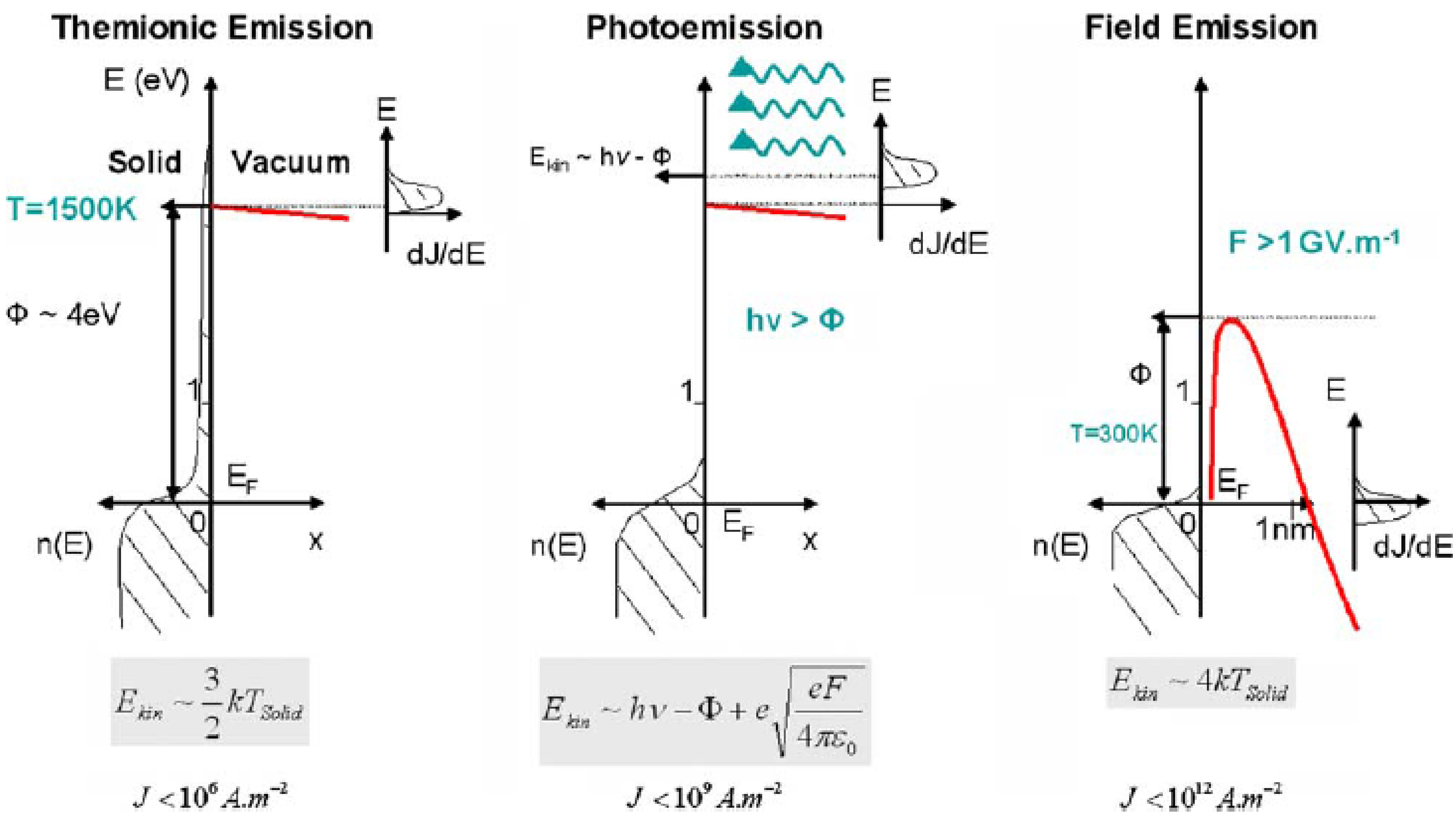
- **Intrinsic emittance**
  - Low as possible
    - Atomically flat: ~few nm p-p, to minimize emittance growth due to surface roughness and space charge
  - Tunable, controllable with photon wavelength
    - May need to "chase" the work function: $\varepsilon_{\text{intrinsic}} \propto \sqrt{\hbar\omega - \phi_{eff}}$
  - Better at cryogenic temperatures?

- **Lifetime, survivability, robustness, operational properties**
  - Require >1 year of operating lifetime
    - reasonable vacuum level: 10^{-10} Torr range
  - Easy, reliable cathode cleaning or rejuvenation or re-activation
  - Low field emission at high electric fields
    - needs to be atomically flat: ~few nm p-p
  - Reliable installation and replacement system (load lock)

Overview

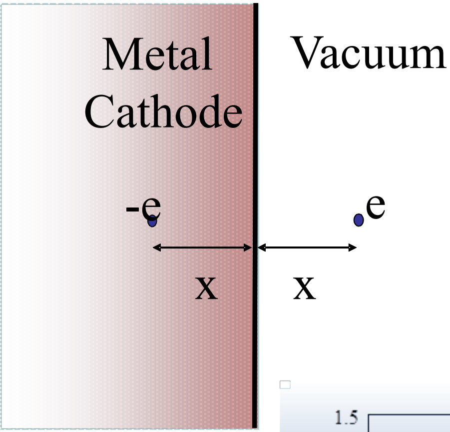
- Thermionic Cathodes
- Field Emitters
  - Field Emitter Arrays
  - Needle Cathodes
- Photocathodes
  - Metallic Photocathodes
    - Normal Conductors
    - Superconductors
  - Semiconductor Photocathodes
    - Positive Electron Affinity
      - Alkali Antimonides
      - Cesium Telluride
    - Negative Electron Affinity (Cs: GaAs)
- Photo-field emission
- Diamond Electron Amplifier

Emission Options

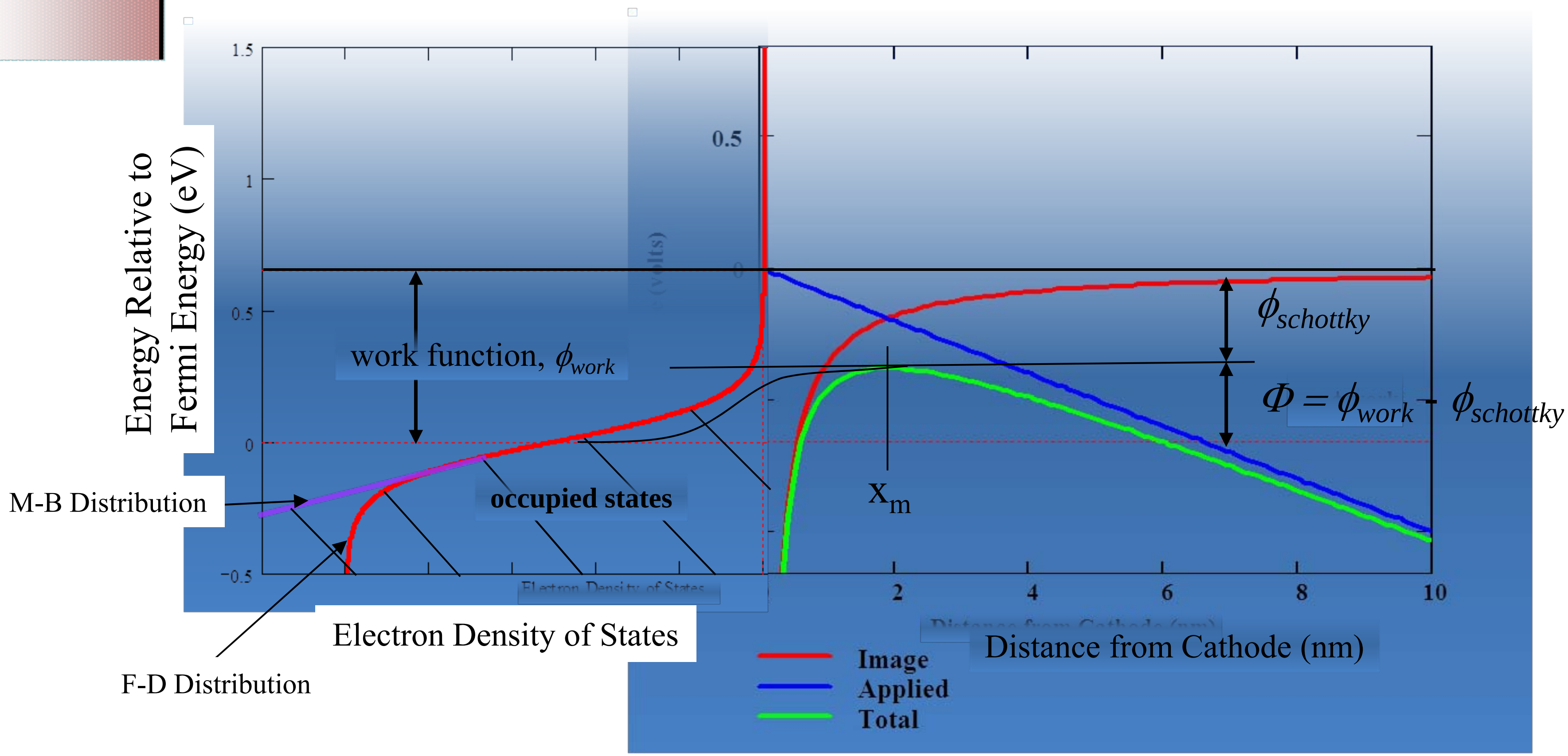


R. Ganter et al. NIM A **565** (2006) 423–429

Emission Barrier and Schottky effect



$$e\Phi = e\phi_{work} - \frac{e^2}{16\pi\epsilon_0 x} - eE_0 x$$



Dave Dowell

Thermionic and Field Emitters

Good for true DC and long pulse duration applications

The good points:

- Low transverse emittance
- Simple
- Tolerant of poor vacuum
- Long lifetime (10^4 hrs)

However:

- Long bunches (100 ps+)
- Large longitudinal emittance
- Lack of control of profile
- Complicate Linac (Bunchers, Compressors)

Types:

Thermionic (LaB$_6$, CeB$_6$, Scandate, BaO)

Field Emitter Arrays (Spindt Cathode)

Needle Cathode

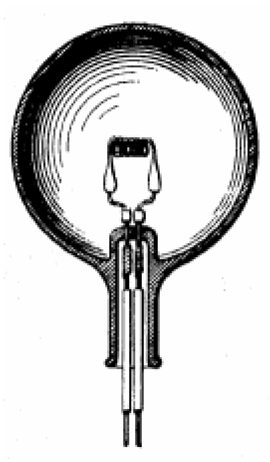
Photo-Assisted Field emission

Georg Gaertner, Keynote Lecture, IVESC 2008, Queen Mary College, London, 4.8.2008

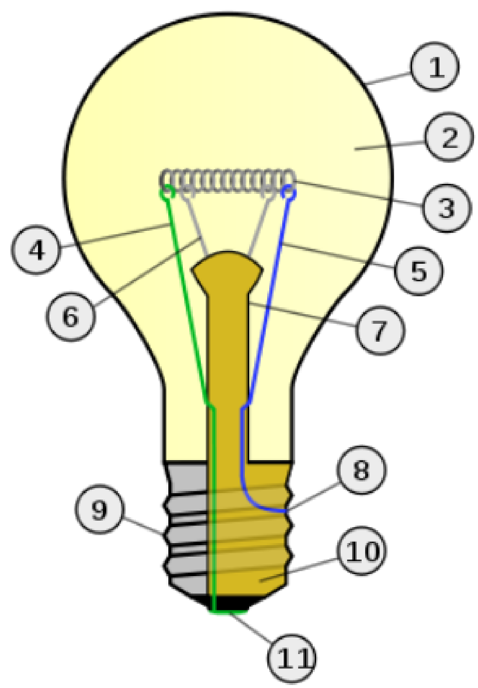
Thermionic Emission

Used to make light….

- Studied since early 1800's and perfected over 100 years, by many inventors (why does Edison get so much credit?)
- Thermionic emission from Tungsten filaments and metalloids like LaB_6 operating at >1000K are common
- > 90% of consumed power simply generates heat
- Often low vapor pressure filaments are used, to avoid coating tubes



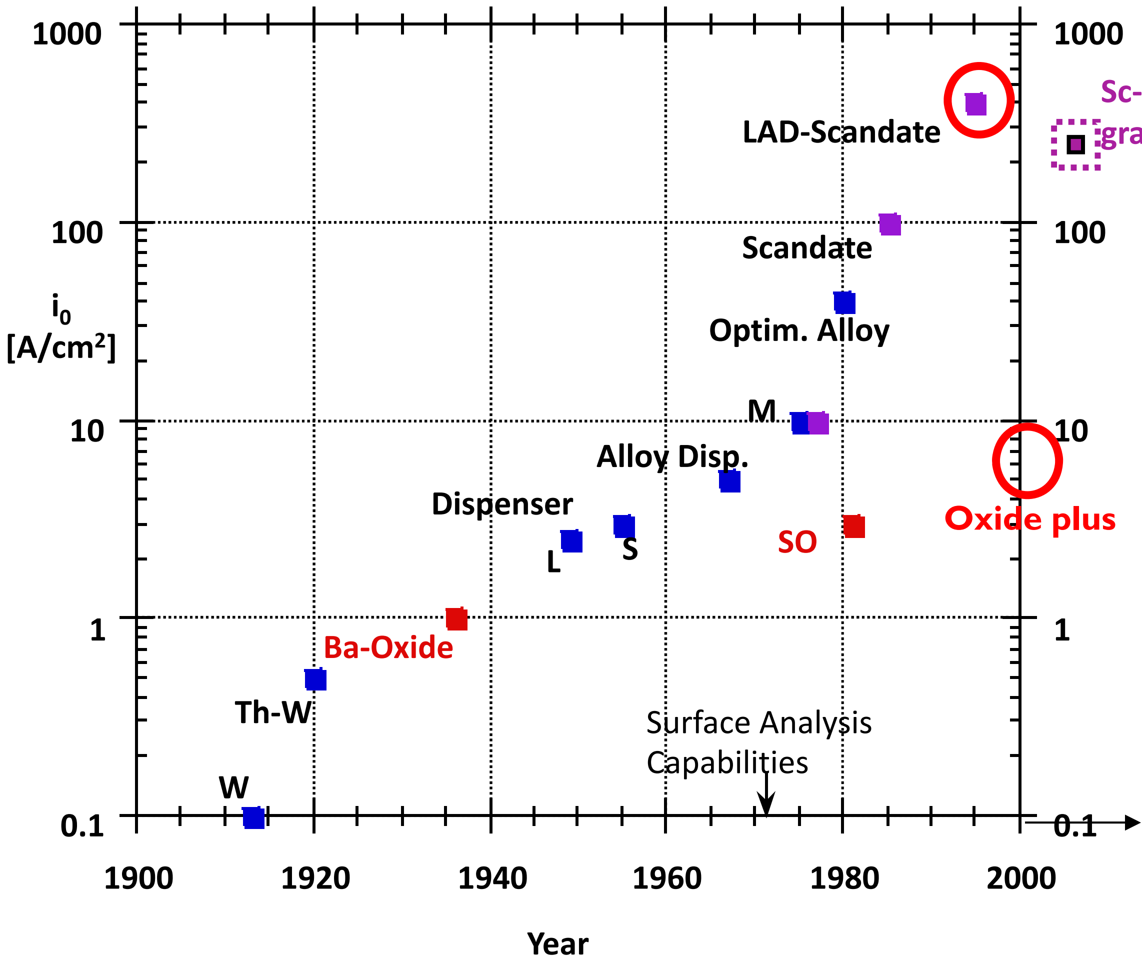
Edison's patent,
Long-lasting filament



1. Outline of Glass bulb
2. Low pressure inert gas (argon, neon, nitrogen)
3. Tungsten filament
4. Contact wire (goes out of stem)
5. Contact wire (goes into stem)
6. Support wires
7. Stem (glass mount)
8. Contact wire (goes out of stem)
9. Cap (sleeve)
10. Insulation (vitrite)
11. Electrical contact

PHILIPS

Vacuum electron sources

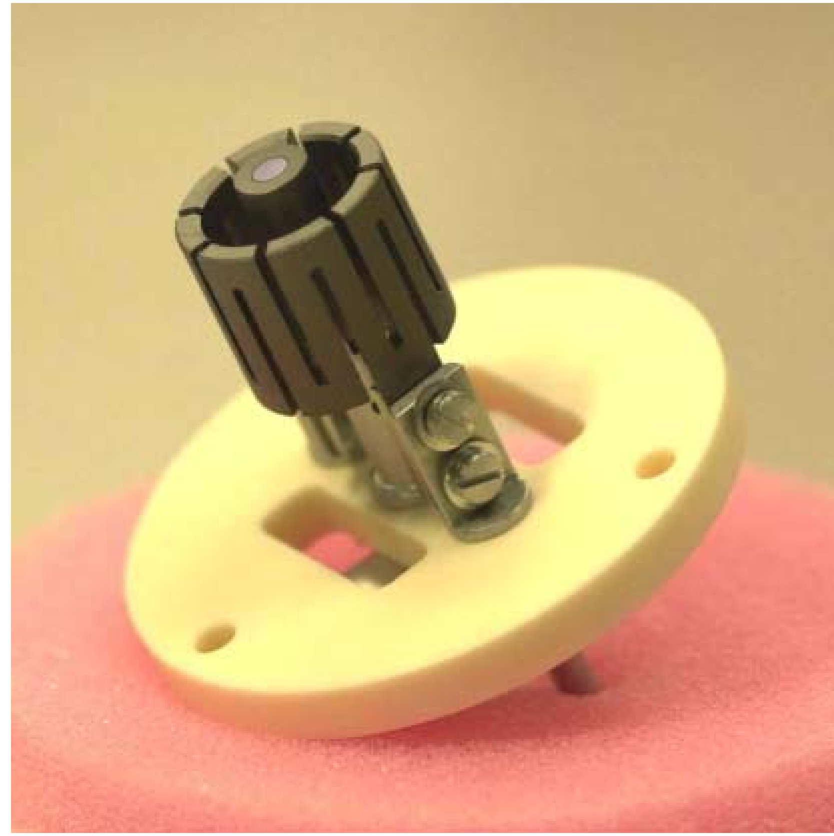


Historical development of thermionic cathode emission capabilities (life $t_{op} \geq$ 4000 h at saturated emission current density i_0).

Slide courtesy of G. Gaertner, Philips

Spring8 CeB_6 Cathode for XFEL (SCSS)

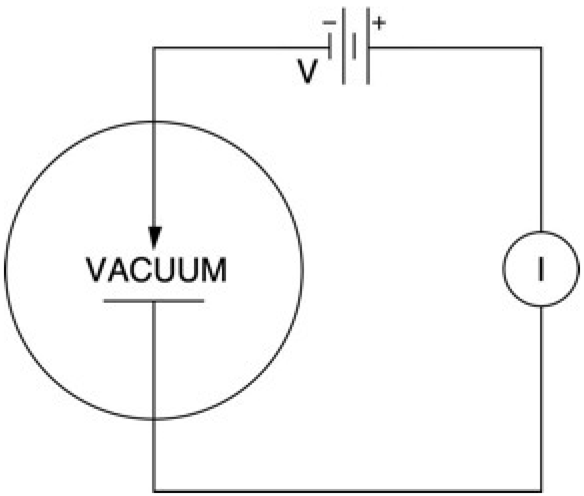
Beam Energy	500 keV
Peak Current	1~3A
Pulse Width (FWHM)	2 μsec
Repetition Rate	60 Hz
Cathode Temperature	1400~1600 deg.C
Cathode Diameter	3mm
Theoretical Thermal Emittance (rms)	0.4 πmm.mrad
Measured Normalized Emittance (rms, 90% particles)	0.6 πmm.mrad [7]



Chopper, Pre-buncher and Bunch compressor used to reduce pulse to 0.7 ps

K. Togawa *et al.*, PAC03, 3332; NIMA **528** (2004) 312
H. Tanaka *et al.*, FEL06, 769

Field Emitter Sources



$I = BV^2 \exp(-C/V)$

Vacuum diode

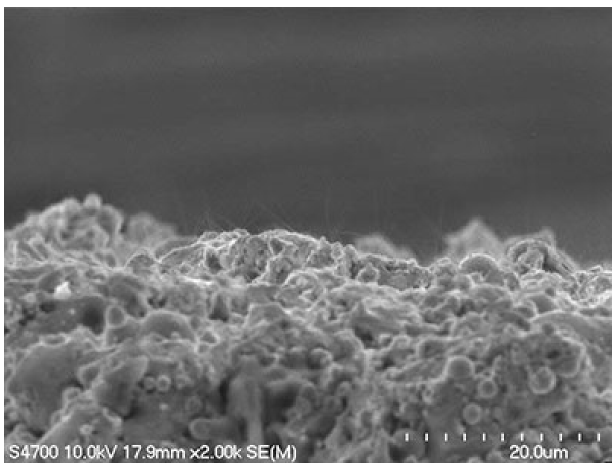
- Explained by Fowler-Nordheim, 1928: a quantum mechanical tunneling effect
- "bright" e-beam, good for surface science

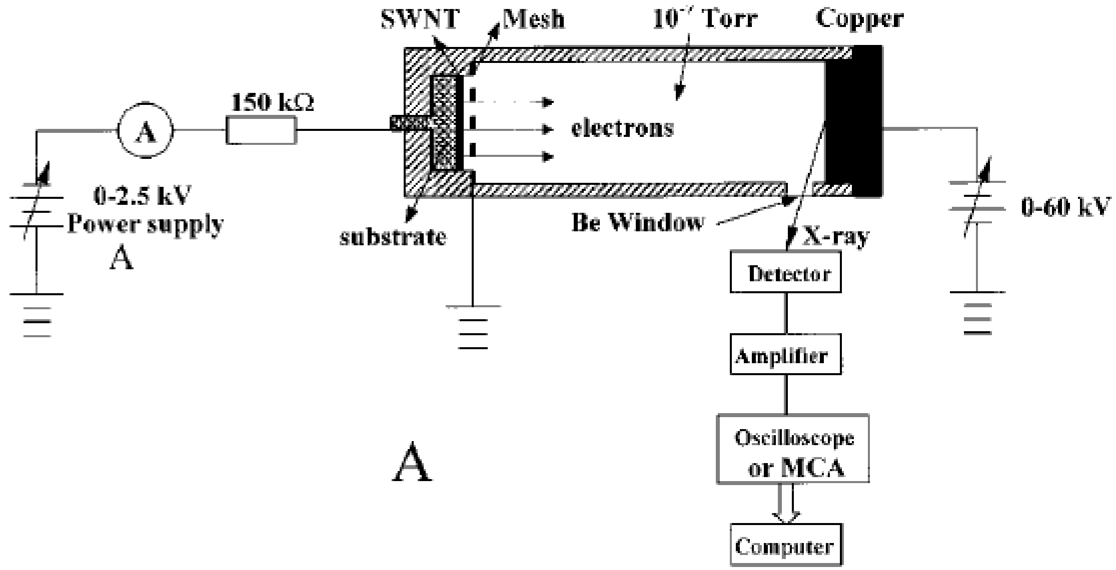
$$I \approx A \times 1.54 \times 10^{-6} \frac{F^2}{\phi} \exp\left[-6.83 \times 10^{9} \frac{\phi^{3/2}}{F} \right]$$

Carbon Nanotube FE source

Yue *et al.*

- Single wall carbon nano-tubes



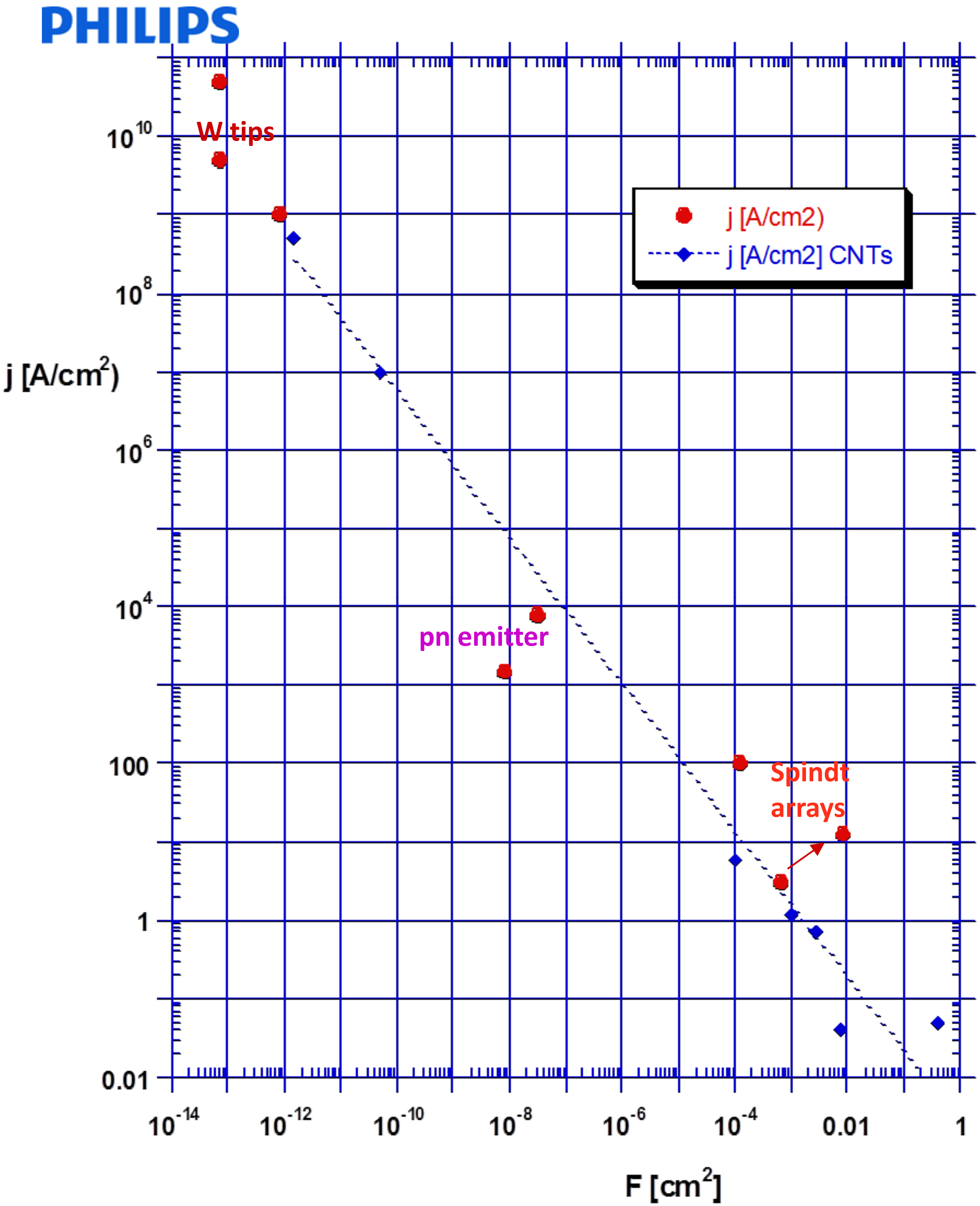


APPLIED PHYSICS LETTERS VOLUME 81, NUMBER 2 8 JULY 2002

Generation of continuous and pulsed diagnostic imaging x-ray radiation using a carbon-nanotube-based field-emission cathode

G. Z. Yue
Department of Physics, University of North Carolina, Chapel Hill, North Carolina 27599

Xintek Nanotechnology Innovations



Field emission (cold emission) current density versus emitter area (including passive parts)

In order to judge an improvement of FE / cold emitters over time a good comparison can only be made for a fixed emitting area; Also the increase of the total area can be seen as improvement

The blue symbols are CNT emitters. The fitted curve is a power law

$j = 0.00246 * (F/cm^2)^{-0.935}$ [A /cm^2]

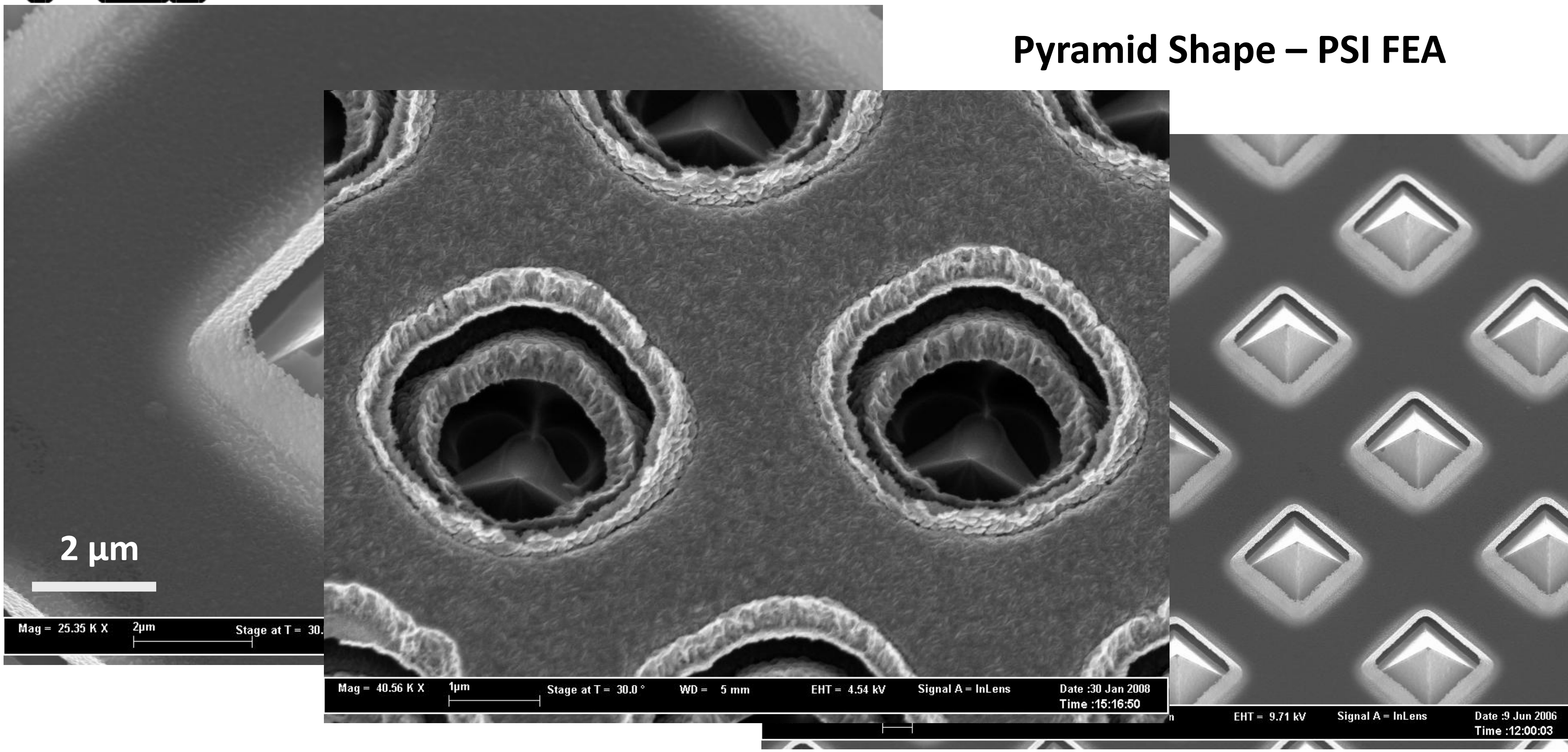
Limiting effects:

non-emitting parts/ gate, field shielding, space charge, thermal load

Slide courtesy of G. Gaertner, Philips

PSI Field Emitter Array

Pyramid Shape – PSI FEA



Source: S. Tsujino; E. Kirk

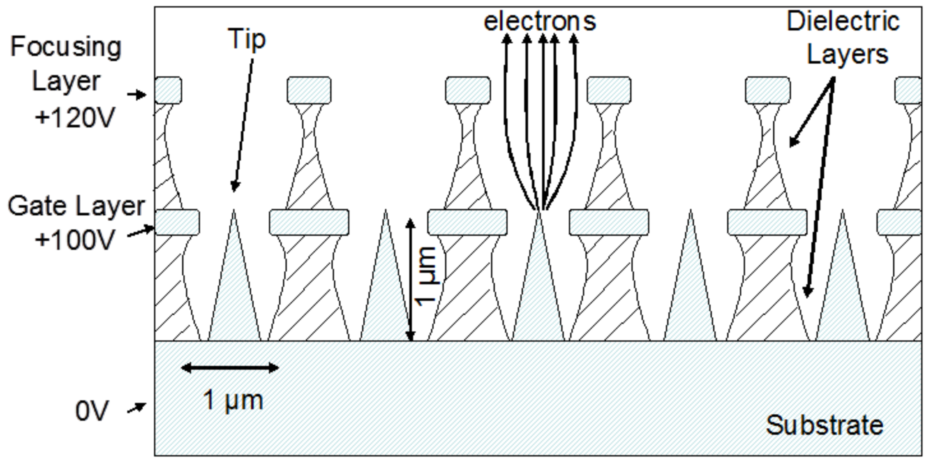
- Mo Tips (Field Enhancement Factor: <β> ~ 90)
- Metallic wafer; Molding Technique
- 10µA per tip DC (gate bias ~200V)

April 2008 PSI: First Double Gated – All Metal FEA

S. C. Leemann, A. Streun, A. F. Wrulich, Phys. Rev. ST Accel. Beams 10, 071302 (2007)
A. Oppelt *et al.*, FEL07, 224

Slide courtesy of R. Ganter, PSI

Double Gated FEA



$$\varepsilon_{n,rms}(1^{st}\,Gate) \sim \beta\gamma.n.\delta x.\vartheta$$

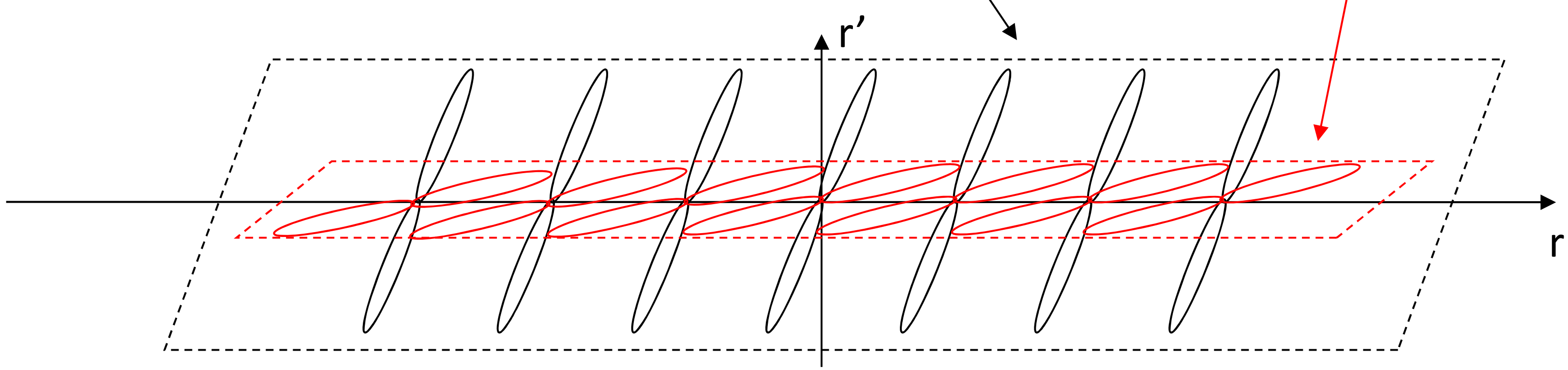
$\beta\gamma.\vartheta = 5mrad$ n=100; δx=2µm

$$\varepsilon_{n,rms}(1^{st}\,Gate) \sim 2\ mm.mrad$$

$$\varepsilon_{n,\mathrm{int}r.}(2^{nd}\,Gate) < 0.1\ mm.mrad$$

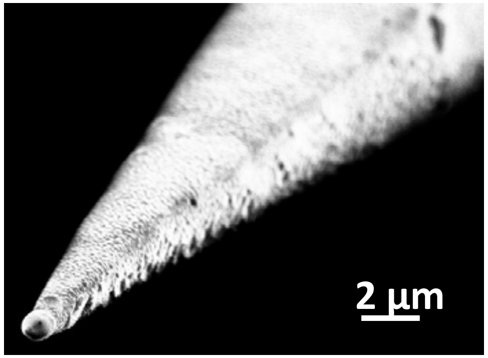
Initially
ε_n ~ 2 mm.mrad

After Focusing
ε_n < 0.1 mm.mrad



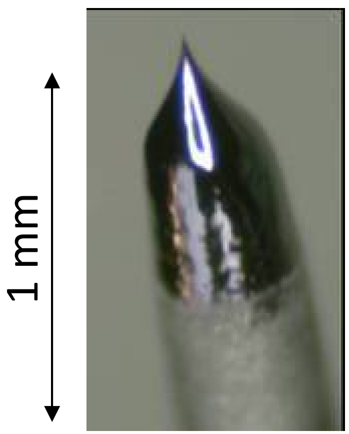
Slide courtesy of R. Ganter, PSI

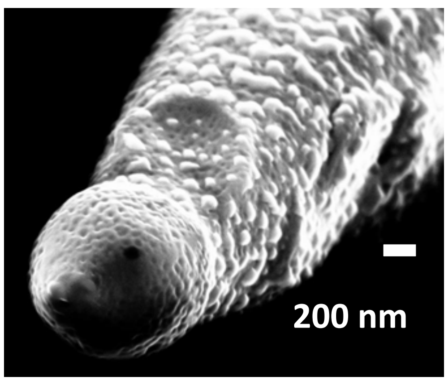
Needle Cathode

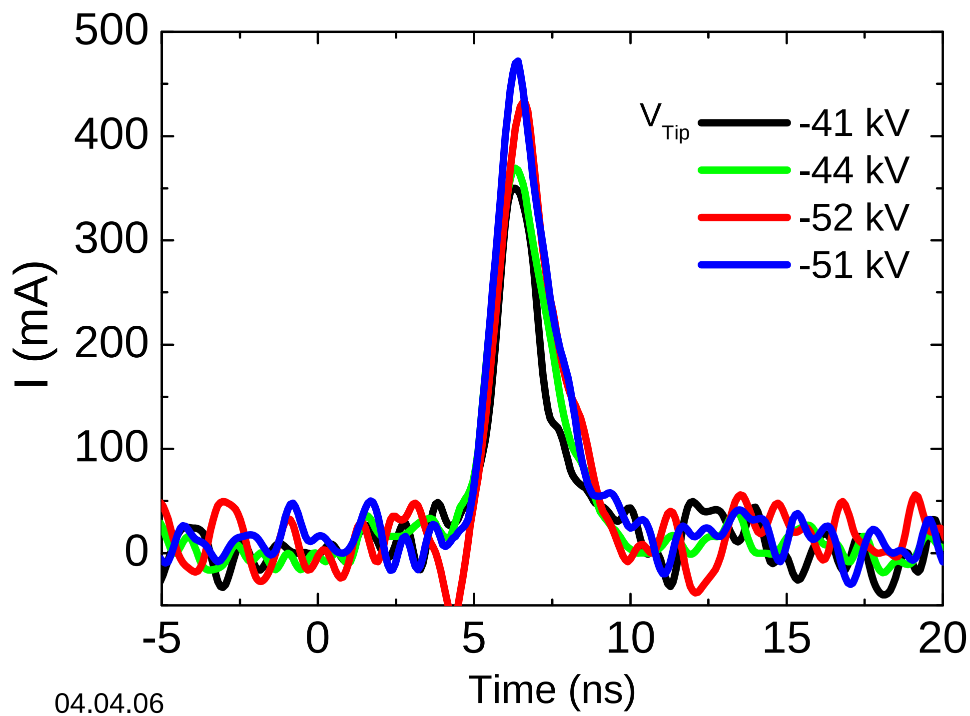


r_{apex} **~ 1 to 5 µr**

ZrC Single Crystal (100):
robust, Φ_{ZrC} ~ 3.5 eV







Commercial Devices from A. P. Tech Inc.

Peak Current
in Field Emission mode
~ 500 mA

Slide courtesy of R. Ganter, PSI

Photoinjector Basics

Why use a Photoinjector?

Electron beam properties determined by laser
- Timing and repetition rate
- Spatial Profile
- Bunch length and temporal profile (Sub-ps bunches are possible)

High peak current density

10^5 A/cm^2

Low emittance/temperature

<0.2 µm-rad

Useful relation:

$$hc = 1239.8[eV \cdot nm] = \lambda \cdot E$$

Cathode/Injector Properties

Quantum Efficiency (QE)

$$QE = \frac{\# e^-_{emitted}}{\# \gamma_{incident}} = h\nu \frac{I}{P}$$

Lifetime: time (or charge) required for QE to drop to 1/e of initial

Response Time: time required for excited electrons to escape

Emittance: Correlation between the position and momentum of particles in the bunch

Peak Current: $I_p = \frac{Q_{bunch}}{\tau_{bunch}}$

G. Suberlucq, EPAC04, 64
JACoW.org

The Old Standby - Metals

Normal conducting RF photoinjectors often use metal cathodes, either Cu (simplicity) or Mg (higher QE)

The good points:

- Basically unlimited lifetime (with occasional laser or ion cleaning)
- Tolerant of poor (nTorr) vacuum
- Prompt response time (fs)
- Low field emission

However

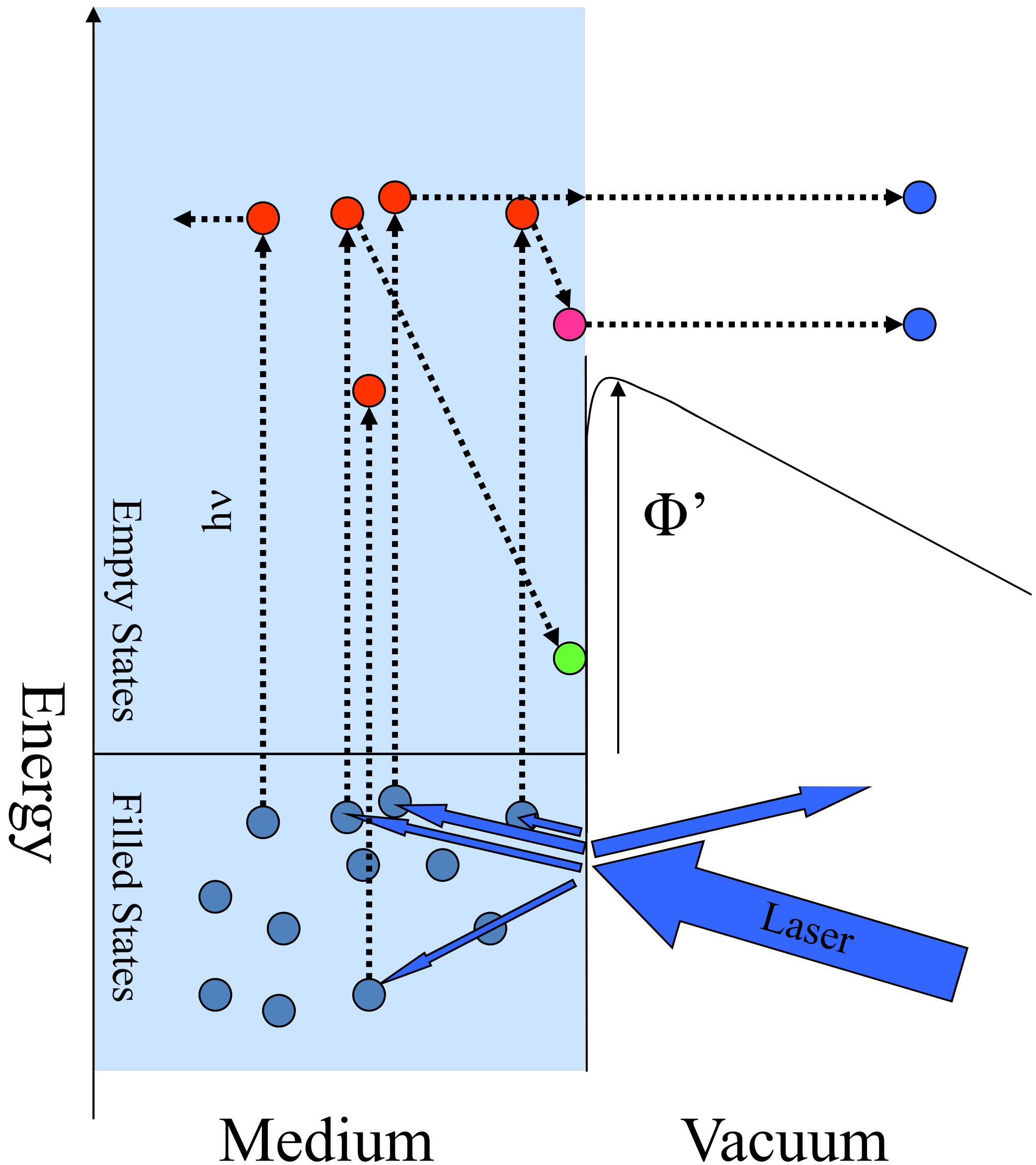
- Require UV laser
- Typical QE of 10^{-5} to 10^{-3}

} Not suitable for >1 mA injectors

Magnesium QE @ 266 nm = 0.2% @ 266nm

W.F. Krolikowski and W.E. Spicer, Phys. Rev. 185, 882 (1969)
D. H. Dowell *et al.*, Phys. Rev. ST Accel. Beams 9, 063502 (2006)
T. Srinivasan-Rao *et al.*, PAC97, 2790

Three Step Model of Photoemission - Metals



1) Excitation of e^- in metal

- Reflection
- Absorption of light
- Energy distribution of excited e^-

2) Transit to the Surface

- e^--e^- scattering
  - mfp ~50 angstroms
- Direction of travel

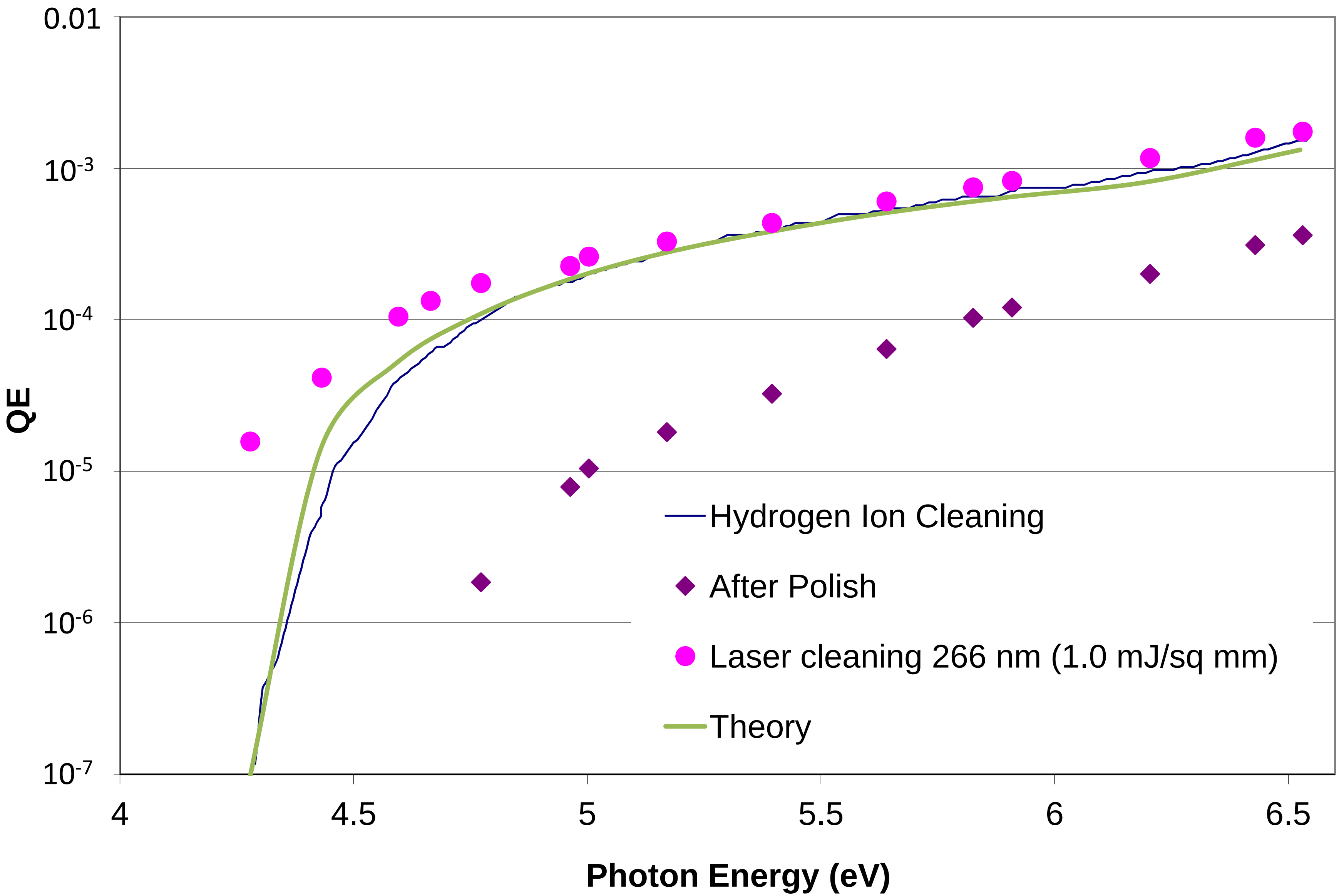
3) Escape surface

- Overcome Workfunction
- Reduction of Φ due to applied field (Schottky Effect)

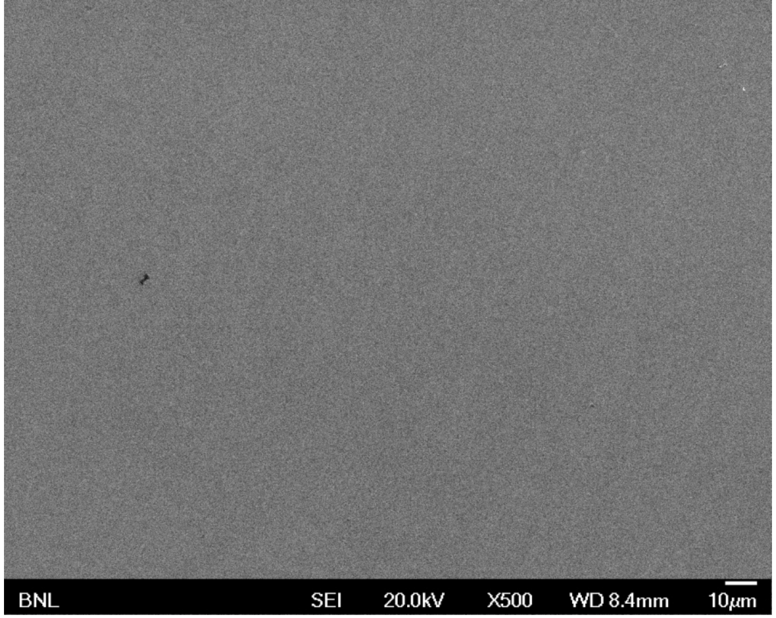
Integrate product of probabilities over all electron energies capable of escape to obtain Quantum Efficiency

M. Cardona and L. Ley: Photoemission in Solids 1, (Springer-Verlag, 1978)

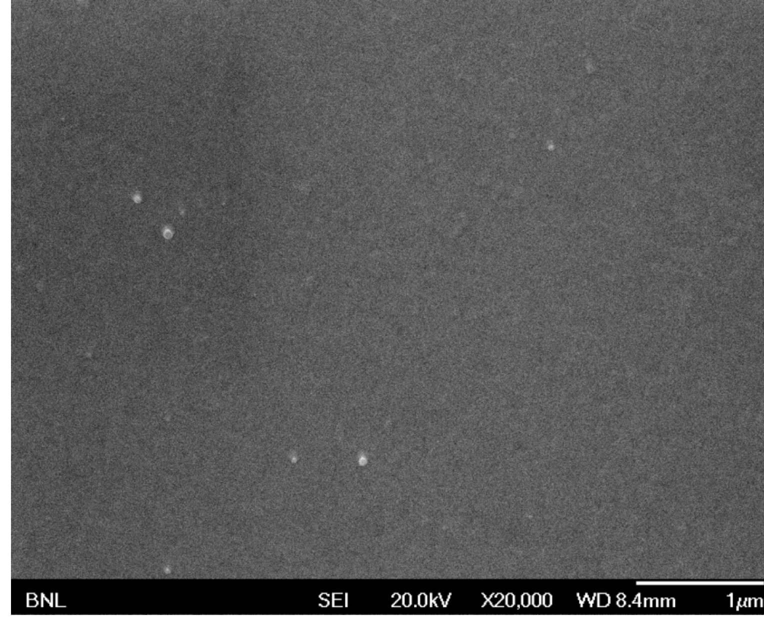
LCLS Copper Cathodes



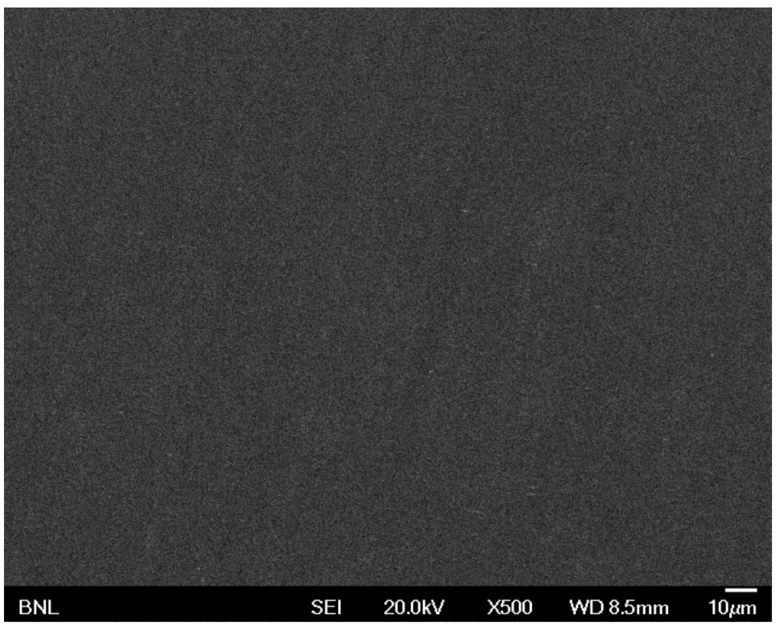
D. H. Dowell *et al.*, Phys. Rev. ST Accel. Beams 9, 063502 (2006)



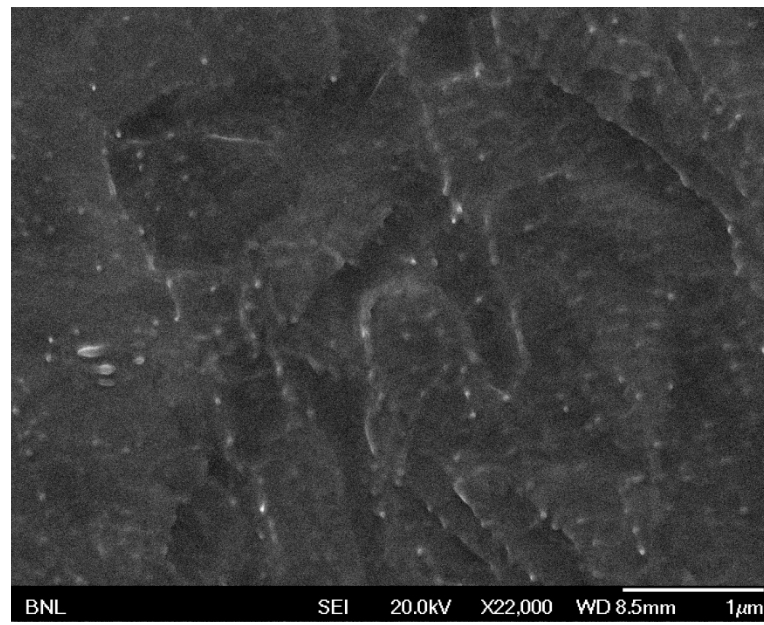
Before, x500



Before, x20k



After, x500



After, x20k

Superconducting Photocathodes

The cathode-cavity interface is the most difficult part a superconducting injector

Using a superconductor as a cathode removes the need for a RF choke, and may allow higher gradients

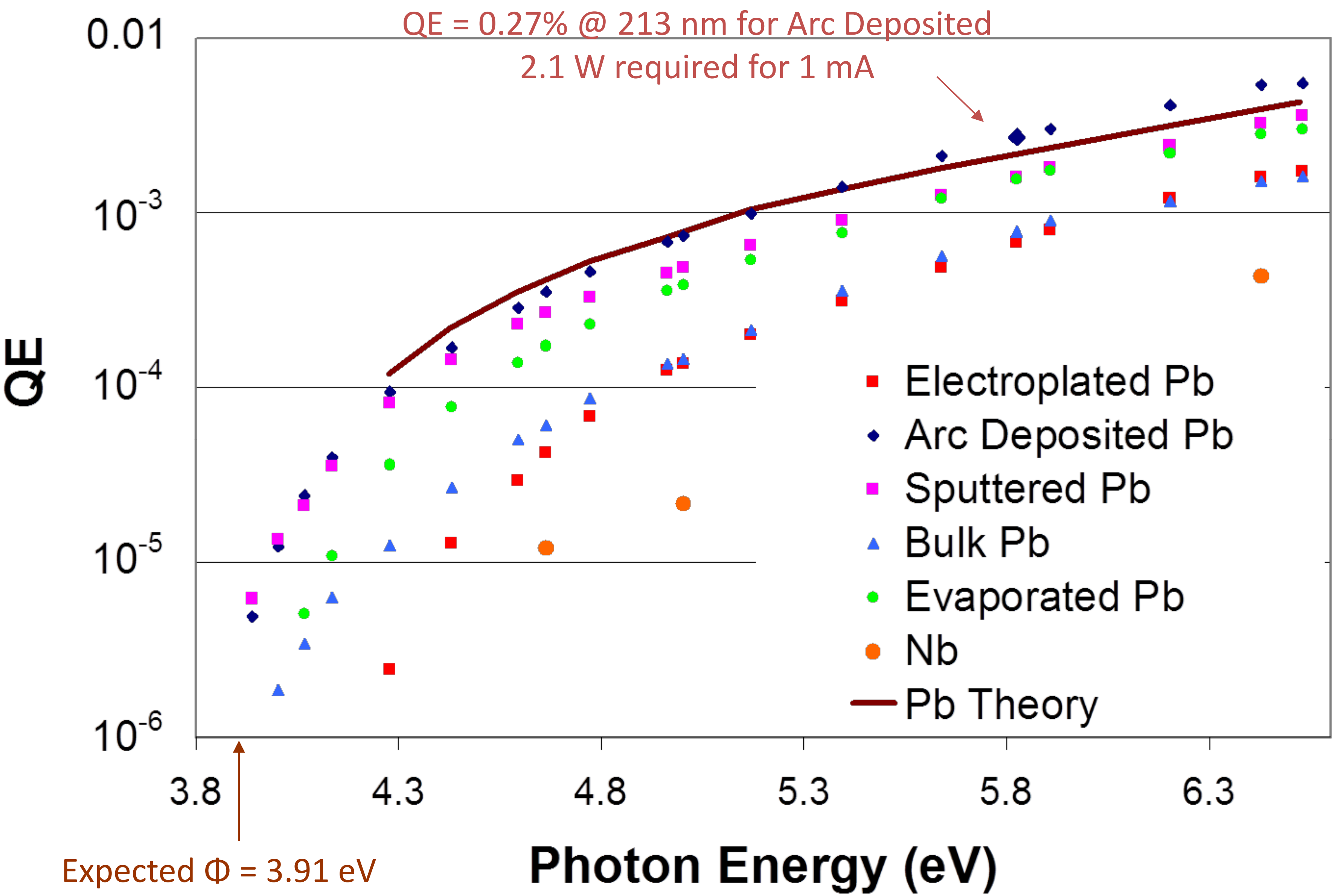
Niobium is a poor photocathode -> use Lead

Two ½ cell cavities (1.3 & 1.42 GHz) have been tested

- Both reached 40 MV/m; RF performance unaffected by lead
- Lead cathode QE comparable to room temperature values
- Peak laser power of 3 MW/cm^2 (@ 248 nm) did not quench the cavity

J. Smedley, T. Rao, and Q. Zhao, J. Applied Physics 98, 043111 (2005)
J. Smedley, T. Rao , J. Sekutowicz, Phys. Rev. ST Accel. Beams 11, 013502 (2008)
J. Smedley *et al.*, PAC07, 1365; J. Sekutowicz *et al.*, PAC07, 962

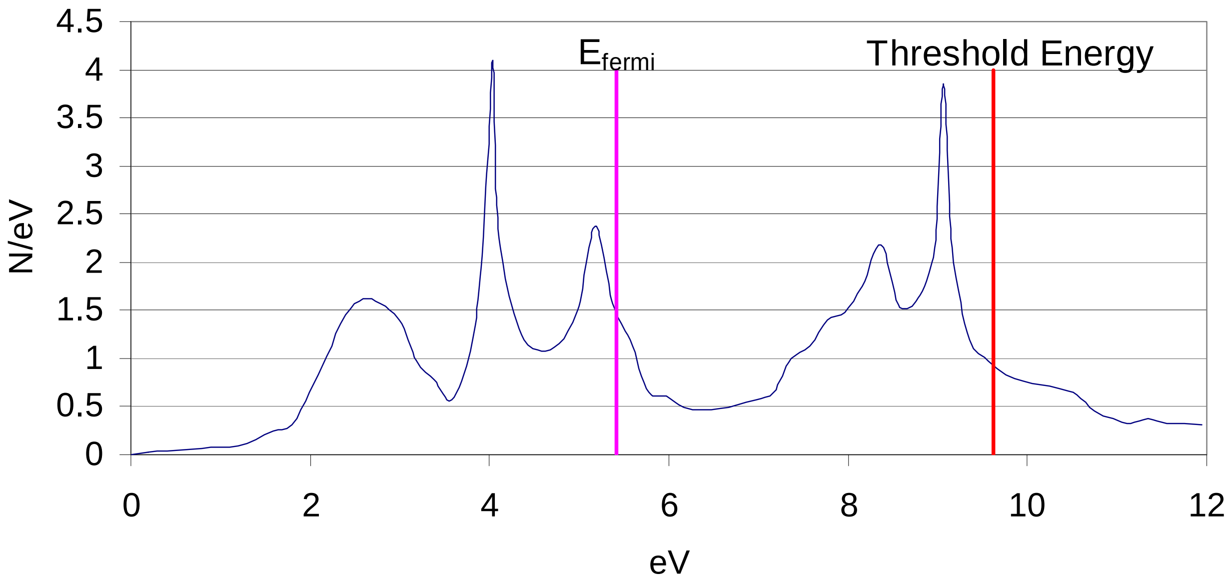
DC Room Temperature Photoemission Results



J. Smedley, T. Rao , J. Sekutowicz Phys. Rev. ST Accel. Beams **11**, 013502 (2008)

W.E. Pickett and P.B. Allen; Phy. Letters **48A**, 91 (1974)

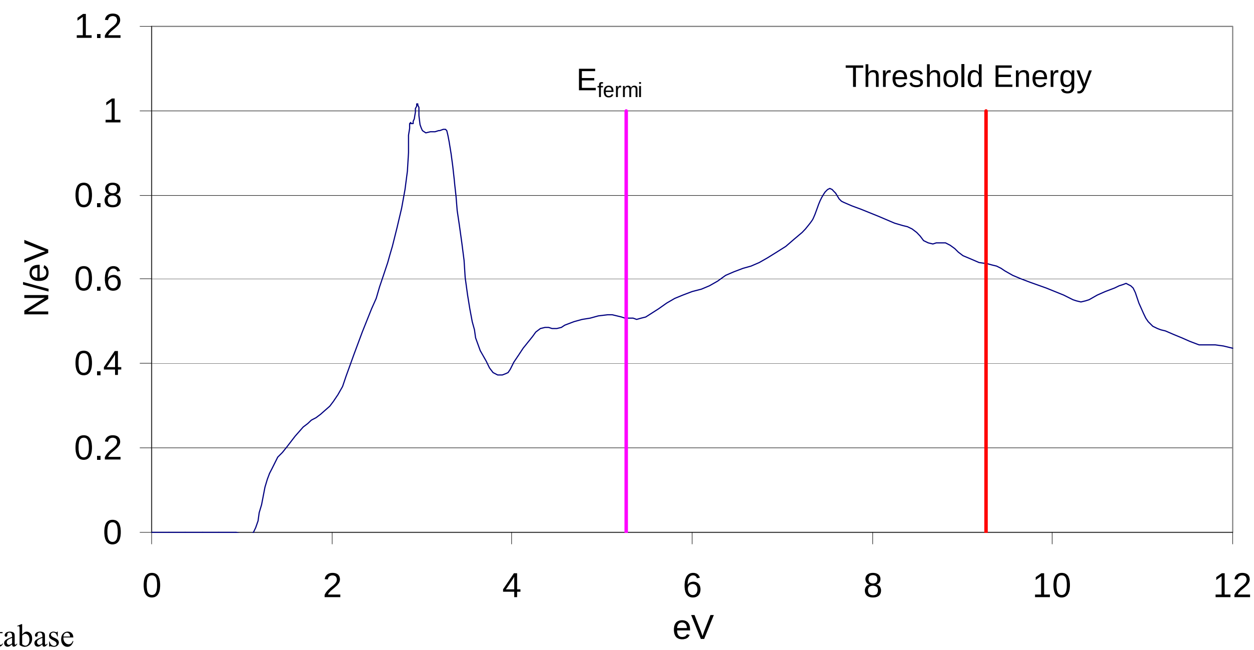
Nb Density of States



Density of States for Nb

Large number of empty conduction band states promotes unproductive absorption

Lead Density of States



Density of States for Lead

Lack of states below 1 eV limits unproductive absorption at higher photon energies

NRL Electronic Structures Database

Semiconductor Photocathodes

The primary path to high average current in photoinjectors

The good points:

- QE can be >10%
- Many use visible light
- Polarized cathodes possible

However:

- Require UHV (<0.1 nTorr)
- Limited Lifetime
- Response time
- Complicated

Common types:

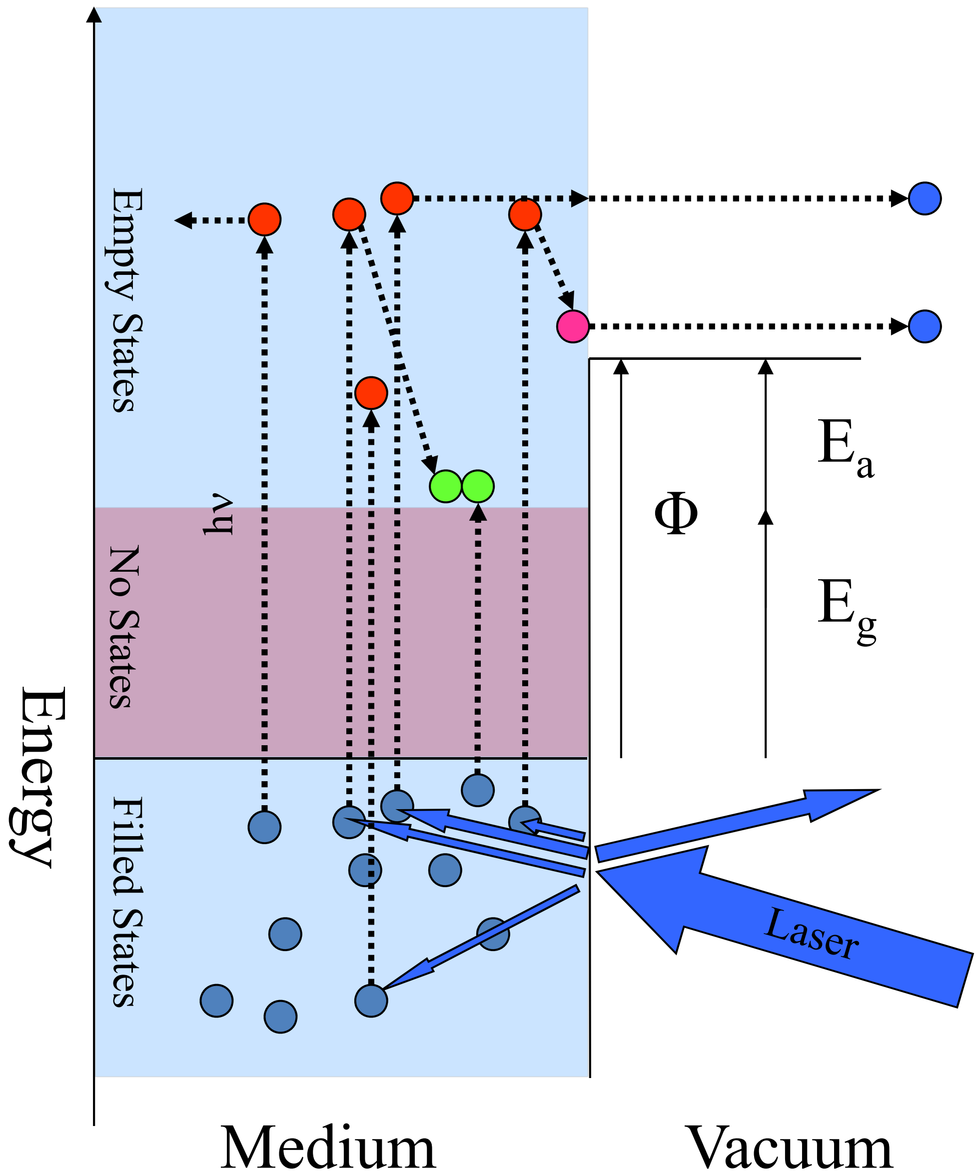
Cs_2Te – QE ~7% @ 262 nm, Lifetime 100's of hrs

K_2CsSb – QE >4% @ 532 nm, Lifetime <10 hrs

Cs:GaAs – QE ~0.5% @ 800 nm (polarized), 6% @ 527 nm

W.E. Spicer & A. Herrera-Gomez, Modern Theory and Applications of Photocathodes, SLAC-PUB-6306 (1993)

Three Step Model - Semiconductors



1) Excitation of e^-

Reflection, Transmission, Interference

Energy distribution of excited e^-

2) Transit to the Surface

e^--lattice scattering

mfp ~100 angstroms

many events possible

e^--e^- scattering (if $h\nu > 2E_g$)

Spicer's Magic Window

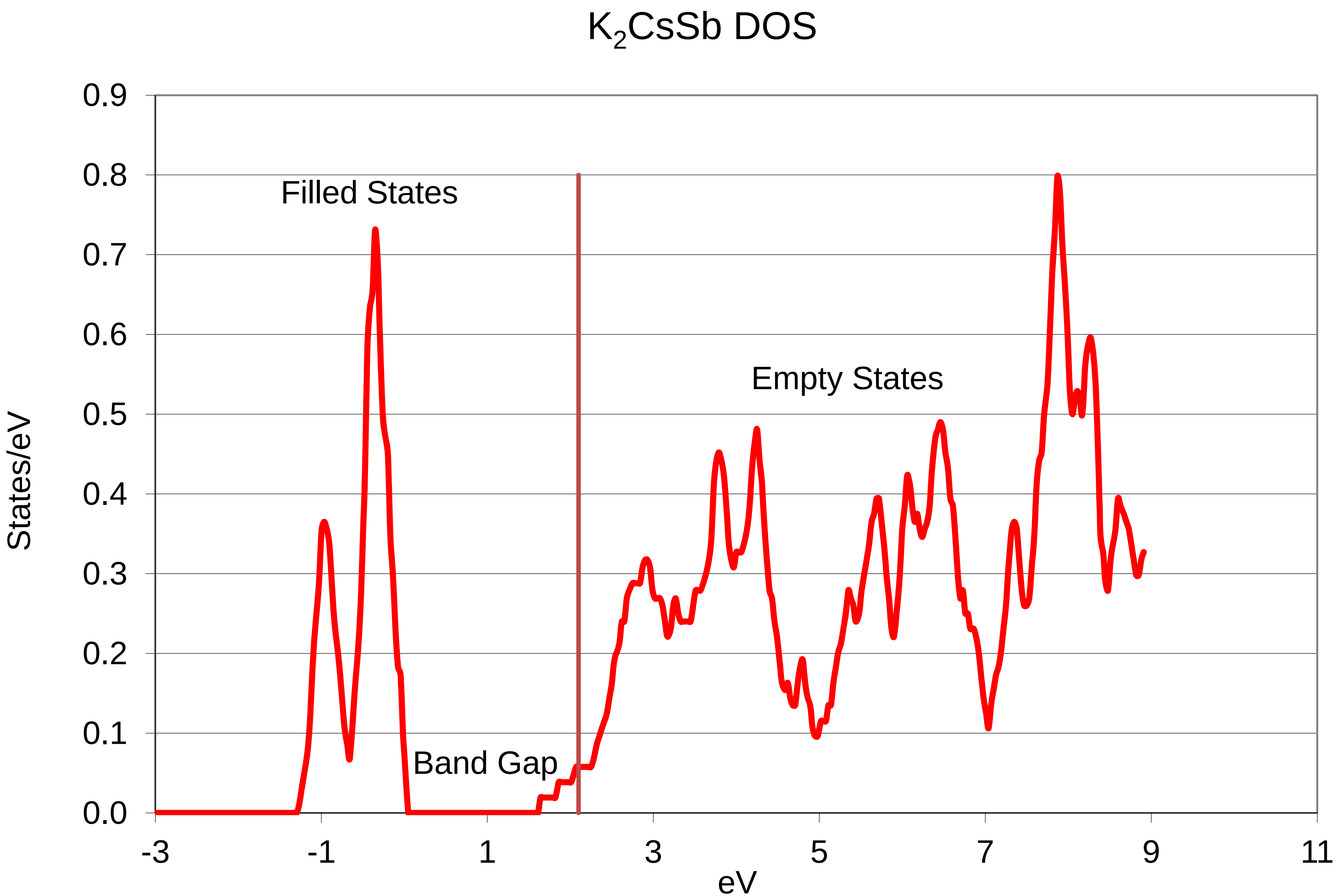
Random Walk

Monte Carlo

Response Time (sub-ps)

3) Escape surface

Overcome Electron Affinity



A.R.H.F. Ettema and R.A. de Groot, Phys. Rev. B **66**, 115102 (2002)

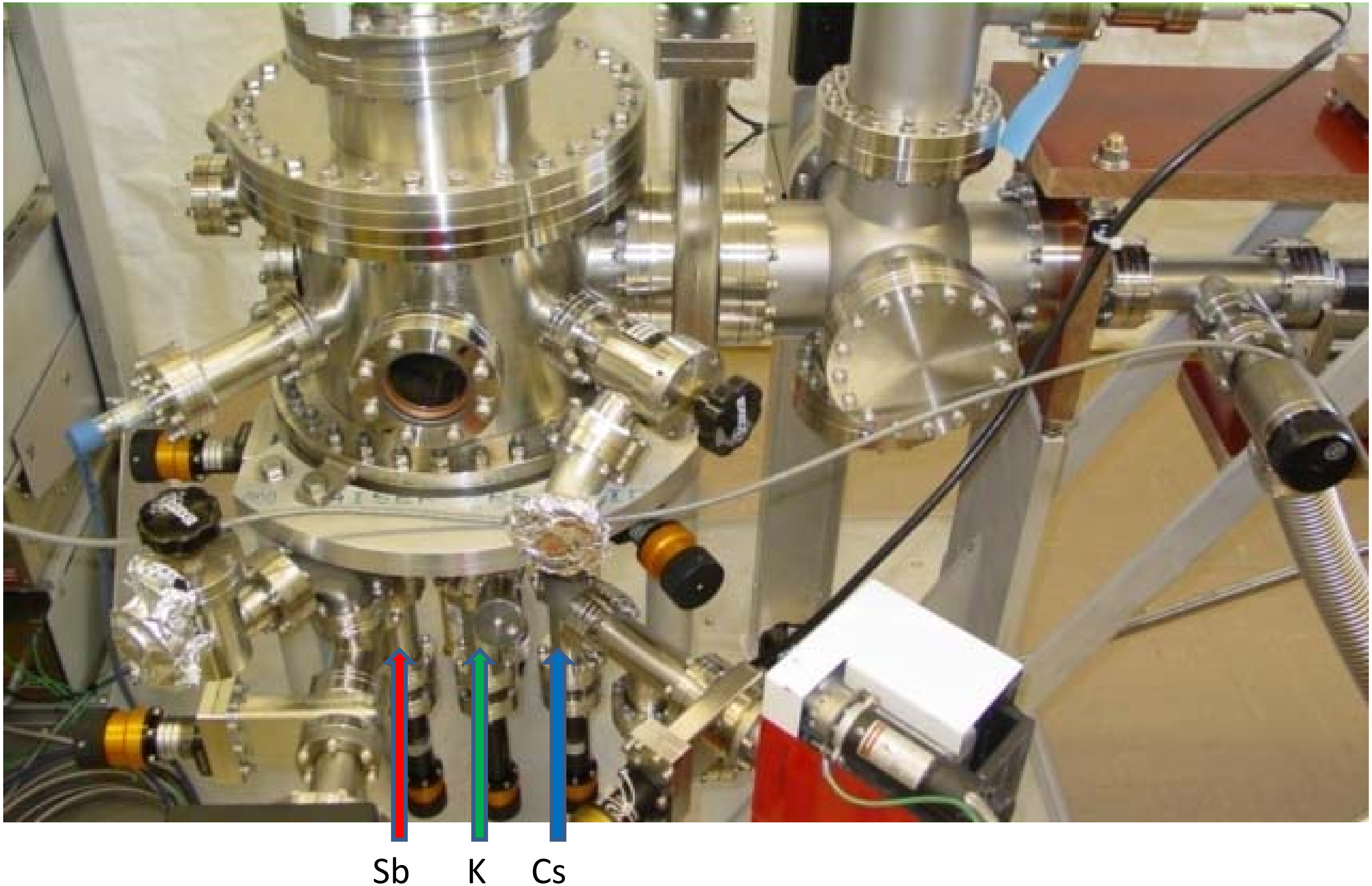
K_2CsSb (Alkali Antimonides)

- Work function 1.9eV, E_g= 1.2 eV
- Very high QE for visible light (4% -12% @ 532 nm, >30% @ 355nm)
- Deposited in 10^{-11} Torr vacuum
  - Typically sequential (Sb->K->Cs); Cs deposition used to optimize QE
  - Surface oxidation to create Cs-O dipole
  - Co-deposition increases performance in tubes
- Cathodes stable in deposition systems (after initial cooldown)
- Typical lifetime in an RF injector is measured in hours
  - Chemical poisoning is major cause of QE loss
  - Cs-dipenser cathodes to allow in-situ rejuvination being investigated
  - Improved vacuum should help (DC/Superconducting injectors)

D. H. Dowell *et al.*, *Appl. Phys. Lett.,* **63**, 2035 (1993)

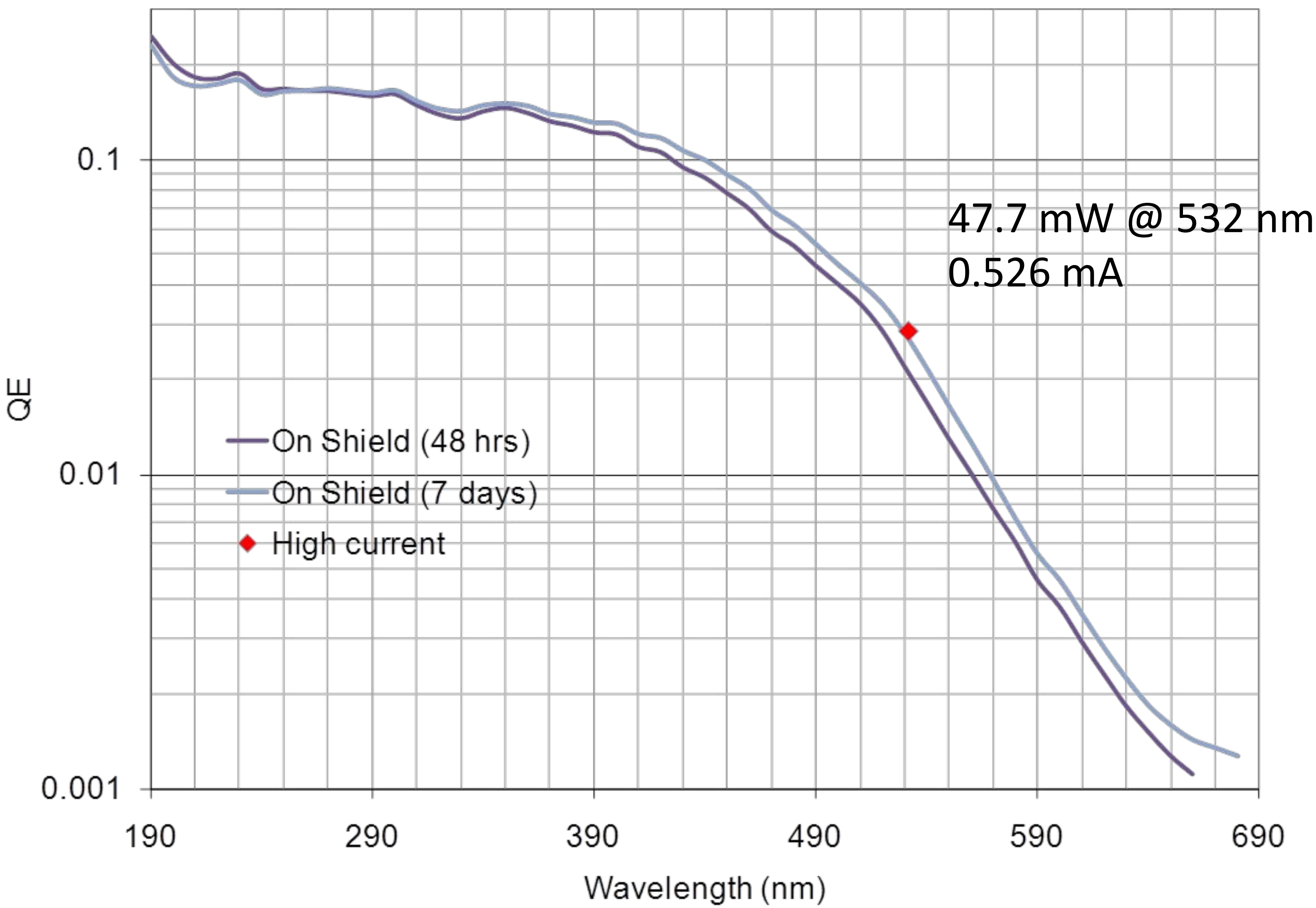
C. Ghosh and B.P. Varma, *J. Appl. Phys.,* **49**, 4549 (1978)

Deposition System

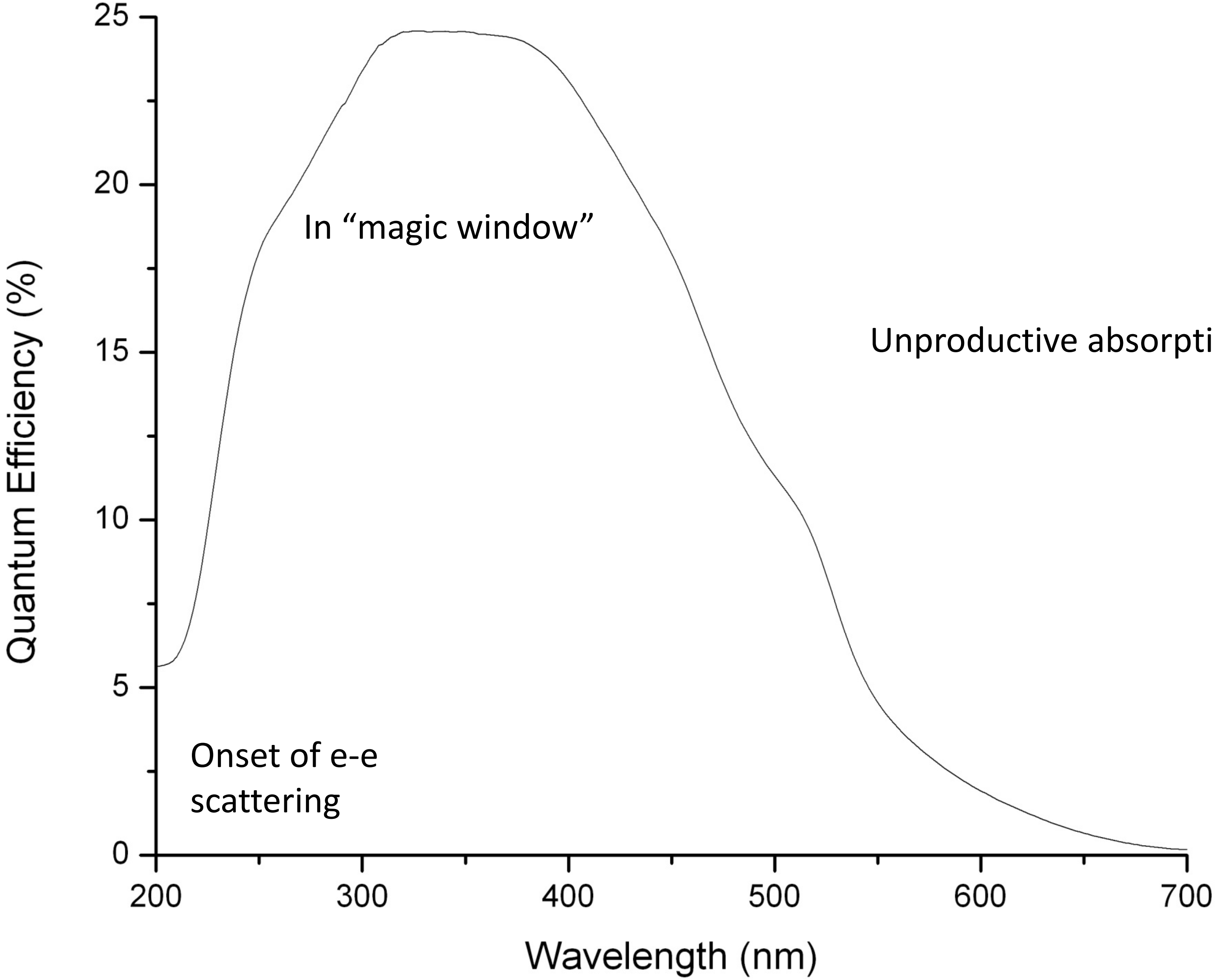


Sequential deposition with retractable sources (prevents cross-contamination)
Cathode mounted on rotatable linear-motion arm
Typical vacuum 0.02 nTorr (0.1 nTorr during Sb deposition)

K_2CsSb Performance
Deposition Chamber, no oxidation



Spectral Response – Bi-alkali



Cs_2Te

Most common cathode for ~1mA injectors

Work function 3.6eV, E_g= 3.2 eV

Good QE for UV light (Max >20%, Average ~7% @ 262 nm)

Deposited in 10^{-11} Torr vacuum

- Typically sequential (Te->Cs); Cs used to optimize QE
- Co-deposition increases performance

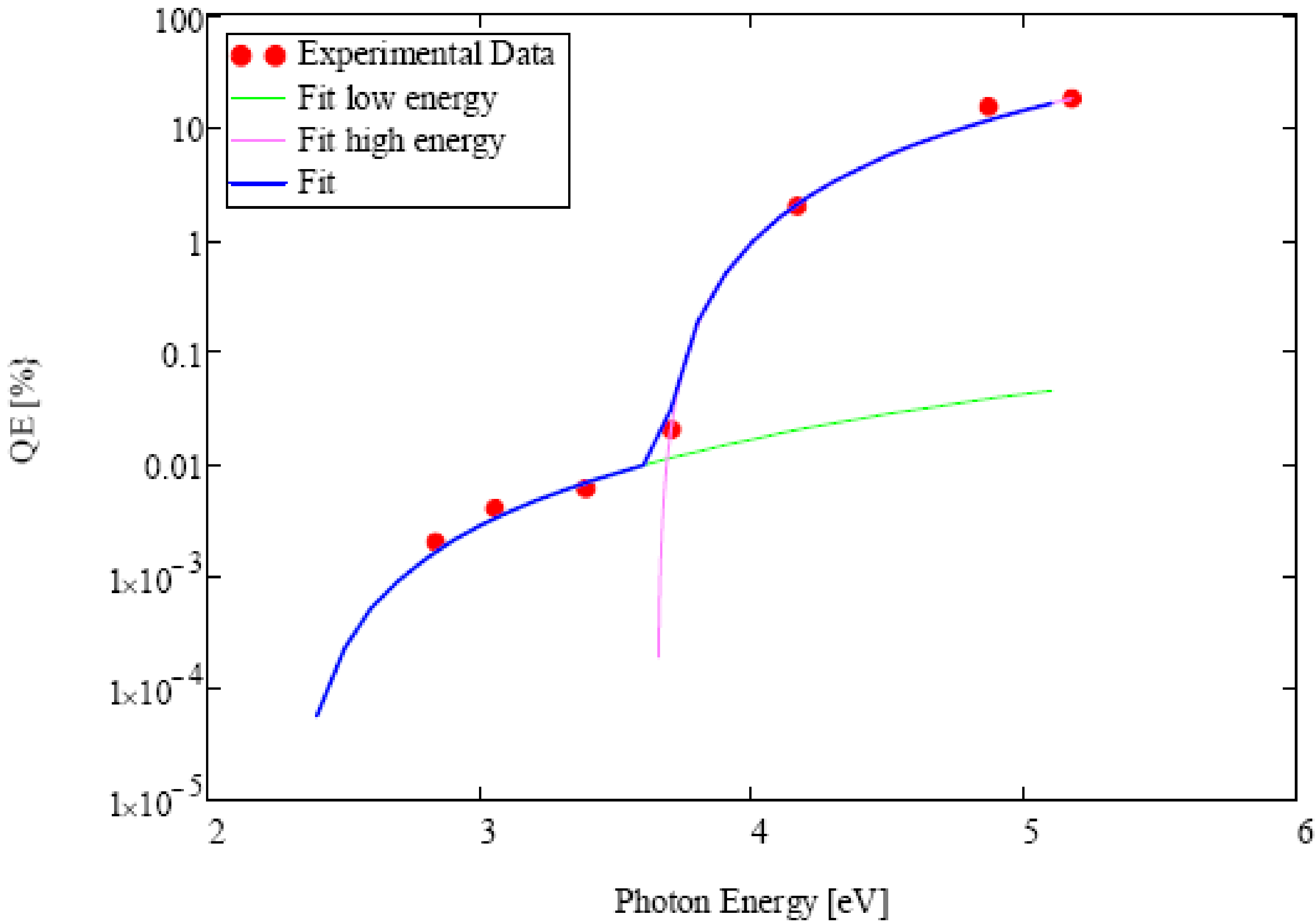
Typical lifetime in an RF injector is measured in weeks-months

- Chemical poisoning (and Cs loss?) is major cause of QE loss
- Improve vacuum should help (DC/Superconducting injectors)

Can be shipped in vacuum suitcase

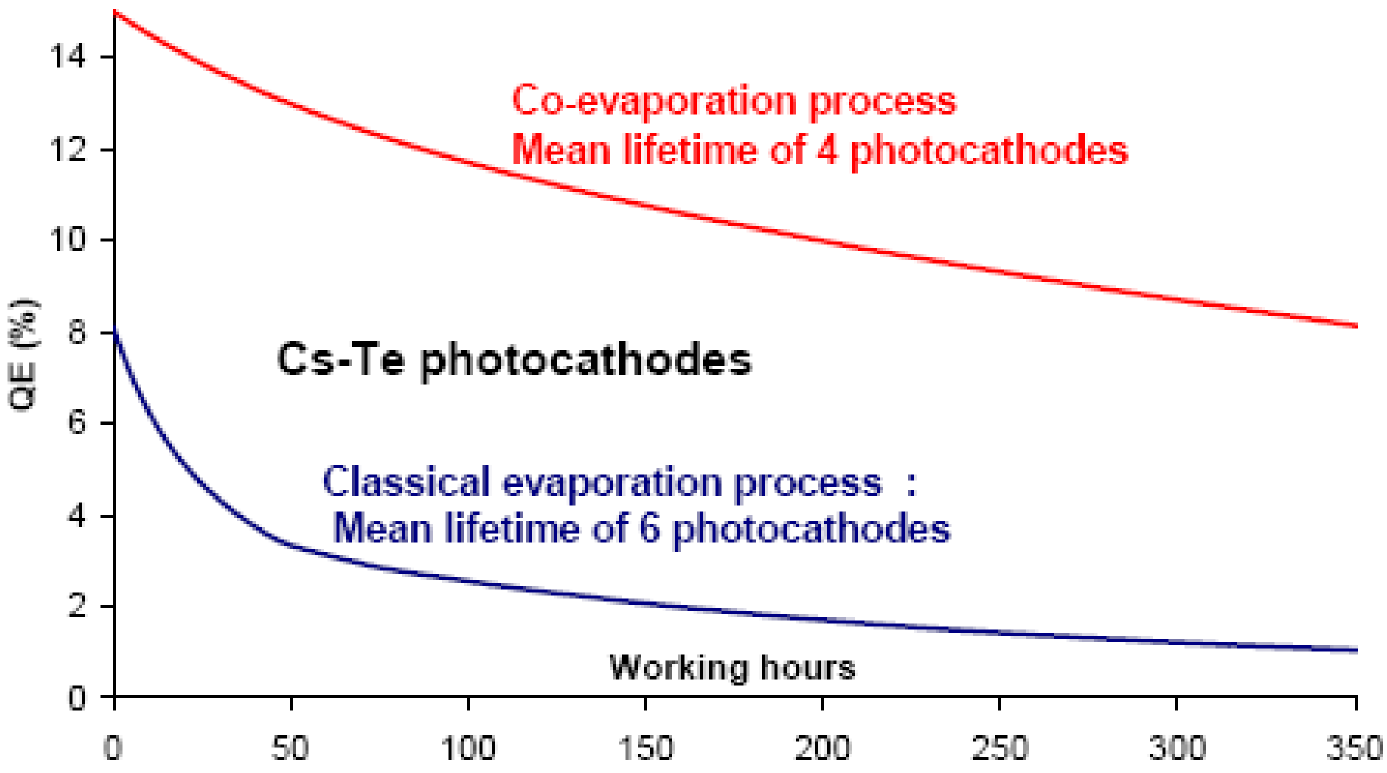
D. Sertore *et al.*, PAC07, 2760
G. Suberlucq, EPAC04, 64
F. Banfi *et al.*, FEL07, 572

Spectral Response



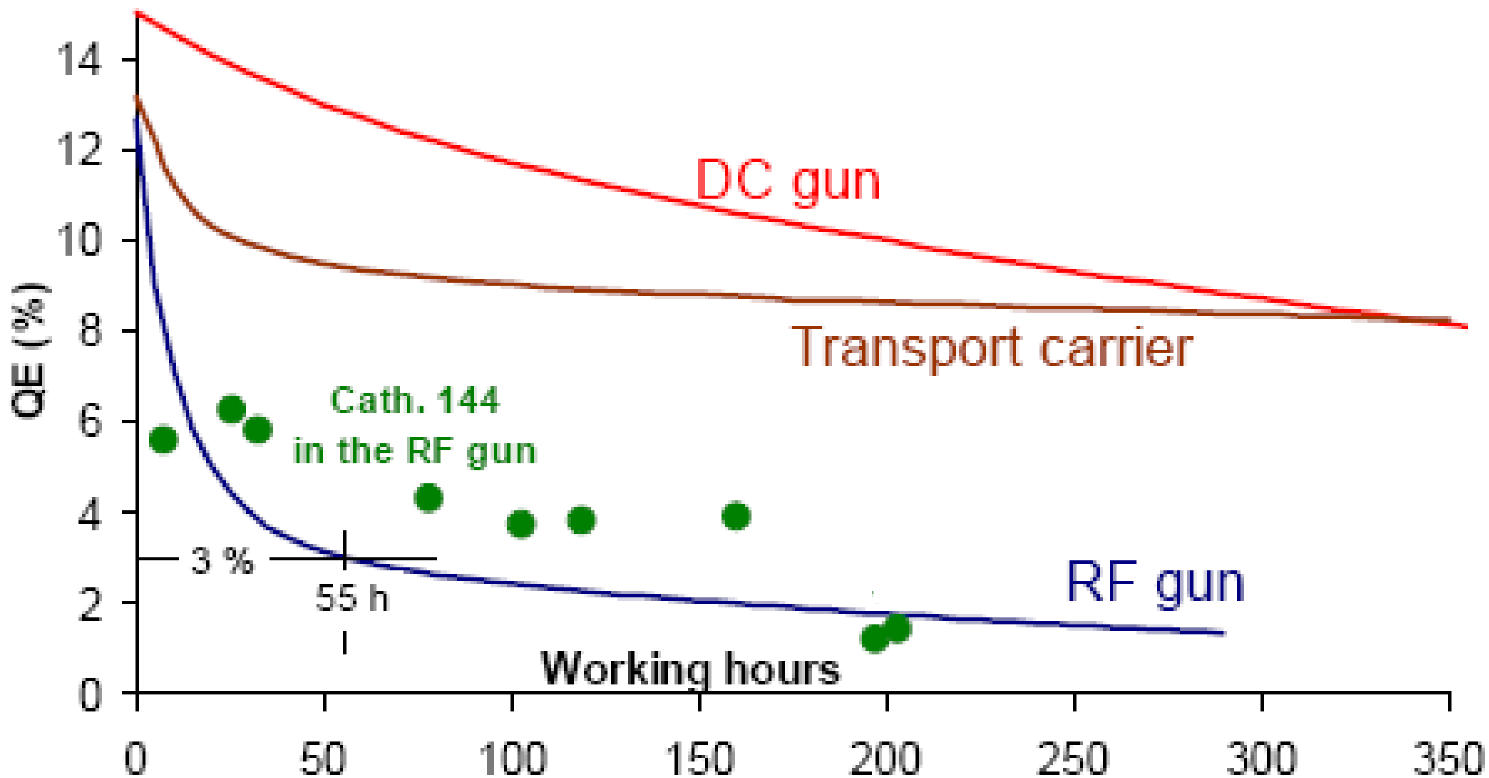
D. Sertore *et al.*, PAC07, 2760

Lifetime in DC gun



G. Suberlucq, EPAC04, 64

Lifetime in RF gun



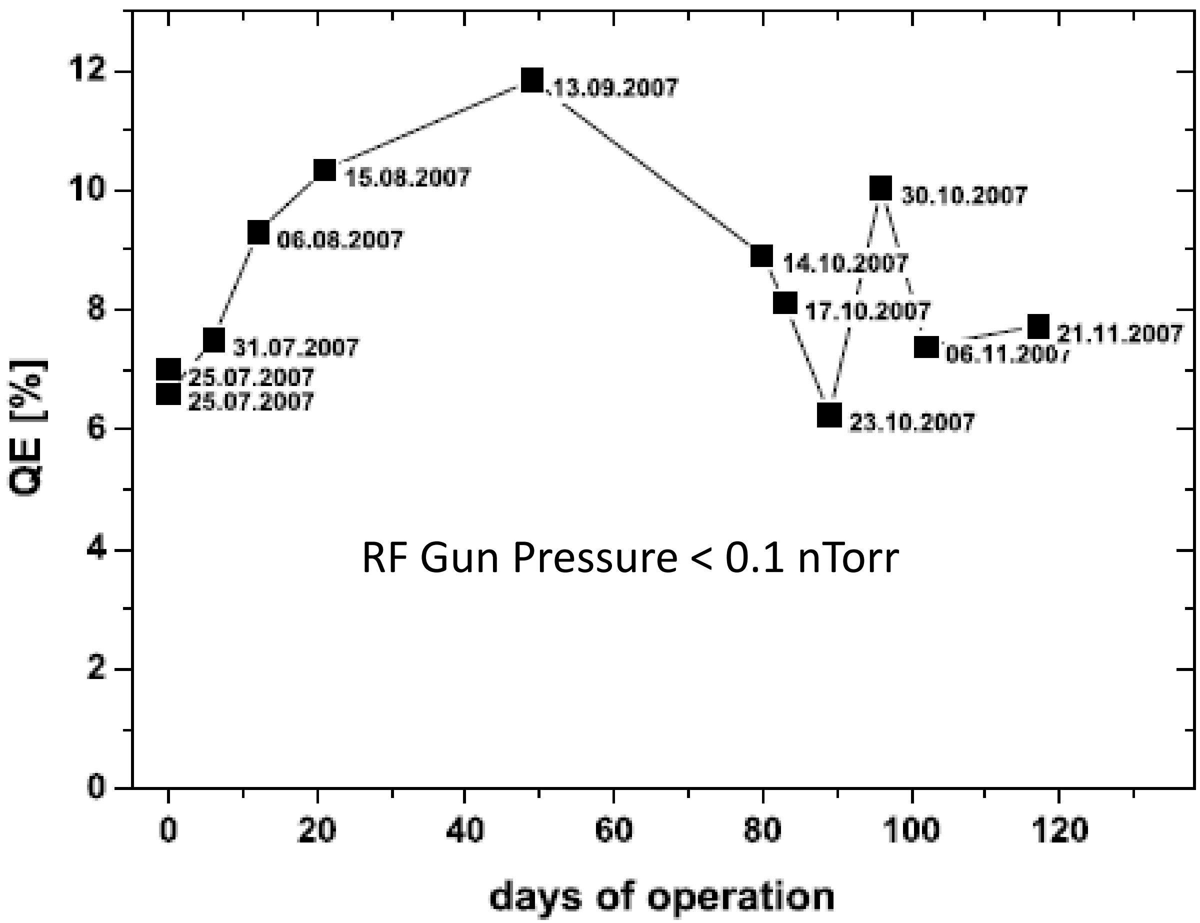
DC Gun Pressure <0.1 nTorr

RF Gun Pressure ~nTorr

G. Suberlucq, EPAC04, 64

Lifetime in RF gun

FLASH/INFN-LASA



S. Lederer *et al.*, EPAC08, 232

Cesiated GaAs

Cathode of choice for DC injectors

Can produce polarized electrons (strained superlattice)

Negative Electron Affinity (~ -0.2eV), E_g= 1.4 eV

Polarized QE: 0.5% @ 800 nm

Unpolarized QE: 6% @ 527 nm (max>15%)

Response time is ~100 ps for 800nm, ~1ps for 527 nm

Preparation:

- Start with clean GaAs wafer (Atomic H clean if necessary)
- Deposit Cs monolayer, expose to oxidizing gas (O_2 or NF_3)
- Alternate while monitoring QE

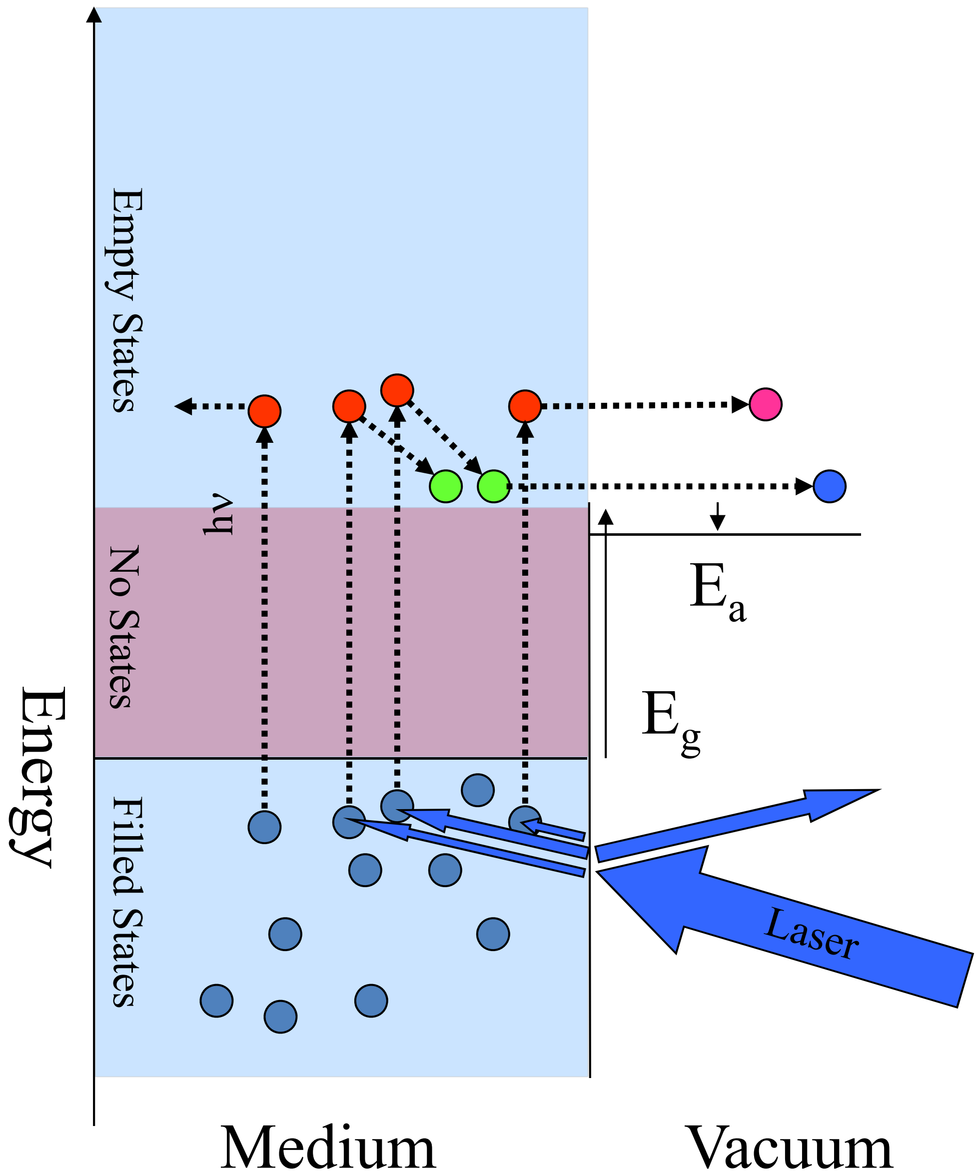
Typical lifetime in an DC injector is 100-500C (can recesiate)

- Ion back-bombardment is the major source of QE loss
- Superconducting Injectors may help

C. Hernandez-Garcia *et al.*, PAC05, 3117

T. Nakanishi , LINAC02, 811

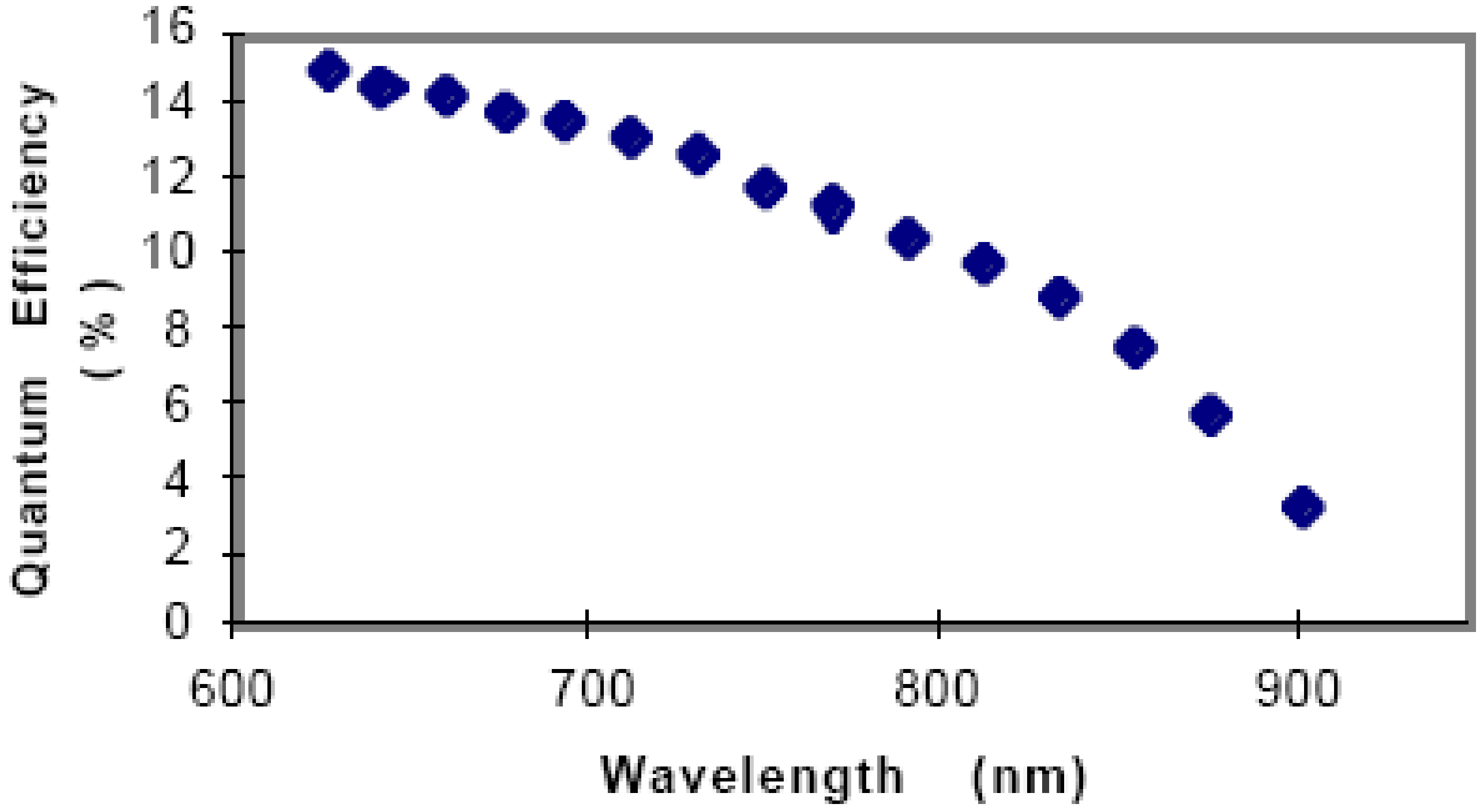
Three Step Model – NEA Semiconductors



1) Excitation of e^-
   - Reflection, Transmission, Interference
2) Transit to the Surface
   - e^--lattice scattering
     - thermalization to CBM
     - diffusion length can be 1μm
     - recombination
   - Random Walk
     - Monte Carlo
     - Response Time (10-100 ps)
3) Escape surface

Spectral Response of Cesiated Bulk GaAs

In Test Chamber



C. K. Sinclair, B. M. Poelker, and J. S. Price, PAC97, 2864

Temporal Response Measurements

- High quality measurements require an RF deflection cavity
- Three measurements with cavities:
  - Aleksandrov et al., Phys. Rev. E 51, 1449 (1995)

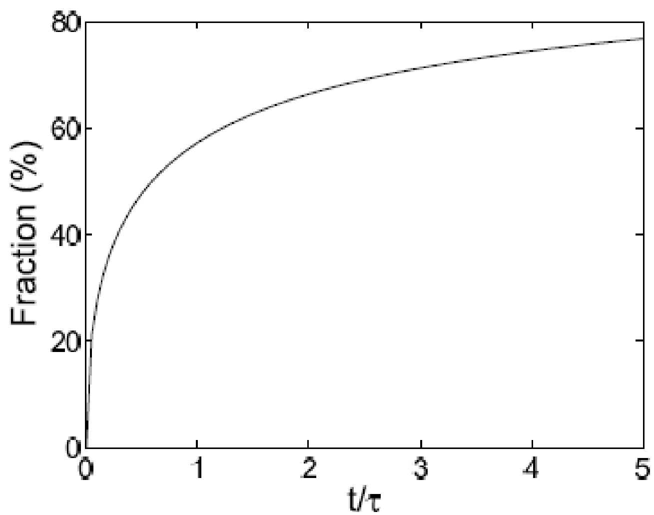
    Had insufficient temporal resolution
  - Hartmann et al., JAP 86, 2245 (1999)

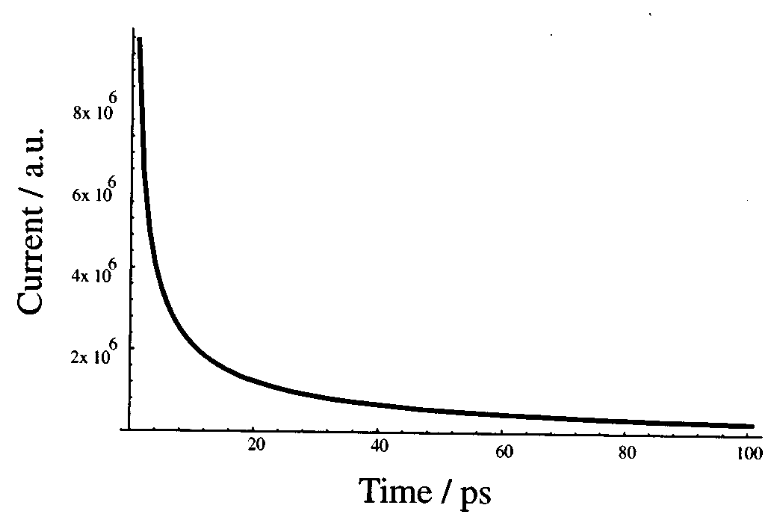
    Studied only near the bandgap
  - Bazarov et al., JAP 103, 054901 (2008), and PRST-AB 11, 040702 (2008)

    Used two techniques, and measured versus λ

Temporal Response

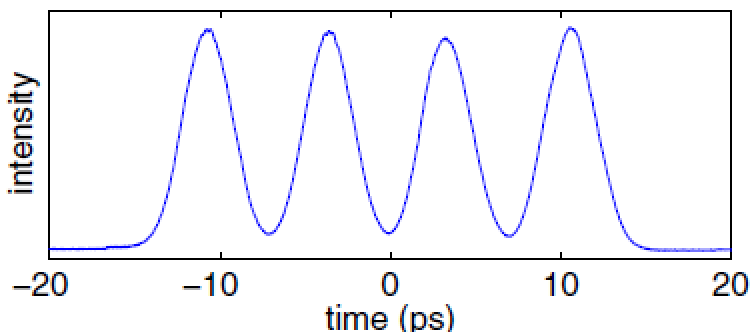
- A solution to the diffusion equation for a delta-function optical pulse gives a fast initial component and a long tail. 57% of the pulse is contained within $t/\tau = 1$, with $\tau = 1/\alpha^2 D$; α is the absorption coefficient, and D is the diffusion constant.



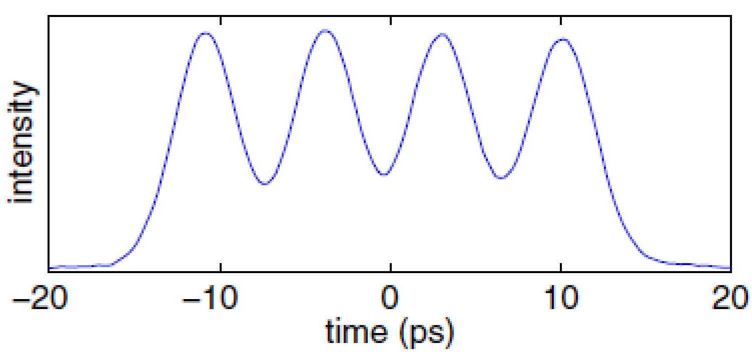


GaAs is prompt at 520 nm

Wavelength	200 kV Gun Voltage	250 kV Gun voltage
860 nm	76 +/- 26 ps	69 +/- 22 ps
785 nm	11.5 +/- 1.2 ps	9.3 +/- 1.1 ps
710 nm	5.8 +/- 0.5 ps	5.2 +/- 0.5 ps
520 nm	≤ 1 ps	
460 nm	≤ 0.14 ps	



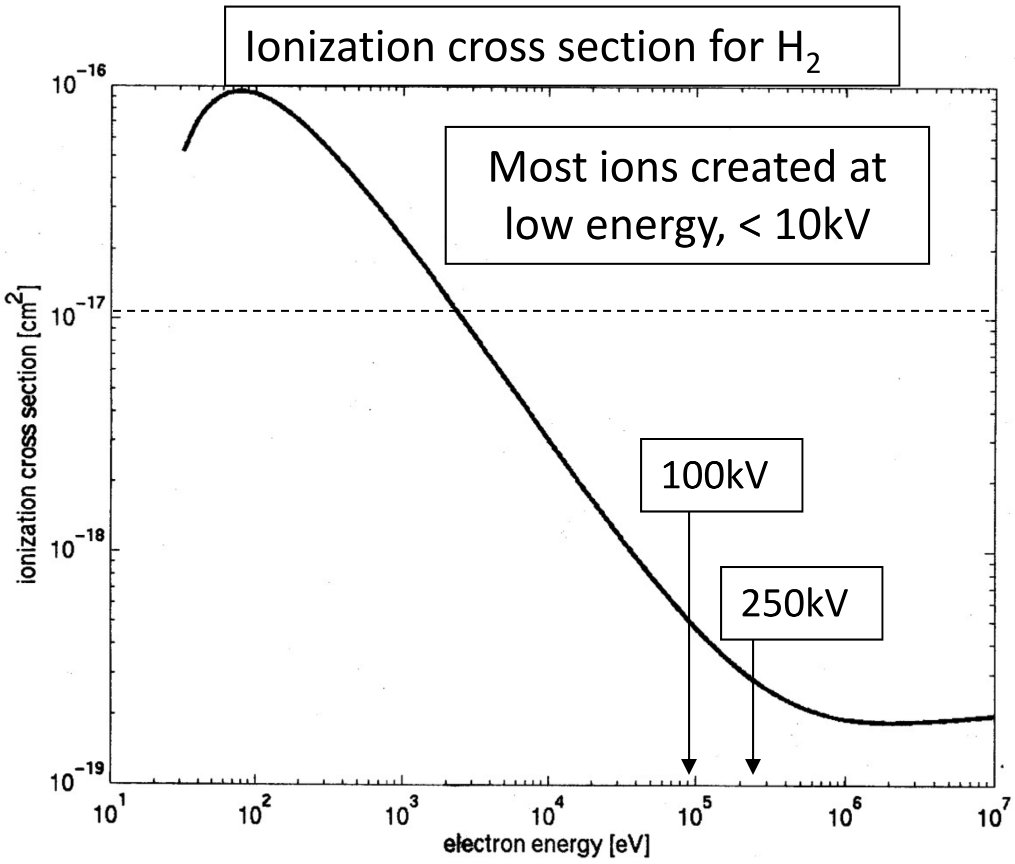
Cross correlation measurement of 520 nm laser beam

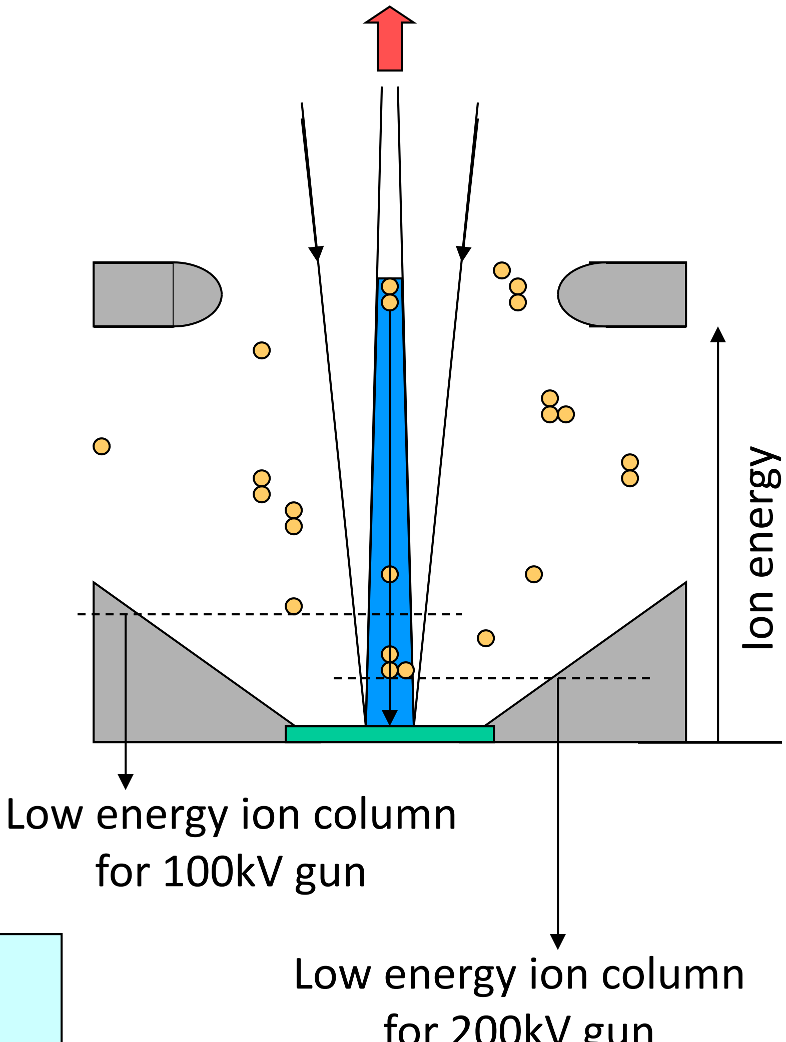


RF deflection cavity measurement of electron beam

Charlie Sinclare – p3 workshop

Improve Lifetime with Higher Bias Voltage?





Hypothesis: Double the gun voltage,
halve the # of "bad" ions, improve lifetime by 2

Slide courtesy of M. Poelker, Jlab

Photocathode Summary
Still a lot of voids….

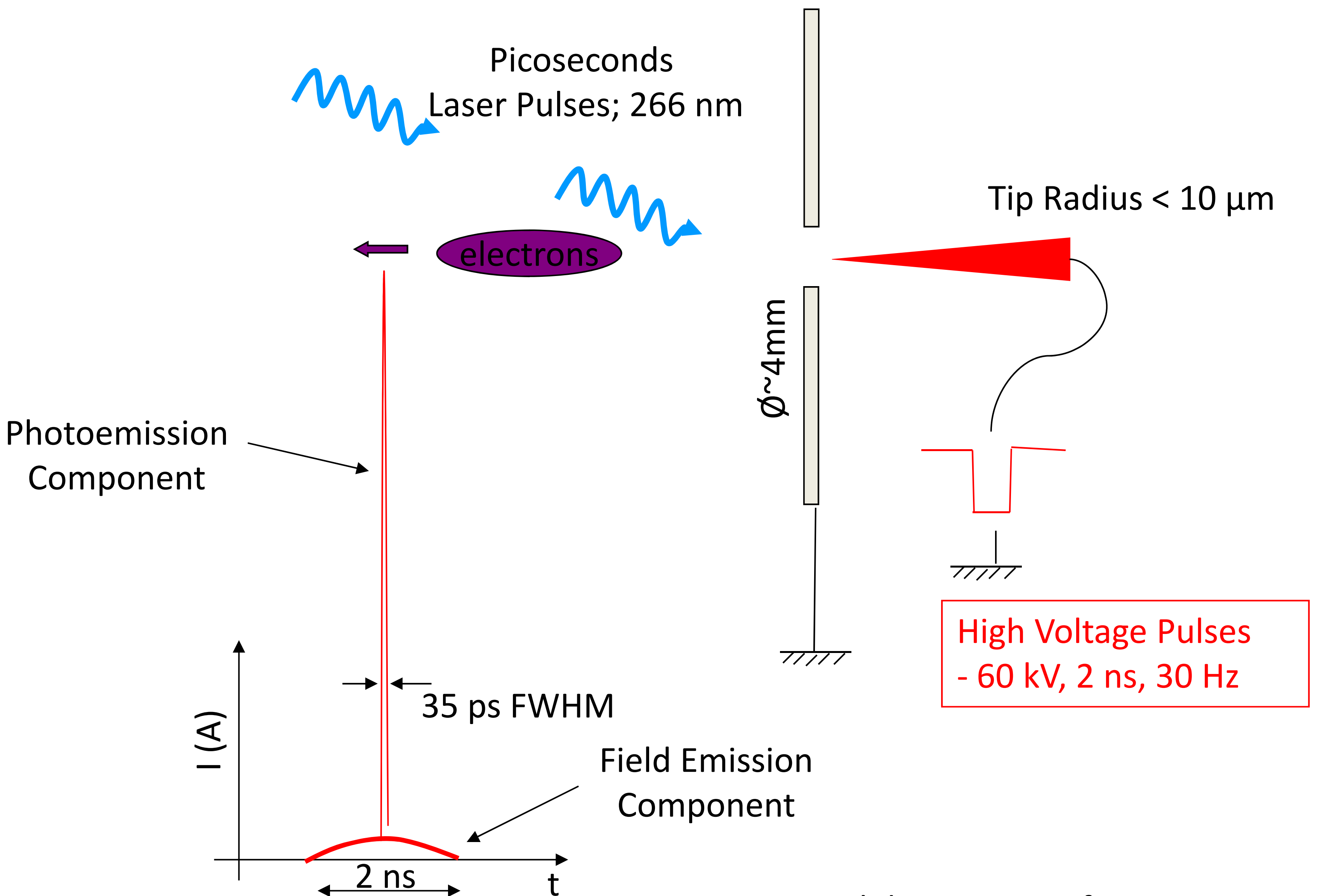
Metal Cathodes	Wavelength& Energy: λ_{opt} (nm), $\hbar\omega$(eV)	Quantum Efficiency (electrons per photon)	Vacuum for 1000 Hr Operation (Torr)	Work Function, ϕ_W(eV)	Thermal Emittance (microns/mm(rms))	
					Eqn. [3]	Expt.
Bare Metal						
Cu	250, 4.96	$1.4x10^{-4}$	10^{-9}	4.6 [34]	0.5	1.0±0.1 [39] 1.2±0.2 [40] 0.9±0.05 [3]
Mg	266, 4.66	$6.4x10^{-4}$	10^{-10}	3.6 [41]	0.8	0.4±0.1 [41]
Pb	250, 4.96	$6.9x10^{-4}$	10^{-9}	4.0 [34]	0.8	?
Nb	250, 4.96	$\sim 2\ 10^{-5}$	10^{-10}	4.38 [34]	0.6	?
Coated Metal						
CsBr:Cu	250, 4.96	$7x10^{-3}$	10^{-9}	~2.5	?	?
CsBr:Nb	250, 4.96	$7x10^{-3}$	10^{-9}	~2.5	?	?

…Waiting to be filled with numbers

Cathode Type	*Cathode*	*Typical Wavelength, λ_{opt}(nm), (eV)*	*Quantum Efficiency (electrons per photon)*	*Vacuum for 1000 Hrs (Torr)*	*Gap Energy + Electron Affinity, $E_A + E_G$ (eV)*	*Thermal Emittance (microns/mm(rms))*	
						Eqn. [7]	*Expt.*
PEA: Mono-alkali	Cs_2Te	211, 5.88 264, 4.70 262, 4.73	~0.1 - -	10^{-9} - -	3.5 [42] " "	1.2 0.9 0.9	0.5±0.1 [35] 0.7±0.1 [35] 1.2 ±0.1 [43]
	Cs_3Sb	432, 2.87	0.15	?	1.6 + 0.45 [42]	0.7	?
	K_3Sb	400, 3.10	0.07	?	1.1 + 1.6 [42]	0.5	?
	Na_3Sb	330, 3.76	0.02	?	1.1 + 2.44 [42]	0.4	?
	Li_3Sb	295, 4.20	0.0001	?	?	?	?
PEA: Multi-alkali	Na_2KSb	330, 3.76	0.1	10^{-10}	1+1 [42]	1.1	?
	$(Cs)Na_3KSb$	390, 3.18	0.2	10^{-10}	1+0.55 [42]	1.5	?
	K_2CsSb	543, 2.28	0.1	10^{-10}	1+1.1 [42]	0.4	?
	$K_2CsSb(O)$	543, 2.28	0.1	10^{-10}	1+<1.1 [42]	~0.4	?
NEA	GaAs(Cs,F)	532, 2.33 860, 1.44	~0.1 -	? ?	1.4±0.1 [42] "	0.8 0.2	0.44±0.01 [44] 0.22±0.01 [44]
	GaN(Cs)	260, 4.77	-	?	1.96 + ? [44]	1.35	1.35±0.1 [45]
	GaAs(1-x)Px x~0.45 (Cs,F)	532, 2.33	-	?	1.96+? [44]	0.49	0.44±0.1 [44]
S-1	Ag-O-Cs	900, 1.38	0.01	?	0.7 [42]	0.7	?

Dowell et al., *NIM-A*, **622**, (2010) 685-697

Laser Photo-Field Emission from Needle



Slide courtesy of R. Ganter, PSI

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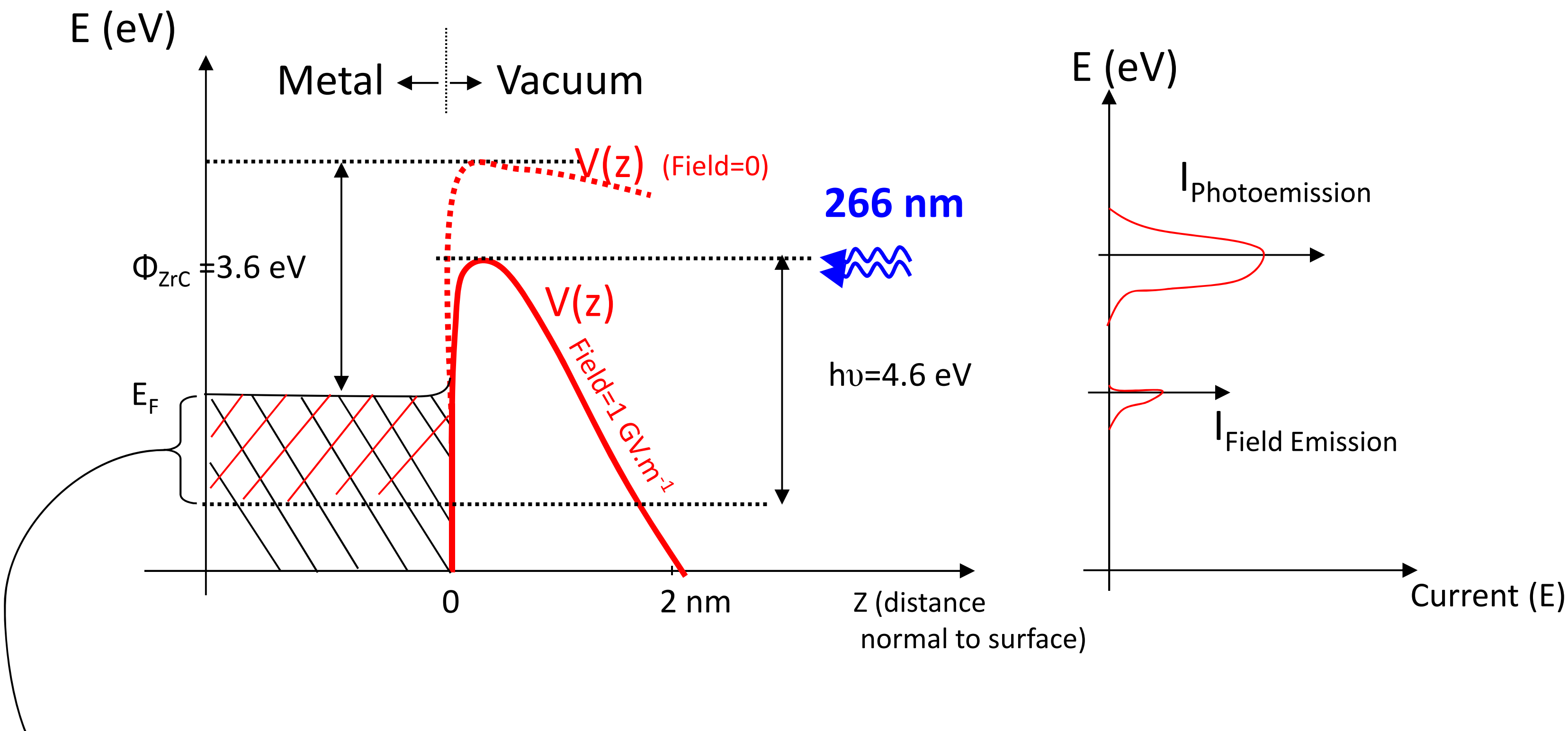
Photo-Field Emission Principle

Schottky Effect → Larger Electron Reservoir for Photoemission → Higher Quantum Efficiency

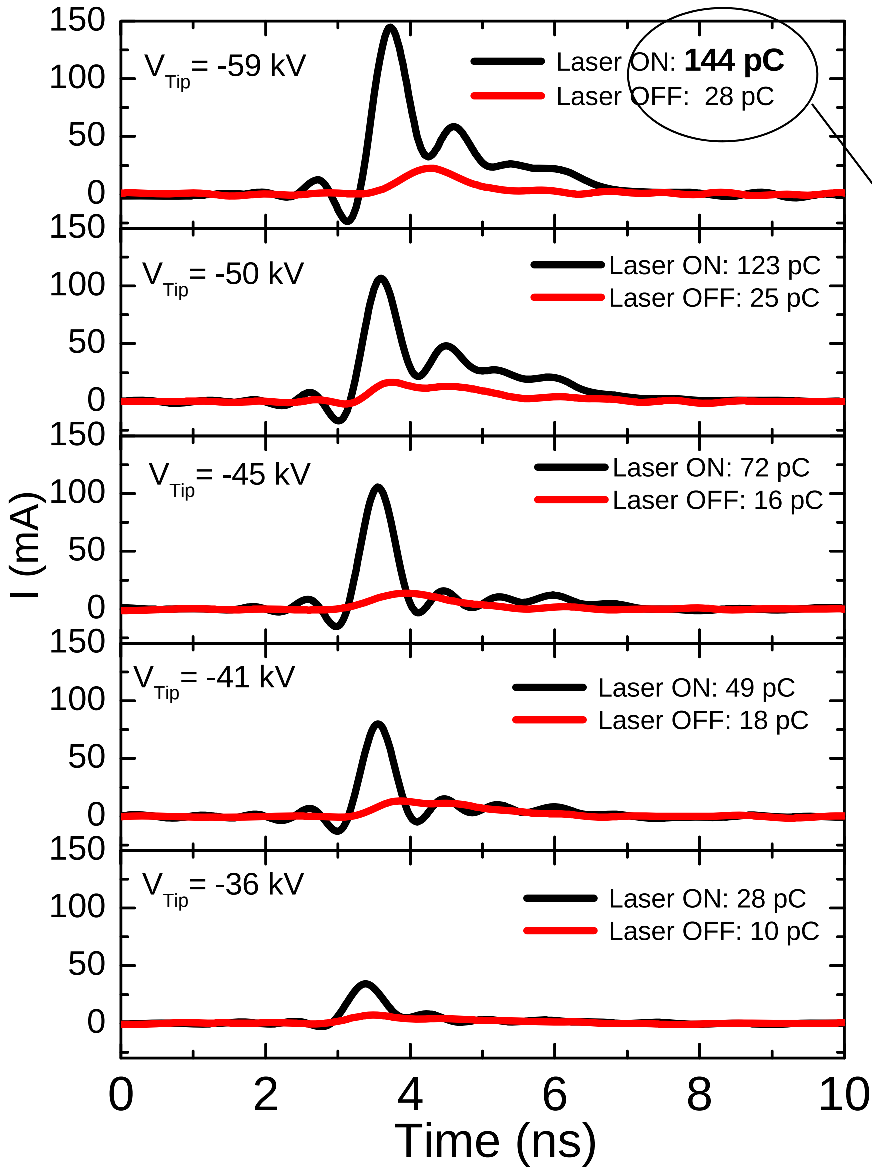


Energy range from where electrons can be directly photo-emitted !

Dubridge's model (L.A. Dubridge, Phys. Rev. **43**, 1933)

Slide courtesy of R. Ganter, PSI

Quantum Efficiency depends on E_{local}



Higher Tip Voltage (E_{Local})

⇩

Larger Quantum Efficiency

144 pC at 6 µJ (266 nm)
Q.E. ~ 10^{-4}

BUT
$QE_{apex} >> QE_{shank}$

Laser: 6 µJ / $\sigma_{t,laser}$=16 ps / $\sigma_{r,laser}$=85 µm / 30 Hz / 266 nm

Slide courtesy of R. Ganter, PSI

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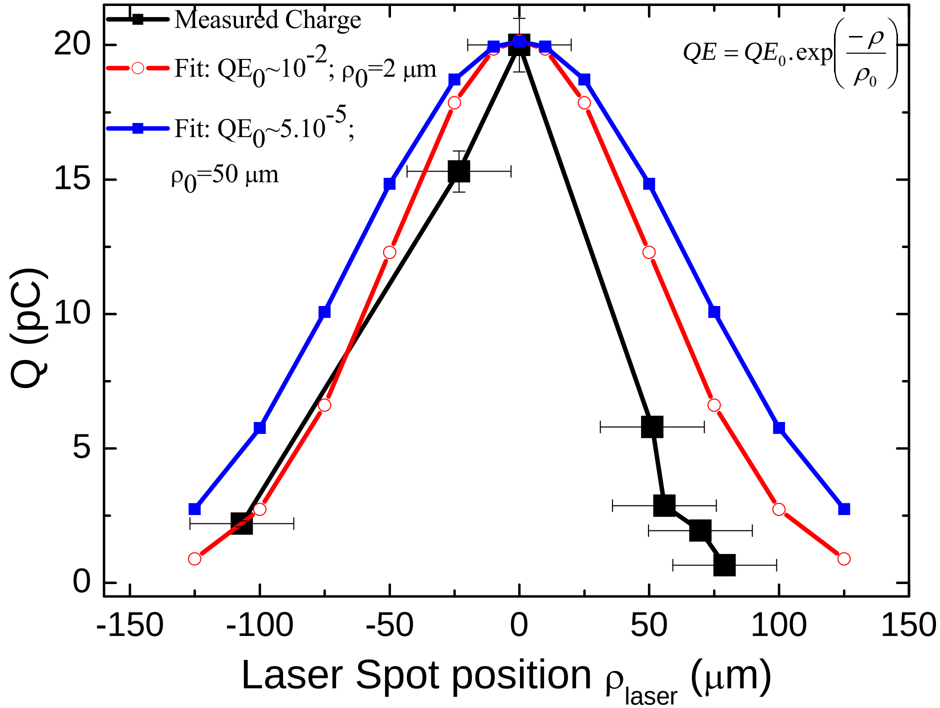
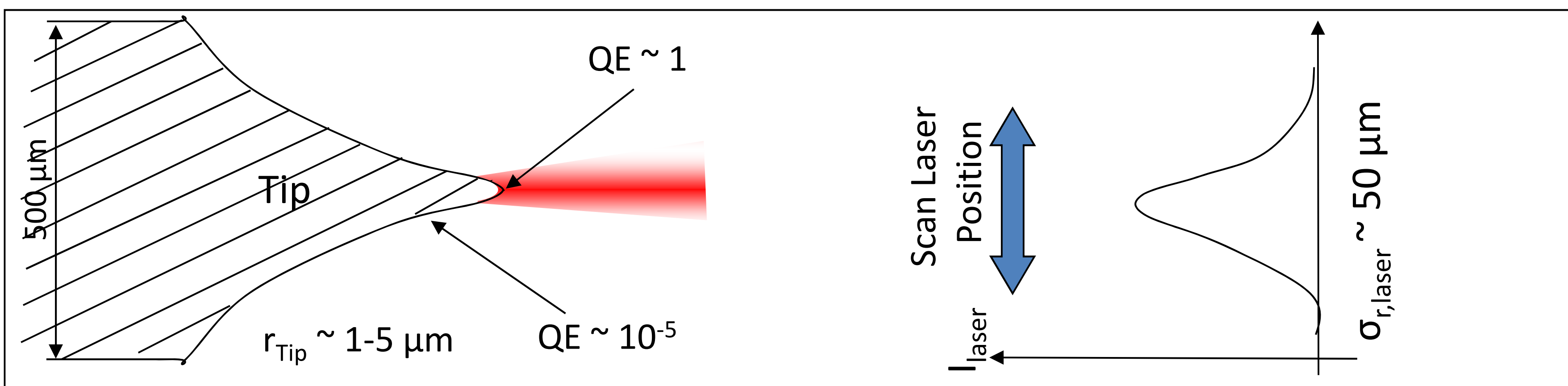
Photo-Field Emission Emitting Area



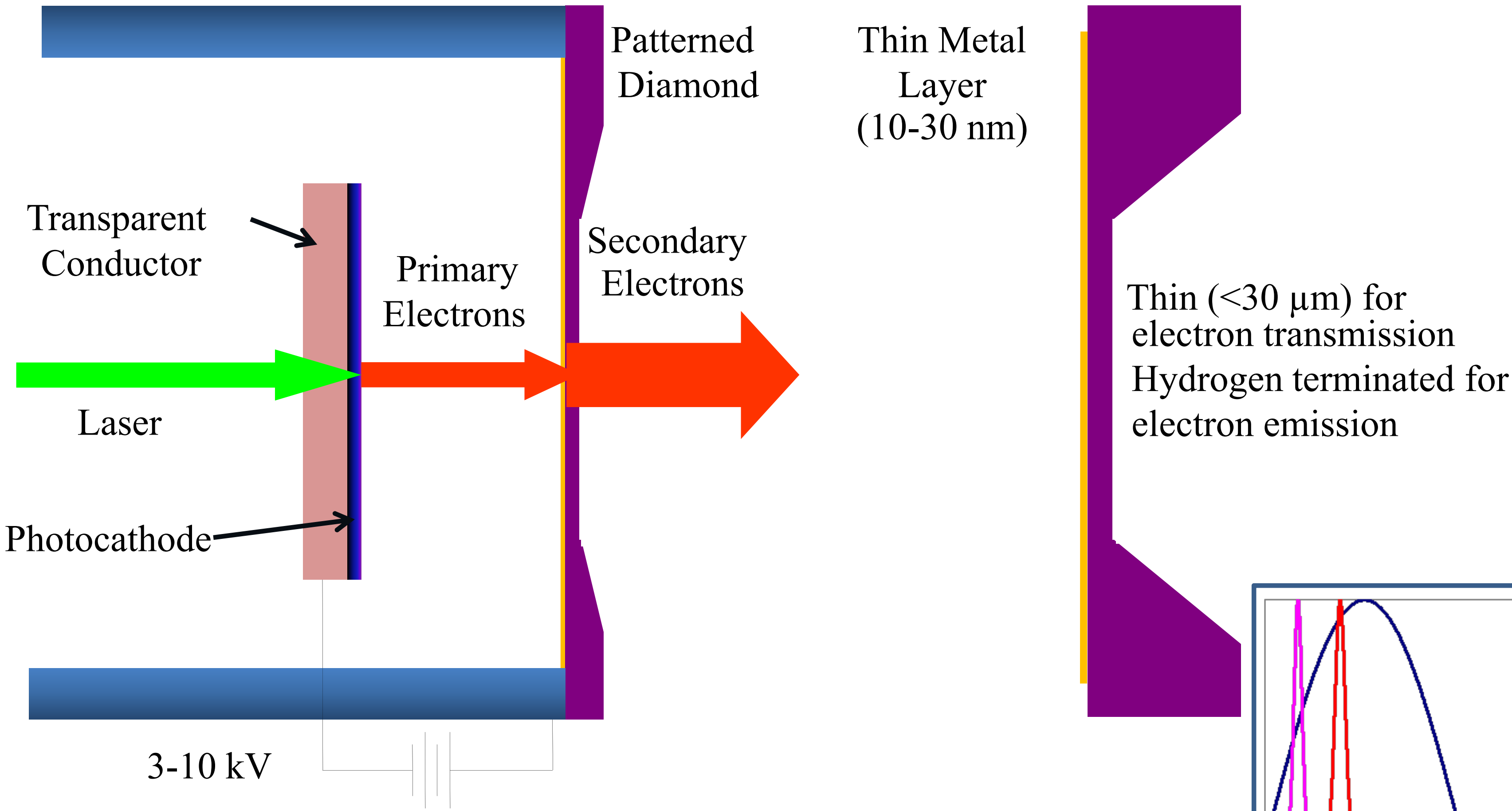
Non uniform QE distribution along Tip Shanks !

Exp. Cond.:
266 nm; 3 μJ; $\sigma_{r,laser}$ ~ 50 μm
$\sigma_{z,laser}$ ~ 16 ps; V_{Tip}=-32 kV

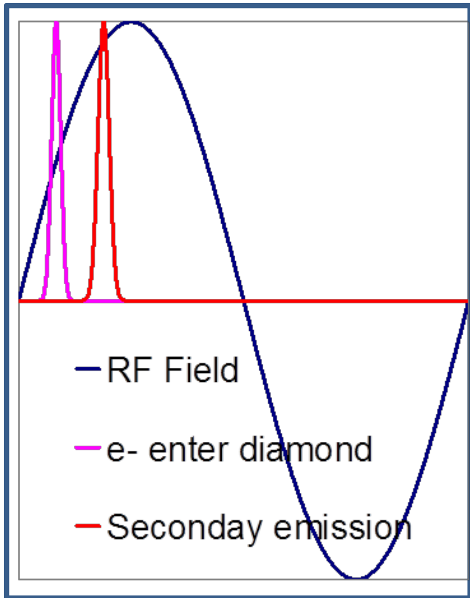


Slide courtesy of R. Ganter, PSI

Diamond Amplifier Concept



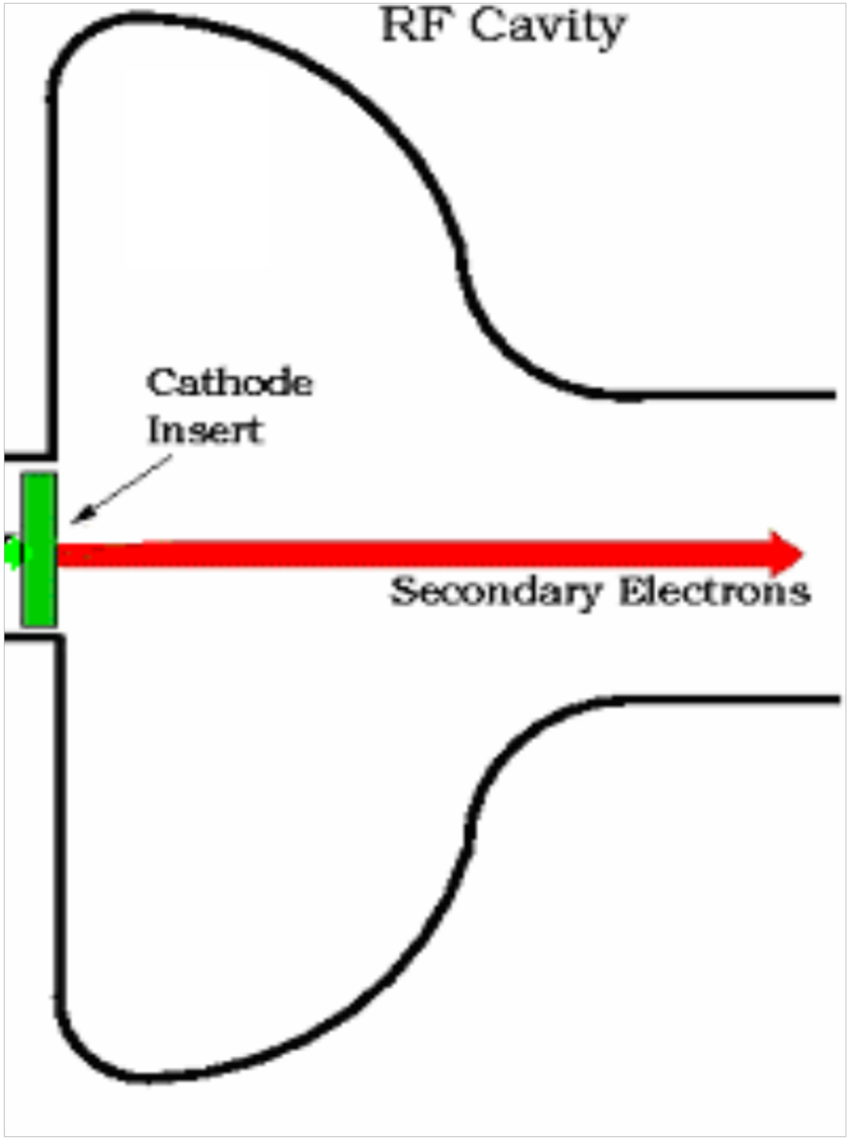
Electron saturation velocity in Diamond is ~.2 µm/ps
Takes 150 ps to go 30 µm = 40 degrees of RF
Electrons must exit diamond in time to escape injector
Irregularity of surface will cause bunch spreading



Diamond Amplifier Concept

Advantages

- Secondary current can be >300x primary current
  - Lower laser power
  - Higher average currents
- Diamond acts as vacuum barrier
  - Protects cathode from cavity vacuum and ion bombardment
  - Protects cavity from cathode (prevents Cs migration)
  - Should improve cathode lifetime
- e^- thermalize to near conduction-band minimum
  - Minimize thermal emittance



Online Resources

Good discussion of work function:
http://www.philiphofmann.net/surflec3/surflec015.html

Materials properties database:

http://mits.nims.go.jp/matnavi/

Accelerator publications:

www.JACoW.org & Physical Review Special Topics Accelerators and Beams

Semiconductor Physics (Don't laugh… well, ok laugh a little - but it is a great site)

http://britneyspears.ac/lasers.htm

Hamamatsu PMT Handbook:

http://sales.hamamatsu.com/assets/pdf/catsandguides/PMT_handbook_v3aE.pdf