U.S. DEPARTMENT OF ENERGY | Office of Science

MICHIGAN STATE UNIVERSITY

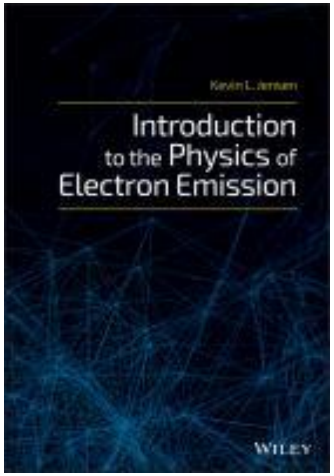
FRIB

PHY862
Introduction to Electron Sources

Guillaume Machicoane
Facility for Rare Isotope Beams

Suggested Literature - Books

- Resources for electron source literature
  - Introduction to the Physics of Electron Emission, Kevin L. Jensen John Wiley & Sons, Inc., 2017 (MSU Library, Online Resource
  - A Tutorial on Electron Sources , Kevin L. Jensen.
    - » IEEE TRANSACTIONS ON PLASMA SCIENCE, VOL. 46, NO. 6, JUNE 2018
  - USPAS 2010, High Brightness Electron Injectors for Light Sources, D. Dowell (Slides + Lectures)
  - USPAS 2016, 2012 Electron Injectors for 4th Generation Light Sources (Fernando Sannibale, Daniele Filippetto)
  - Electron sources for accelerators, Physics Today 61, 2, 44 (2008)
  - CERN Accelerator School (Scrivens, Thuillier)



- Advanced Topics
  - Future Electron Sources, Report of the Basic Energy Sciences Workshop on the Future of Electron Sources, September 8-9, 2016, SLAC

Basic properties of electrons

Accelerating Voltage (MV)	Wavelength (Å)	γ (m/m0)	Velocity (% c)
0.001	0.387	1.0019	6.15
0.01	0.122	1.0195	19.5
0.1	0.0370	1.196	55
0.5	0.0142	1.979	86.3
1	0.0087	2.957	97
10	0.0012	20.568	99.8
1000	0.000758	1958	99.999

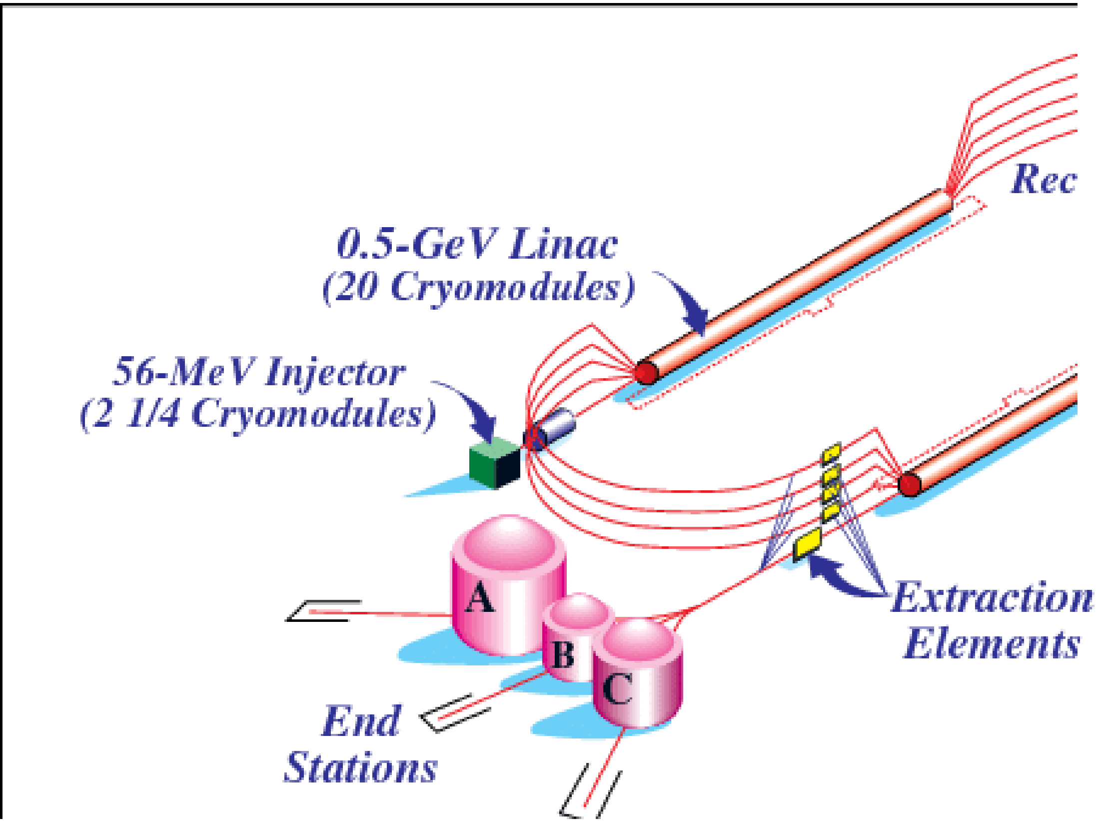
$$E = \frac{m_0c^2}{\sqrt{1-(\frac{v^2}{c^2})}} - m_0c^2 \qquad \lambda = \frac{h}{p}$$

Use of Electron Beams (I)

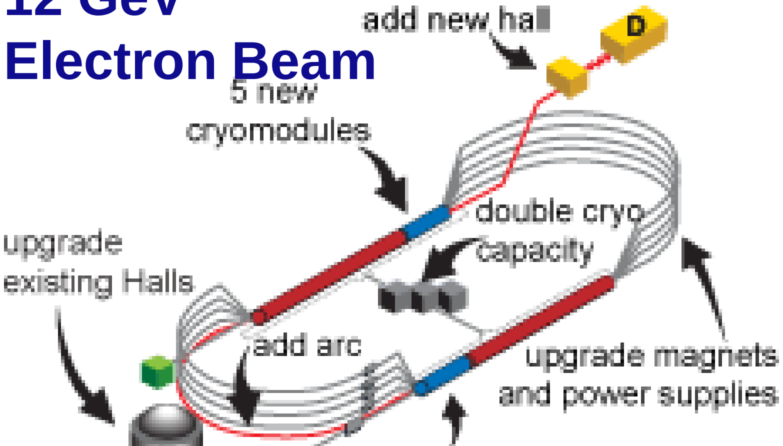
- Use of electron beam are very widespread either for industrial applications and accelerators:
- Industrial Applications
  - Electron microscopy
  - RF Generation (Microwave ovens, Klystrons, TWT)
  - Industrial Heating (Furnaces, Welding, Surface treatments, Machining)
  - Semi Conductors (high Resolution Lithography, doping, Plasma etching)
  - Material Sciences (Physical-vapor-deposition)
  - Medical treatment and Imaging
- Accelerator Use for Nuclear and High Energy Physics: The electron energy determines what length scale is being probed
  - 1 MeV to 1 GeV, electrons can probe quarks and gluons
  - Higher-energy machines, such as 12-GeV electron beam at JLAB - CEBAF can investigate constituent quarks, structure of nuclei, tests parity violations
  - Electron-positron collider (gluon structure, nature of proton spin)

Continuous Electron Beam Accelerator Facility (CEBAF, JLAB)

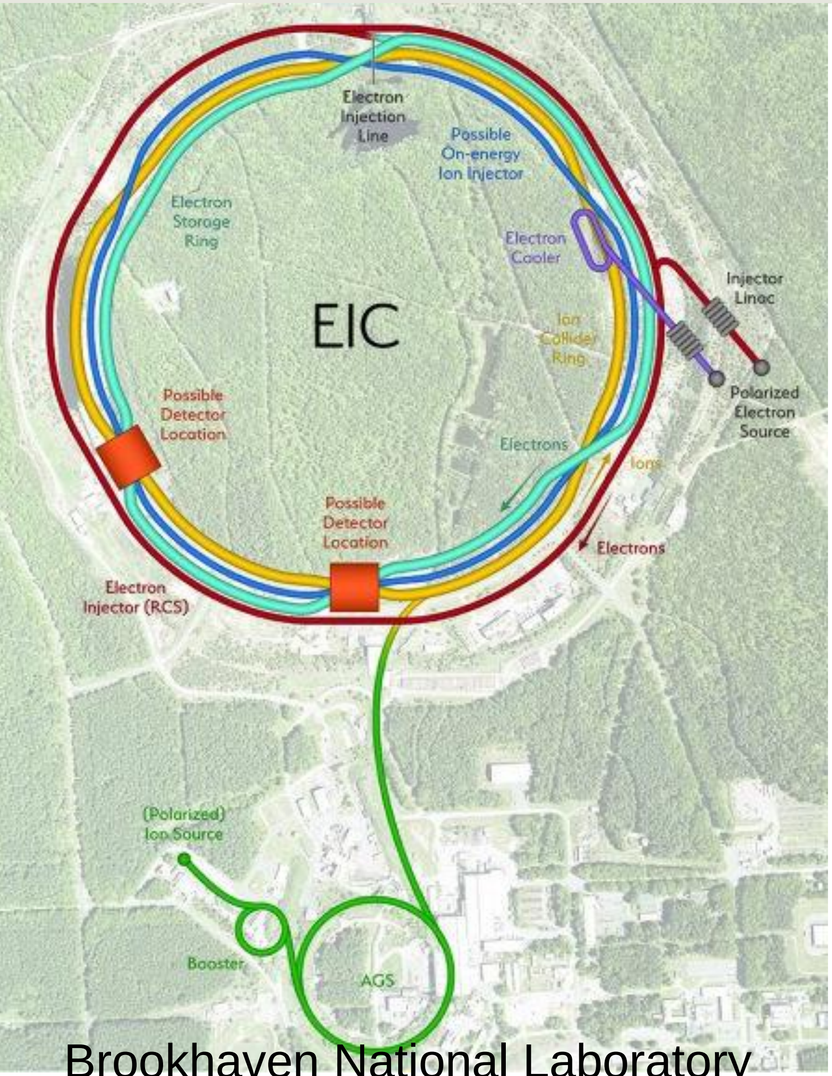
6 GeV Electron Beam



12 GeV Electron Beam



Electron – Ion Collider (RHIC)



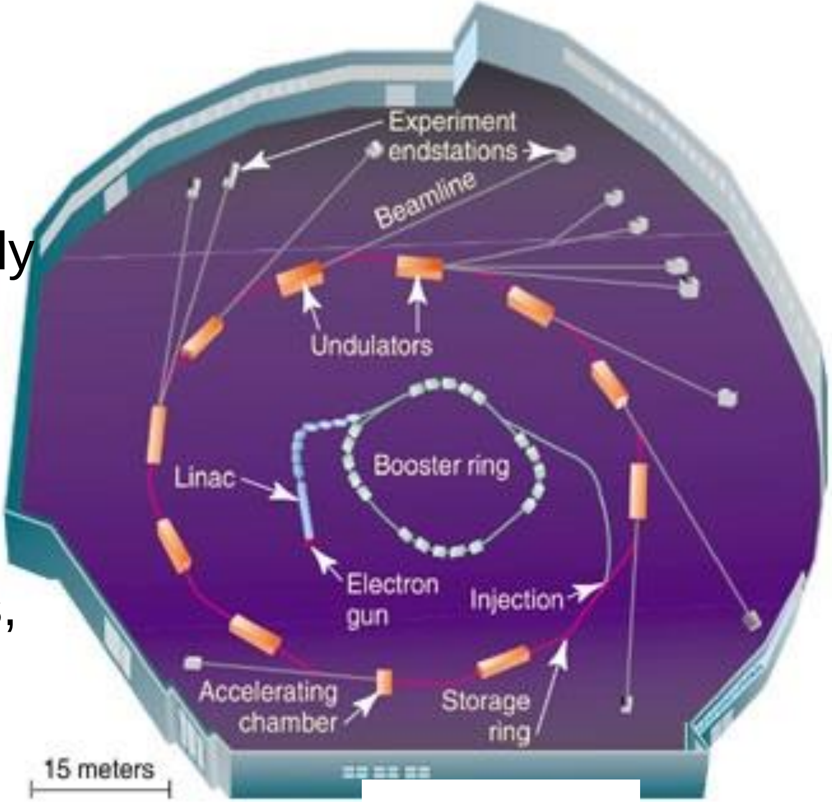
Brookhaven National Laboratory

- The Electron-Ion Collider (EIC) is planned to be built at Brookhaven National Laboratory (New York)
  - The project utilizes the existing infrastructure of the Relativistic Heavy Ion Collider (RHIC) accelerator complex
- Project Requirements
  - High Luminosity: L= 10^{34} cm^{-2} sec^{-1}
  - Highly Polarized Beams: 70%
  - Large Center of Mass Energy up 140GeV:
    - » **Electron Energy of 10 GeV**
    - » Proton Energy of 275 GeV
- Project preparing for Approval of formal Design Phase

Use of Electron Beams (II)

- Used in particle accelerators and colliders to cool proton or heavy-ion beams.
  - Help reduce beam transverse dispersion and reach higher luminosity as the beams propagate

- Used extensively in Synchrotron Radiation Facilities (APS, ALS, LCLS)
  - An electron beam is used to produce highly specialized forms of electromagnetic radiation to study the structure and dynamics of substances ranging from biological materials to nanocomposites
  - In 1st, 2^{nd} and 3^{rd} generation light sources, electron sources are part of the injector chain that typically includes a small linac and a "booster" ring.

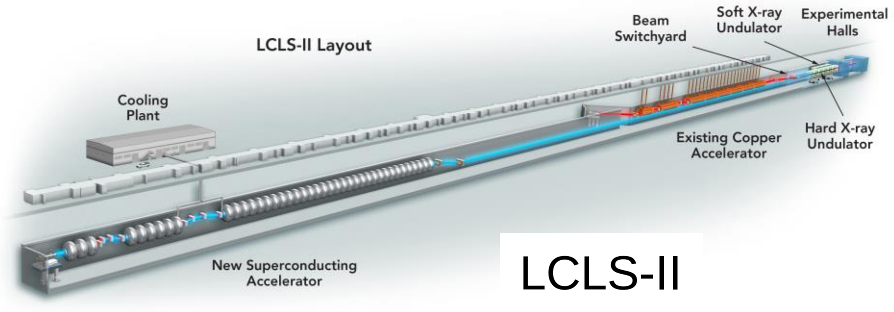


ALS, LBNL

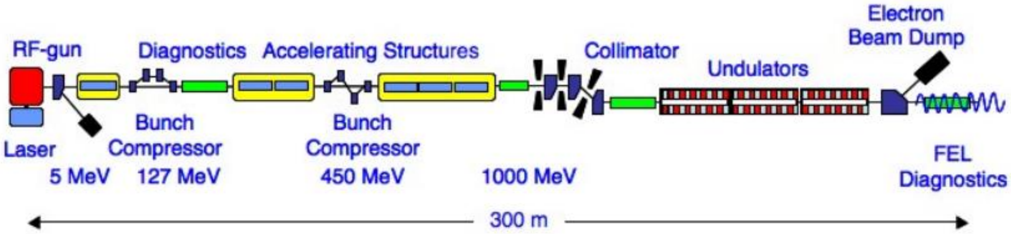
4th Generation Light Sources

- In linac based 4th generation light sources, such as free electron lasers (FELs) and energy recovery linacs (ERLs) the final beam quality is set by the linac and ultimately by its injector and electron source


LCLS-I



LCLS-II



FLASH, Desy XFEL

Examples of 4th generation based light sources using FELs

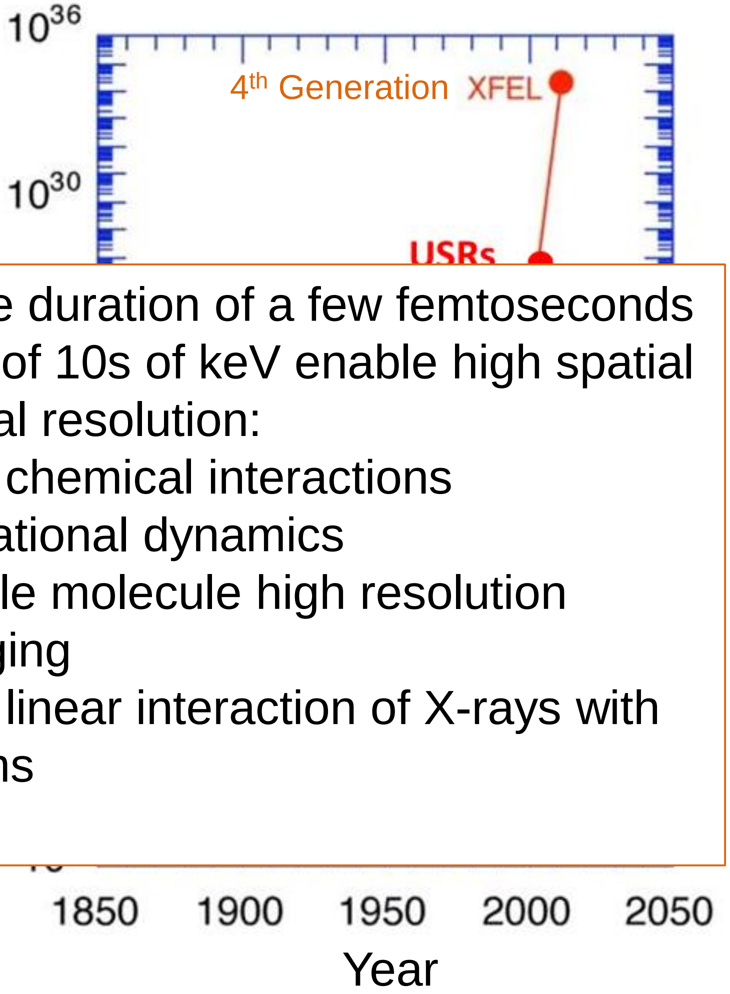
Outstanding Characteristic of Synchrotron Radiation

Spectral Brightness

$$B = \frac{\dot{N}_{ph}}{4\pi^2 \sigma_x \sigma_y \sigma_{x'} \sigma_{y'} \frac{d\omega}{\omega}}$$

(photons/s/mm^2/mr^2/0.1%BW)

- User Requirements
  - High Brilliance and Flux
  - Wavelength tunability
  - Beam Size tunability
  - Polarization
  - Time Structure



XFEL: Pulse duration of a few femtoseconds and energy of 10s of keV enable high spatial and temporal resolution:

- Live chemical interactions
- Vibrational dynamics
- Single molecule high resolution imaging
- Non linear interaction of X-rays with atoms

Components of an Electron Source

- The cathode, (Greek (*kathodos*), 'descent' or 'way down)
  - A material from which the electrons are extracted. In thermionic emission, a heated surface serves as the cathode; in a photoemission source, the cathode is a light sensitive material called a photocathode.
- A source of energy to excite electrons above the material’s work function,
  - The difference between its Fermi energy and the vacuum energy. That source can be thermal, in the case of thermionic emission, or electromagnetic (usually laser light), as in photoemission.
- An electric field to accelerate the electrons and form a collimated beam.
  - Field can be DC or RF depending on the application
- A vacuum environment, which prevents the scattering of electrons by gas molecules and protects the cathode from contamination.

Forms of electron emission

- Ectrons are bound to materials and we must add energy to get them to escape
- The Three forms of electron emission discussed in PHYS862:
  - Thermionic emission,
  - Field emission
  - Photo-electric emission
  - Secondary Emission

Most Common method industrial or Accelerator

4th generation light source, Polarized beam

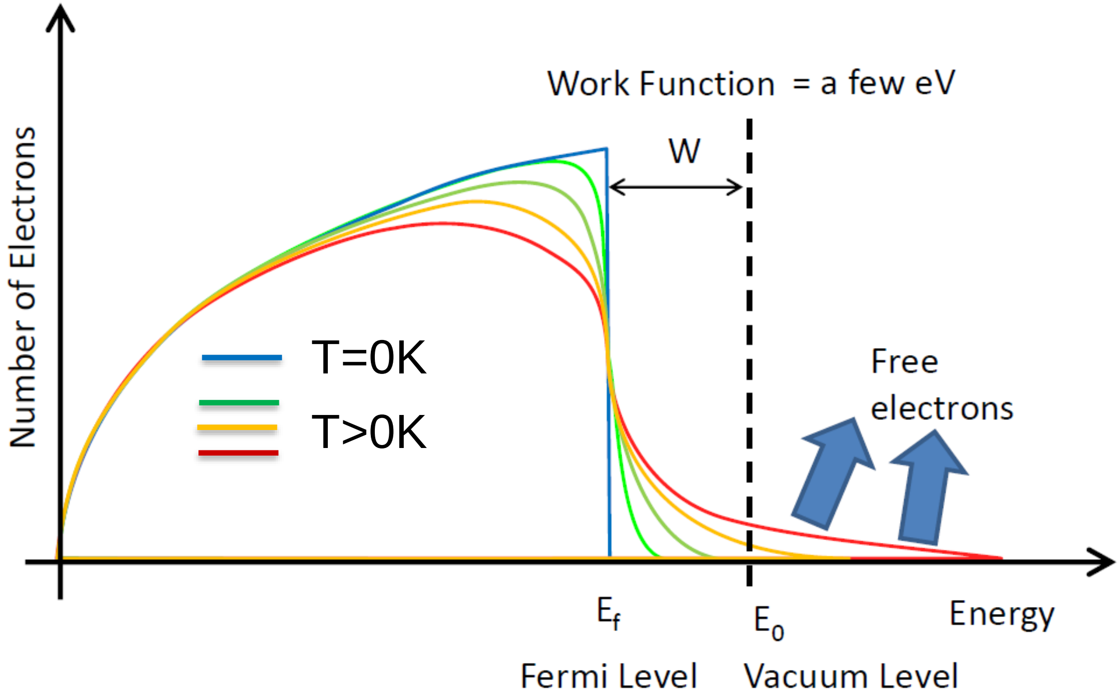
Electrons Obey Fermi-Dirac Statistics

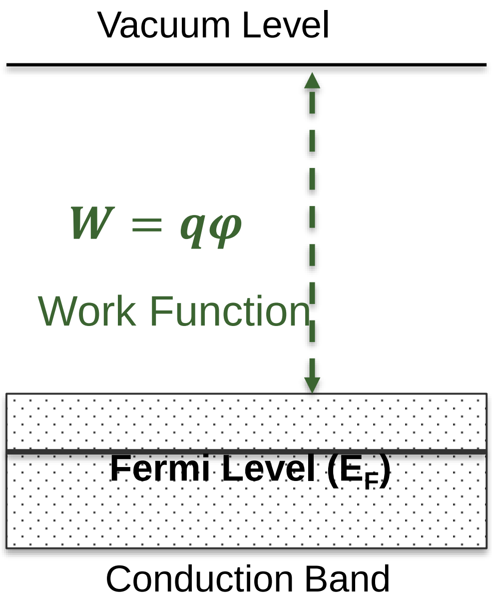
- Electron are elementary particle (leptons) and are fermions i.e
  - Half integer spin (1/2)
  - Follow Dirac-Fermi Statistics
- Fermions obey the Pauli-exclusion principle: Two or more identical fermions cannot occupy the same quantum state within a quantum system simultaneously
- For a system of identical fermions with thermodynamic equilibrium, the average number of fermions in a single-particle state *i* is given by the **Fermi–Dirac (FD)** distribution defined as**:**

$$\boxed{f_{FD} = \frac{1}{1 + e^{(E-E_F)/k_B T}}}$$

Work Function

- The work function corresponds to the minimum amount of energy needed to remove an electron from the metal from the highest occupied energy level.
- At T=0K all electrons are below fermi energy. For T>0K some electrons will have enough thermal energy to overcome the work function

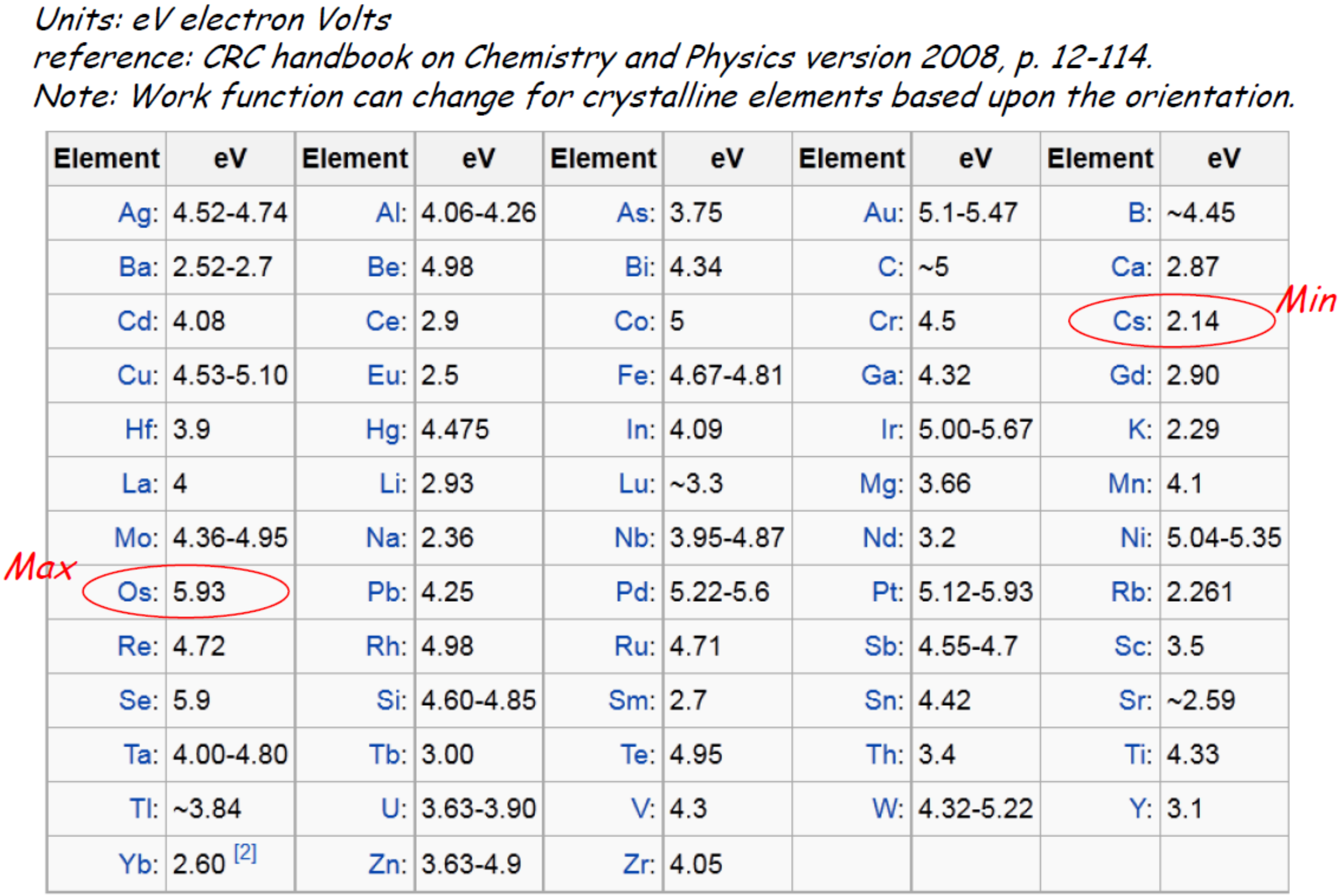




$$W = q\varphi$$

Work Function

Work Function of electrons in Metals (eV)



Units: eV electron Volts
reference: CRC handbook on Chemistry and Physics version 2008, p. 12-114.
Note: Work function can change for crystalline elements based upon the orientation.

Element	eV	Element	eV	Element	eV	Element	eV	Element	eV
Ag:	4.52-4.74	Al:	4.06-4.26	As:	3.75	Au:	5.1-5.47	B:	~4.45
Ba:	2.52-2.7	Be:	4.98	Bi:	4.34	C:	~5	Ca:	2.87
Cd:	4.08	Ce:	2.9	Co:	5	Cr:	4.5	Cs:	2.14
Cu:	4.53-5.10	Eu:	2.5	Fe:	4.67-4.81	Ga:	4.32	Gd:	2.90
Hf:	3.9	Hg:	4.475	In:	4.09	Ir:	5.00-5.67	K:	2.29
La:	4	Li:	2.93	Lu:	~3.3	Mg:	3.66	Mn:	4.1
Mo:	4.36-4.95	Na:	2.36	Nb:	3.95-4.87	Nd:	3.2	Ni:	5.04-5.35
Os:	5.93	Pb:	4.25	Pd:	5.22-5.6	Pt:	5.12-5.93	Rb:	2.261
Re:	4.72	Rh:	4.98	Ru:	4.71	Sb:	4.55-4.7	Sc:	3.5
Se:	5.9	Si:	4.60-4.85	Sm:	2.7	Sn:	4.42	Sr:	~2.59
Ta:	4.00-4.80	Tb:	3.00	Te:	4.95	Th:	3.4	Ti:	4.33
Tl:	~3.84	U:	3.63-3.90	V:	4.3	W:	4.32-5.22	Y:	3.1
Yb:	2.60 [2]	Zn:	3.63-4.9	Zr:	4.05				

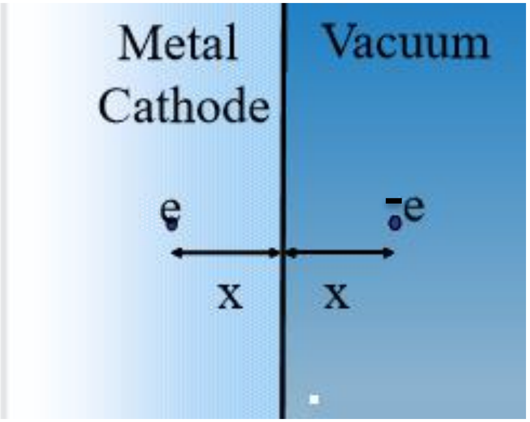
Min

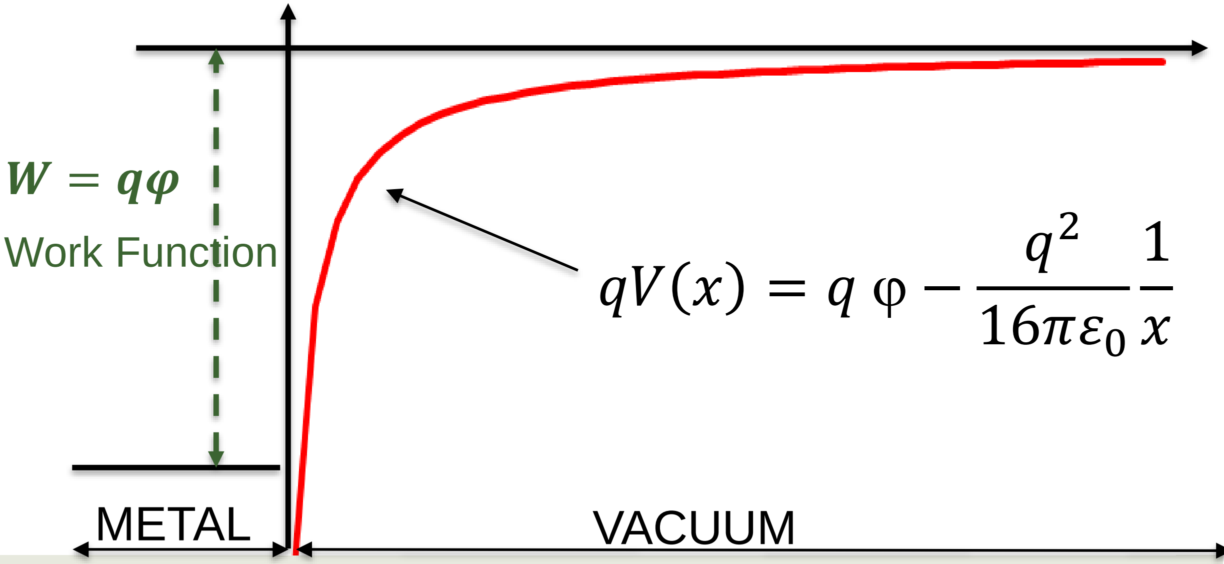
Max

Dipolar effect at the surface and charge image

- When an electron (-q charge) is extracted from a metal, a +q image charge (hole) is created in the metal that screens exactly the electric field generated by the electron at the metal surface (at x=0)
- The Electric Field E(x) and potential generated by the charge image (hole) acting on the electron are:

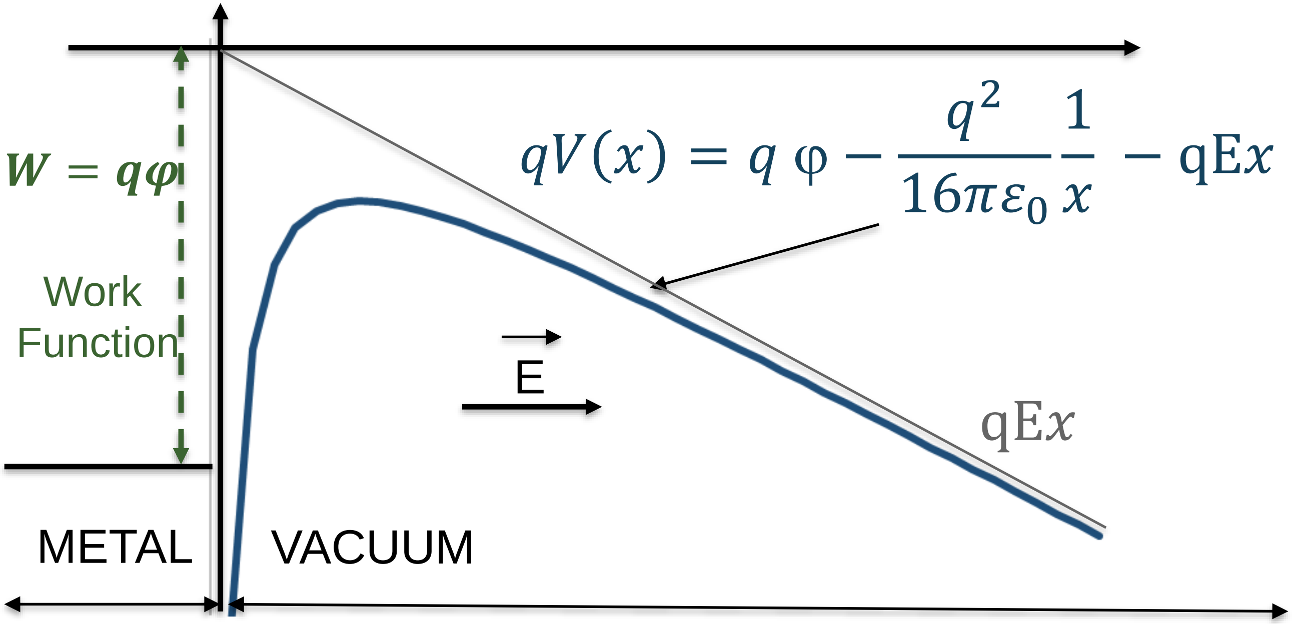
$$E(x) = \frac{+q}{4\pi\varepsilon_0}\frac{1}{(2x)^2} \qquad V(x) = \frac{-q}{16\pi\varepsilon_0}\frac{1}{x}$$





$$qV(x) = q\,\varphi - \frac{q^2}{16\pi\varepsilon_0}\frac{1}{x}$$

Potential near Cathode with Applied External Field E



$W = q\varphi$

Work Function

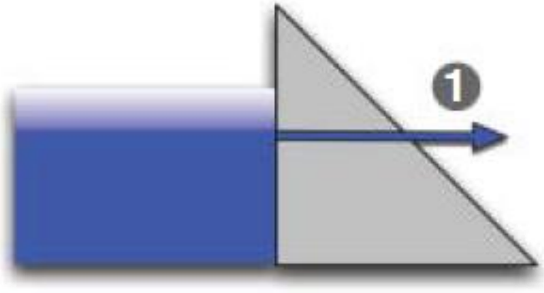
$$qV(x) = q\,\varphi - \frac{q^2}{16\pi\varepsilon_0}\frac{1}{x} - \mathrm{qE}x$$

$\vec{\mathrm{E}}$

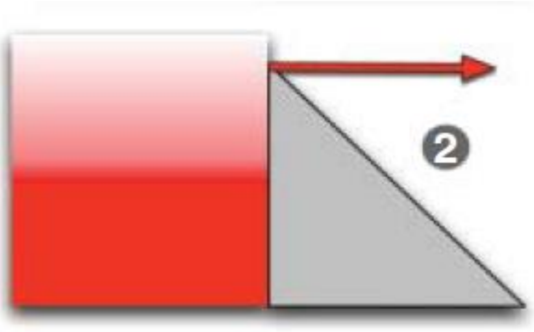
qEx

METAL

VACUUM



Field Emission



Thermo-ionic Emission

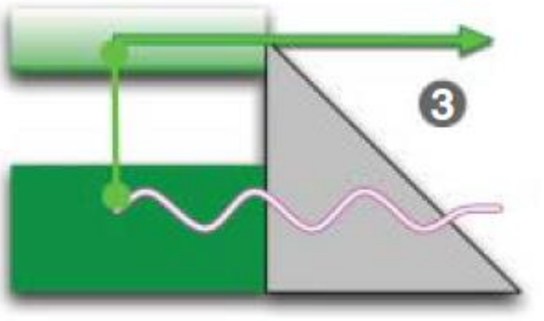
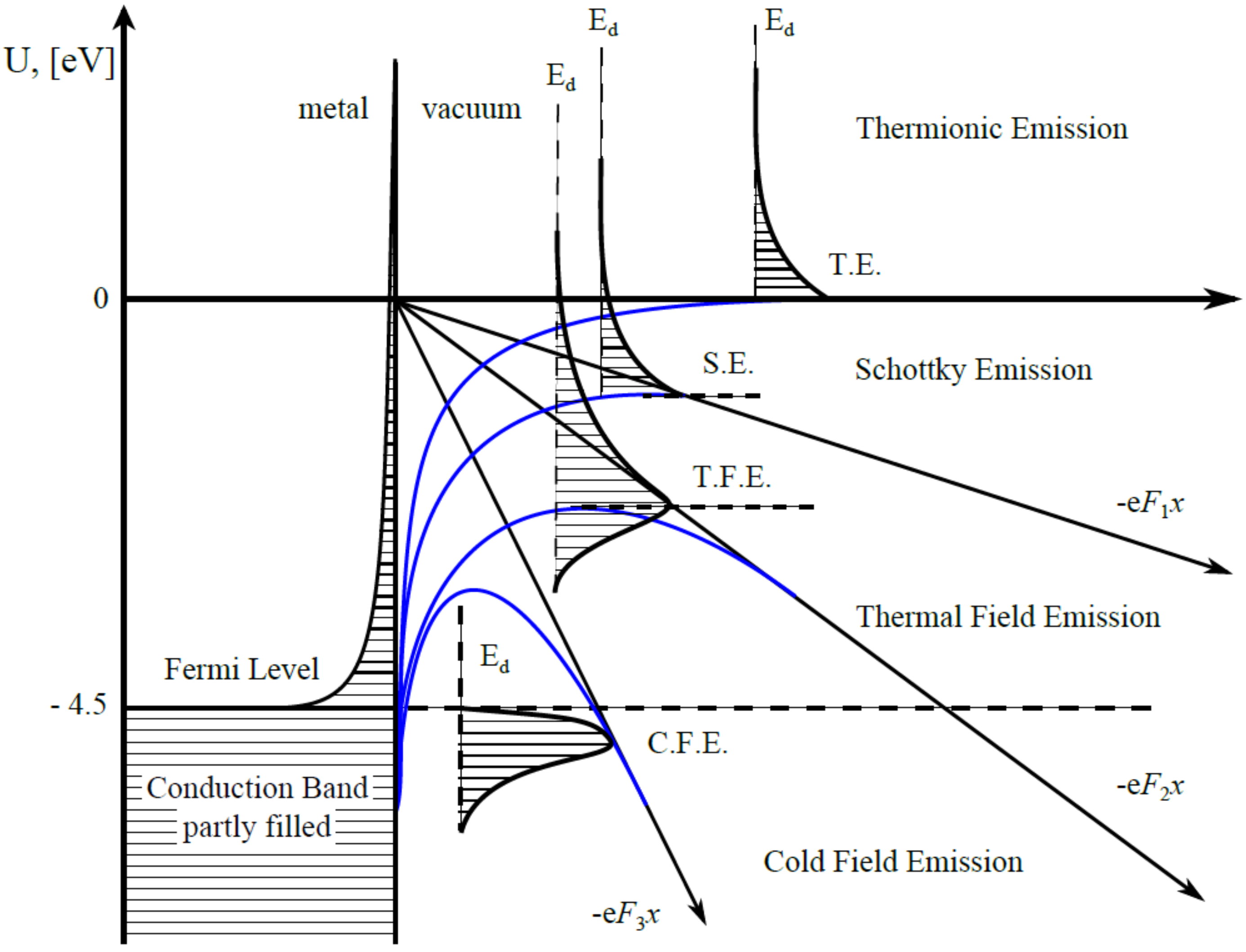


Photo-electric Emission

Introduction to the Physics of Electron Emission, Kevin L. Jensen

Energy Distribution for different potentials profile (Thermo-ionic emission + FE)

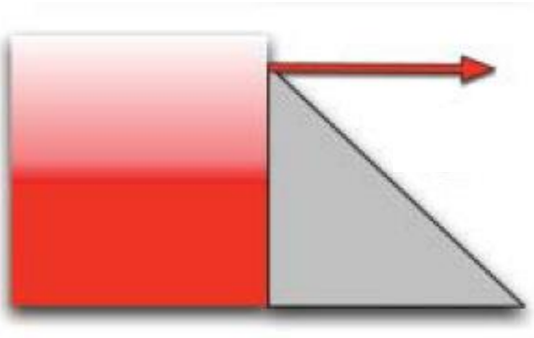


Methods of Preparation and Characterisation of Experimental Field-Emission Cathodes
Alexandr Knápek
(Ph.D Thesis)

Thermo-ionic emission

- The current Density for thermo-ionic emission is expressed by the Richardson–Dushman (RD) equation:

$$\boxed{J = AT^2 e^{-W/k_B T}}$$



- Experimental Results by W. Richardson in 1901
- Law demonstrated by S. Dushman in 1923

- Assumption to establish RD Equation (1D treatment)
  - An electric field exist above the cathode large enough to remove electron but small enough to not affect the barrier
  - Semi-Classic treatment

Richardson-Dushman Equation [1]

- For an electron to escape a metal it needs to have sufficient kinetic energy in the direction of the barrier (x) to overcome the work function

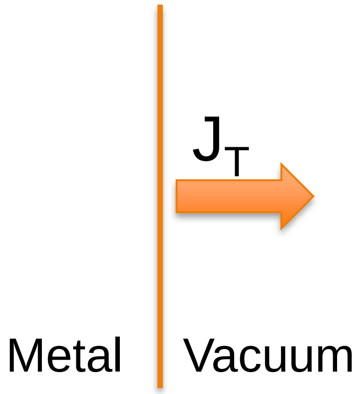
$$\frac{mv_x^2}{2} > q\varphi_{work} \rightarrow v_{min} = \sqrt{\frac{2q\varphi_{work}}{m}} = \sqrt{\frac{2W}{m}}$$

- Current Density normally expressed as

$$J_{Thermoionic} = qn_e v_x \text{ with } v_x > v_{min}$$

Case of electrons with charge q and density n leaving a surface in x direction with energy E and velocity v_x

$$J_x = \int qn(E)v_x(E)dE$$



Richardson-Dushman Equation [2]:

- Electronic density n(E) in metal can be described using:

$$n(E) = g(E)f(E)$$

$$f(E) = \frac{1}{1+\exp(\frac{E-E_f}{kT})} = \text{The probability for a given state with energy E}$$

Only electrons with $E \gg E_F$ can escape metal

$$f(E) \sim \exp\left(-\frac{E-E_f}{k_B T}\right)$$

Maxwell Distribution

$$g(E) = \frac{8\sqrt{2}\pi}{h^3} m_e^{3/2}\sqrt{E}$$ = Density of State with energy E

m_e mass of electron ; h Planck Constant

$$J_x = \int q n(E) v_x(E) dE$$

→

$$\boxed{J_x = \iiint q v_x(E) \frac{8\pi}{h^3} m_e^3 exp\left(-\frac{E-E_F}{k_B T}\right) v_x^2 dv}$$

Richardson-Dushman Equation [3]:

$$J_x = \iiint q v_x(E) \frac{8\pi}{h^3} m_e^3 exp\left(-\frac{E - E_F}{k_B T}\right) v_x^2 dv$$

$$J_x = q \frac{8\pi}{h^3} m_e^3 exp\left(\frac{E_F}{k_B T}\right) \iiint v_x(E) exp\left(-\frac{E}{k_B T}\right) v_x^2 dv$$

$$J_x = q \frac{8\pi}{h^3} m_e^3 exp\left(\frac{E_F}{k_B T}\right) \int_{vmin}^{+\infty} v_x(E) exp\left(-\frac{m v_x^2}{2 k_B T}\right) v_x^2 dv_x \int_{-\infty}^{+\infty} exp\left(-\frac{m v_y^2}{2 k_B T}\right) v_x^2 dv_y \int_{-\infty}^{+\infty} exp\left(-\frac{m v_z^2}{2 k_B T}\right) v_x^2 dv_z$$

$$J_x = q \frac{8\pi}{h^3} m_e^3 exp\left(\frac{E_F}{k_B T}\right) \int_{vmin}^{+\infty} v_x(E) exp\left(-\frac{m_e v_x^2}{2 k_B T}\right) v_x^2 dv_x \int_{-\infty}^{+\infty} exp\left(-\frac{m_e v_y^2}{2 k_B T}\right) v_x^2 dv_y \int_{-\infty}^{+\infty} exp\left(-\frac{m_e v_z^2}{2 k_B T}\right) v_x^2 dv_z$$

$$J_x = q \frac{8\pi}{h^3} m_e^3 exp\left(\frac{E_F}{k_B T}\right) exp\left(-\frac{q\varphi}{k_B T}\right) \frac{k_B T}{m_e} \sqrt{\frac{2\pi k_B T}{m_e}} \sqrt{\frac{2\pi k_B T}{m_e}}$$

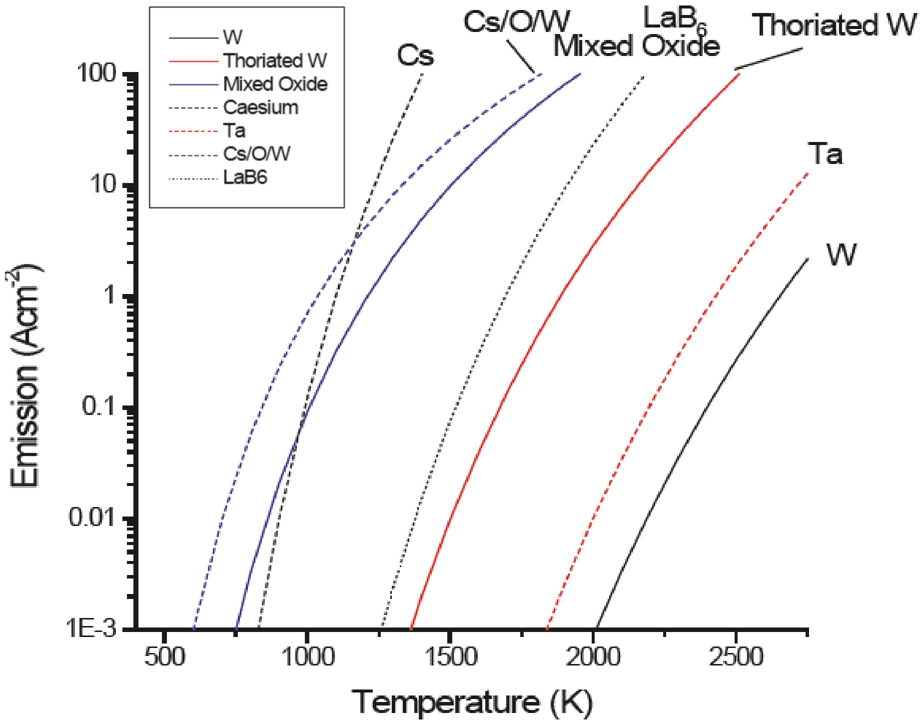
$$J_x = q m_e \frac{4\pi {k_B}^2}{h^3} T^2 exp\left(\frac{E_F - q\varphi}{k_B T}\right)$$

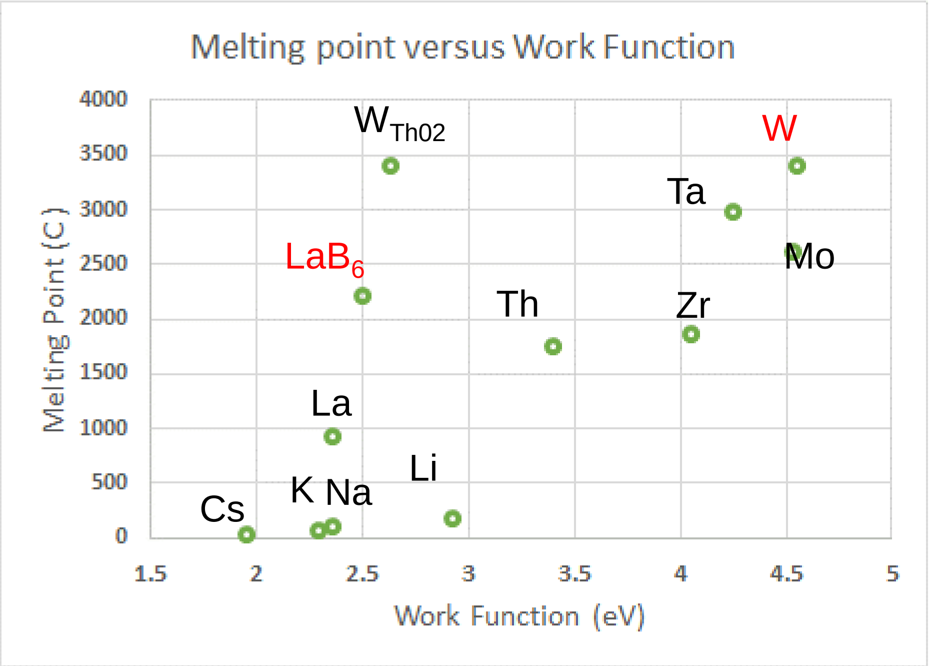
$$\boxed{J_x = A T^2 exp\left(-\frac{W}{k_B T}\right)}$$

$$A = \frac{4\pi m_e k_B^2 e}{h^3}$$

Hint: $\int_{-\infty}^{+\infty} exp(Cx^2) dx = \sqrt{\frac{\pi}{C}}$

Thermionic emission





	A (A cm^{-2} K^{-2})	ϕ_{work} (eV)		A (A cm^{-2} K^{-2})	ϕ_{work} (eV)
W	60	4.54	Mixed oxide†	0.01	~1
Ta	60	4.12	Cs/O/W†	0.003	0.72
Thoriated W	3	2.63	LaB_6	29	2.66
Cesium	160	1.81			

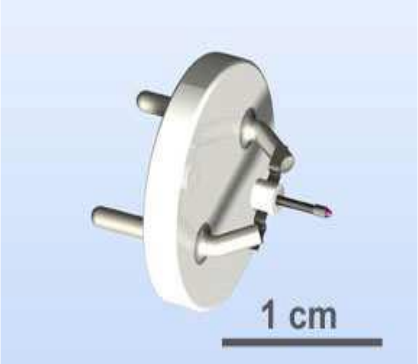
† Parameters for mixed oxide (SrO/BaO) and CsO on W substrate depend critically on the mixture and activation. Typical values are given.

$$J = AT^2 e^{-\phi/k_B T}$$

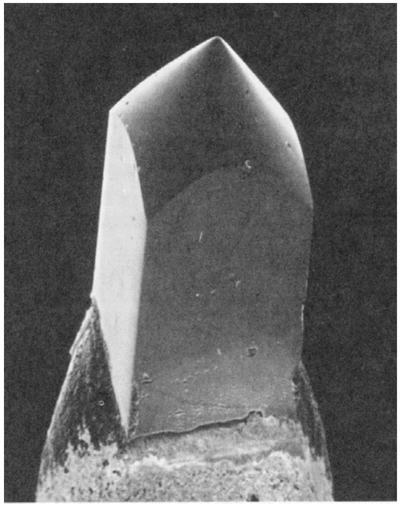
$$A = \frac{4\pi m_e k_B^2 e}{h^3} = 1.210^2 Acm^{-2}K^{-2}$$

A few rules on thermionic emission

- Pure metals with low work function typically have low melting point
- Because of its high melting point, Tungsten is one of the most common thermionic emitters.
  - But high temperatures operation result in evaporation and oxidation!
  - Oxide coated tungsten (W=1.6eV), but they are sensitive to vacuum and very brittle
- Lanthanum Hexaboride (LaB6)
  - Much lower work function than W (2.4eV vs 4.5eV)
- Dispenser cathodes
  - made of porous tungsten impregnated with BaO, CsO maybe coated with Ir, Os, Rh can generate 10s of A/cm^{2}for 1000’s of hours



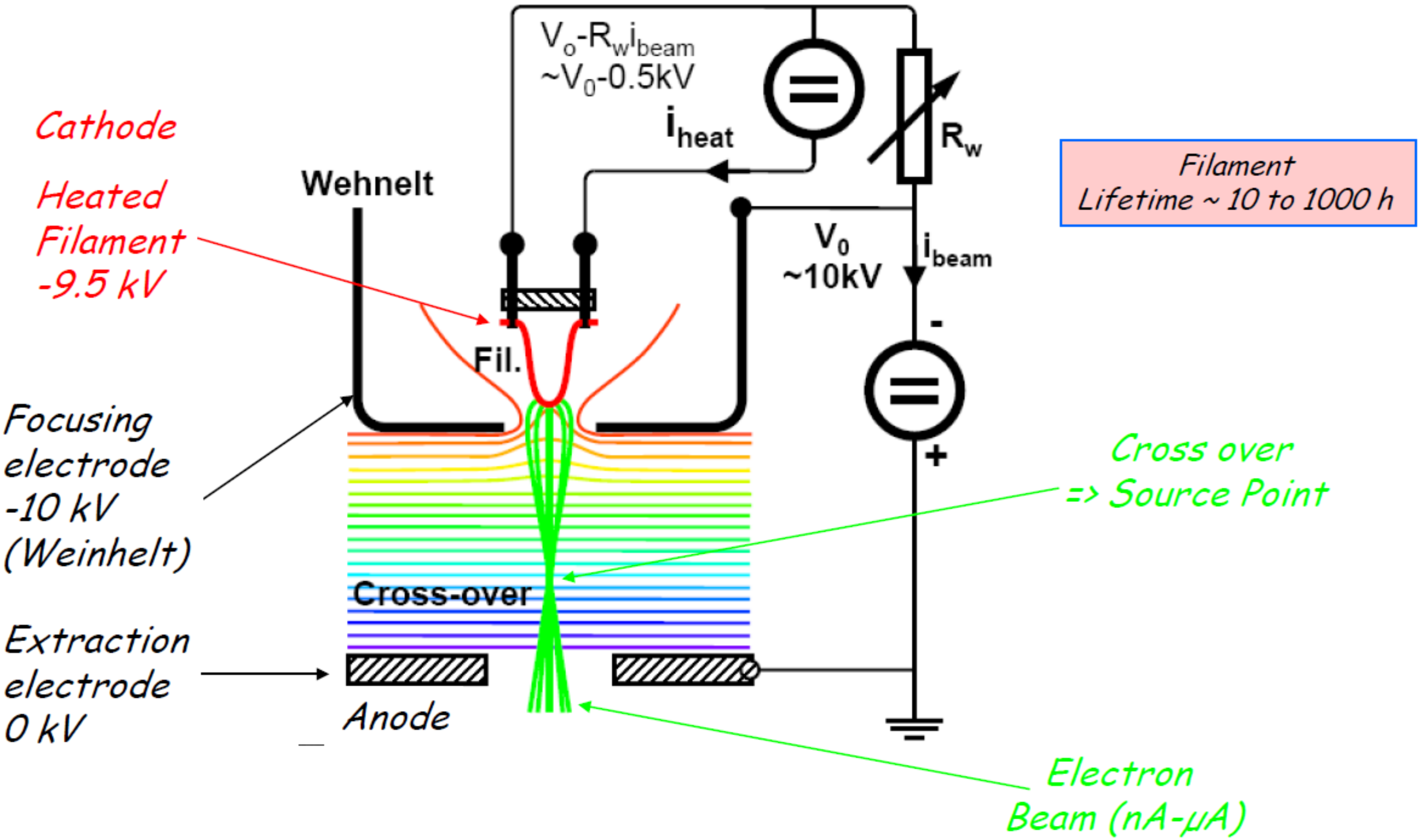
W



LaB6

Example of Thermionic Electron Gun

Electronic Microscope source



Cathode

Heated Filament -9.5 kV

Filament Lifetime ~ 10 to 1000 h

Focusing electrode -10 kV (Weinhelt)

Cross over => Source Point

Extraction electrode 0 kV

Electron Beam (nA-μA)

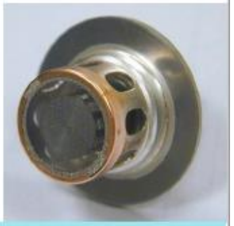
High Intensity Thermionic Electron Gun

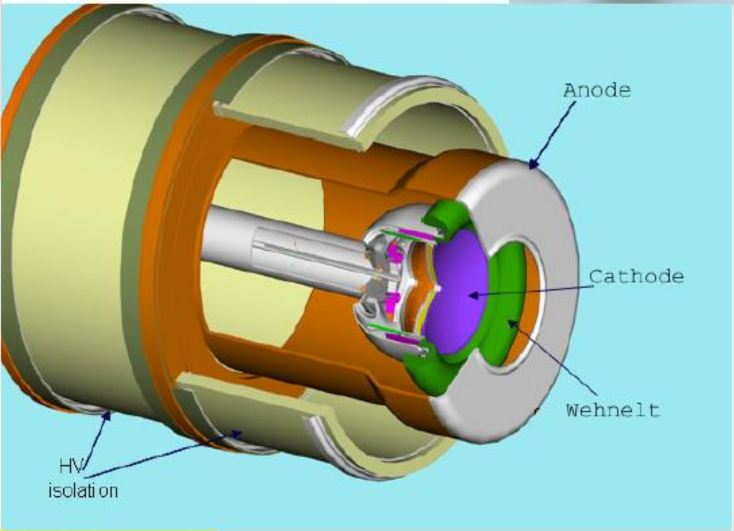
Depending on the design:

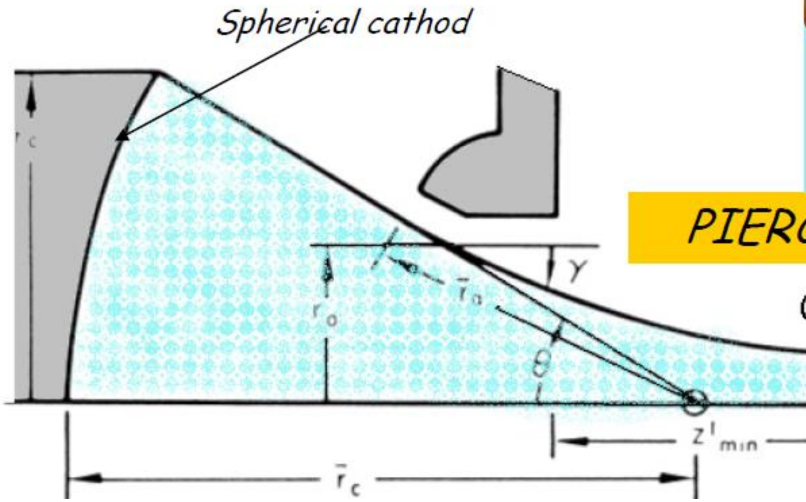
Currents from μA to ~100 A

Example of cathodes

cathodes damaged by sputtering (see later)







PIERCE GUN

Pierce Geometry: Edge of Cathode with 67.5º w.r.t direction of propagation

Perveance

- Space charge created by the electrons already extracted from a surface ultimately limit the number of additional electrons that can be extracted following the relation:
  - $I = \frac{4}{9}\epsilon_0 (\frac{2Ze}{m_e})^{1/2} \frac{\pi r_a^2}{d^2} V_O^{3/2}$ r_a electron beam radius; d distance to anode
- Perveance is the ratio of current extracted to the Accelerating voltage $V_O^{3/2}$
  - $P = \frac{I}{V_0^{3/2}} = \frac{4}{9}\epsilon_0 (\frac{2Ze}{m_e})^{1/2} \frac{\pi r_a^2}{d^2} \approx 1.8E^{-6} (\frac{2r_a}{d})^2$ only depends on geometry
- The value of perveance indicates how significant the space charge effect is on the beam's motion
  - Low perveance i.e < $0.1E^{-6}\ AV^{-3/2}$ can follow pierce geometry
  - High perveance > $0.1E^{-6}\ AV^{-3/2}$ influence of space charge more significant

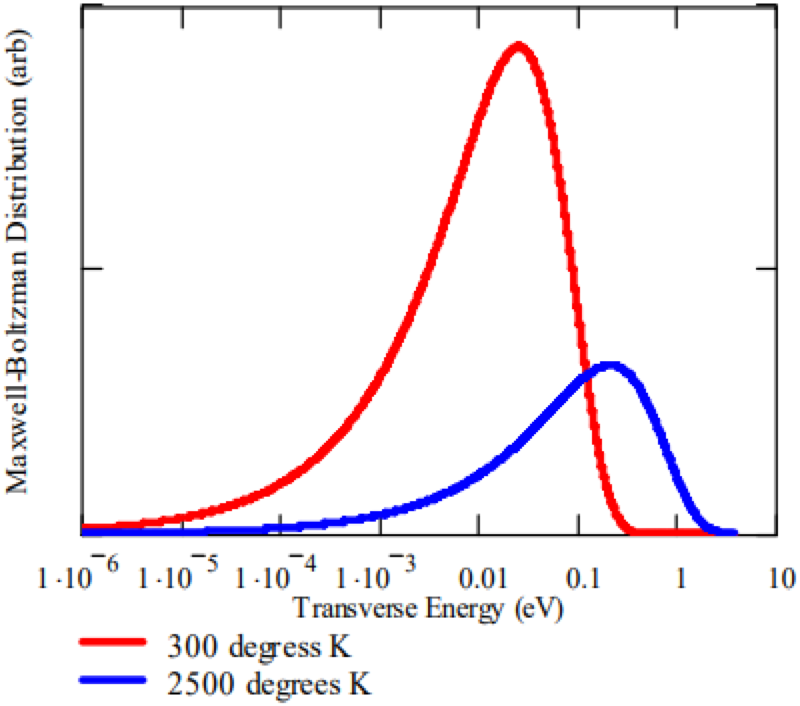
Thermionic emittance

- The velocity distribution for thermally emitted electrons is obtained from the derivative of Maxwell

$$f(v_x) = \left(\frac{m_e}{2\pi k_b T}\right)^{3/2} v_x^2 e^{\frac{-m_e v_x^2}{2k_b T}} dv_x$$

Maxwell-Boltzmann electron energy distributions at 300 degK where the rms electron energy spread is 0.049 eV, and at 2500 degK corresponding to an rms energy spread of 0.41 eV. The initial spread in transverse velocity due to the electron temperature gives the beam angular divergence and hence its thermionic emittance.

Maxwell-Boltzmann distribution



- Normalized Emittance

$$\epsilon_N = \beta\gamma\sigma_x\sigma_{x'}$$

$$\boxed{\epsilon_N = \sigma_x \frac{\sqrt{k_b T}}{m_e c^2}}$$

Schottky Emission (I)

- Shottky effect: Application of external field lowers work function (barrier suppression)
- New total potential $V_S(x)$:

$$qV(x) = q\,\varphi - \frac{q^2}{16\pi\varepsilon_0}\frac{1}{x} - \mathrm{qE}x$$

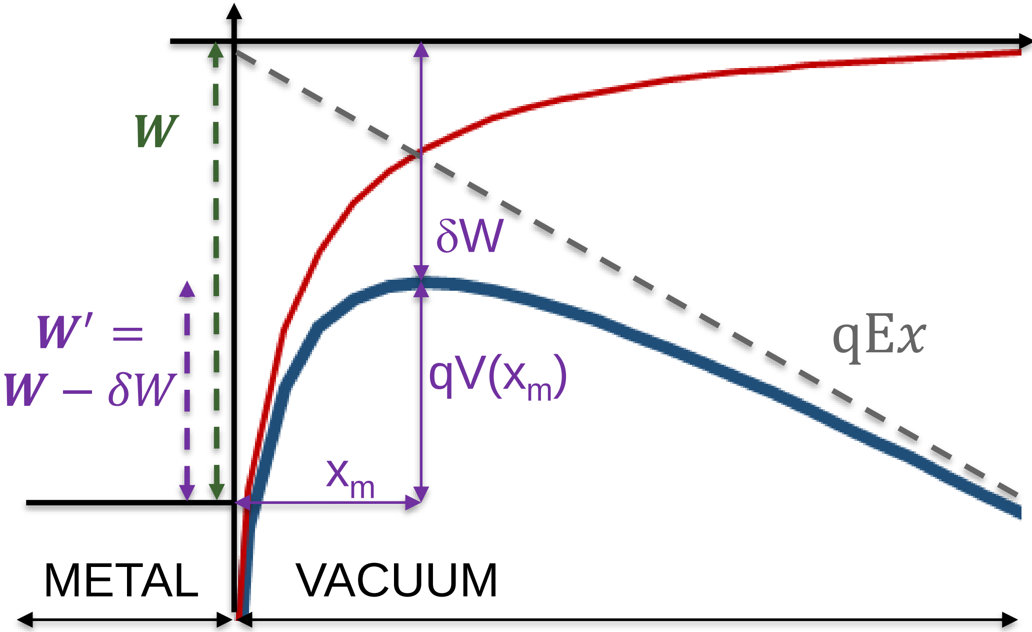
- Location of the optimum in xm:

$$x_m = \sqrt{\frac{q}{16\pi\varepsilon_0 E}}$$

- The reduction of work function δW is:

$$\delta W = q\varphi - qV(x_m)$$

$$\delta W = 2qEx_m = \sqrt{\frac{q^3 E}{4\pi\varepsilon_0}}$$



$$J_S = AT^2 e^{-(W-\delta W)/k_B T}$$

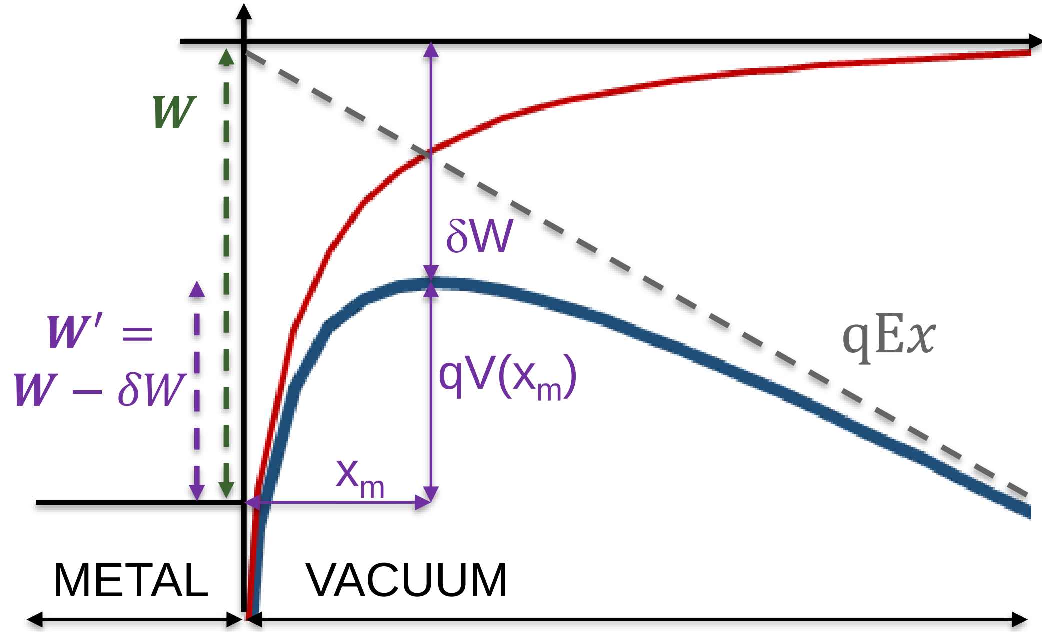
$$J_S = AT^2 e^{\delta W/k_B T} e^{-W/k_B T}$$

$$\boxed{J_S = J_{th} e^{\delta W/k_B T}}$$

Schottky Emission (II)

- $\delta W(eV) = 3.810^{-5}\sqrt{E}$ (E in V/m)

E (V/m)	δW (eV)
10^5	0.012
10^6	0.038
10^7	0.12
10^8	0.38
10^9	1.2



Beyond Applied field of 10^9 V/m the barrier is not only getting lower but also thinner and electrons can start tunneling through: That's Field Emission (FE)

$$J_S = AT^2 e^{-(W-\delta W)/k_B T}$$

$$J_S = AT^2 e^{\delta W/k_B T} e^{-W/k_B T}$$

$$\boxed{J_S = J_{th} e^{\delta W/k_B T}}$$

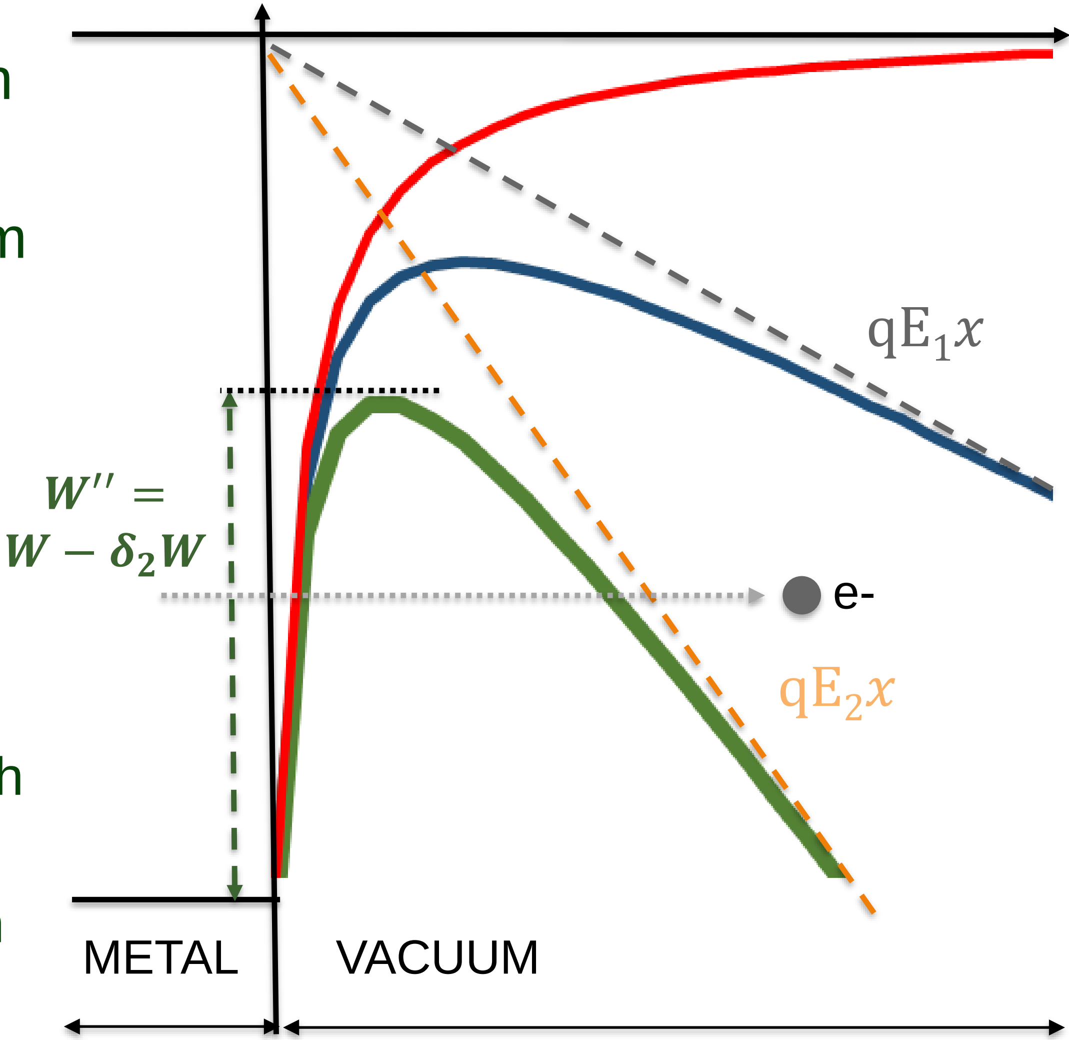
Field Emission (I)

- For electric Fields in the order of $10^9 - 10^{10}\ V/m$ electron can tunnel through the barrier
- Electron tunneling is a quantum mechanical effect and can be expressed as:

$$J_{FE} = \int f(E,T)D(E,E_0)dE$$

$f(E,T)$ represent the flux of electrons incident on the barrier with energy E

$D(E,E_0)$ represent the transmission of electrons through the barrier defined with electric field E_0



Field Emission (II)

- Expression of Transmission function $\mathrm{D}(\mathrm{E}, \mathrm{E}_0)$ and Supply function $\mathrm{f}(\mathrm{E}, \mathrm{T})$ are normally very complicated
- Most common form of equation describing Field Emission was developed by Fowler and Nordheim (FN) for a perfectly planar surface and triangular barrier and take the following form:

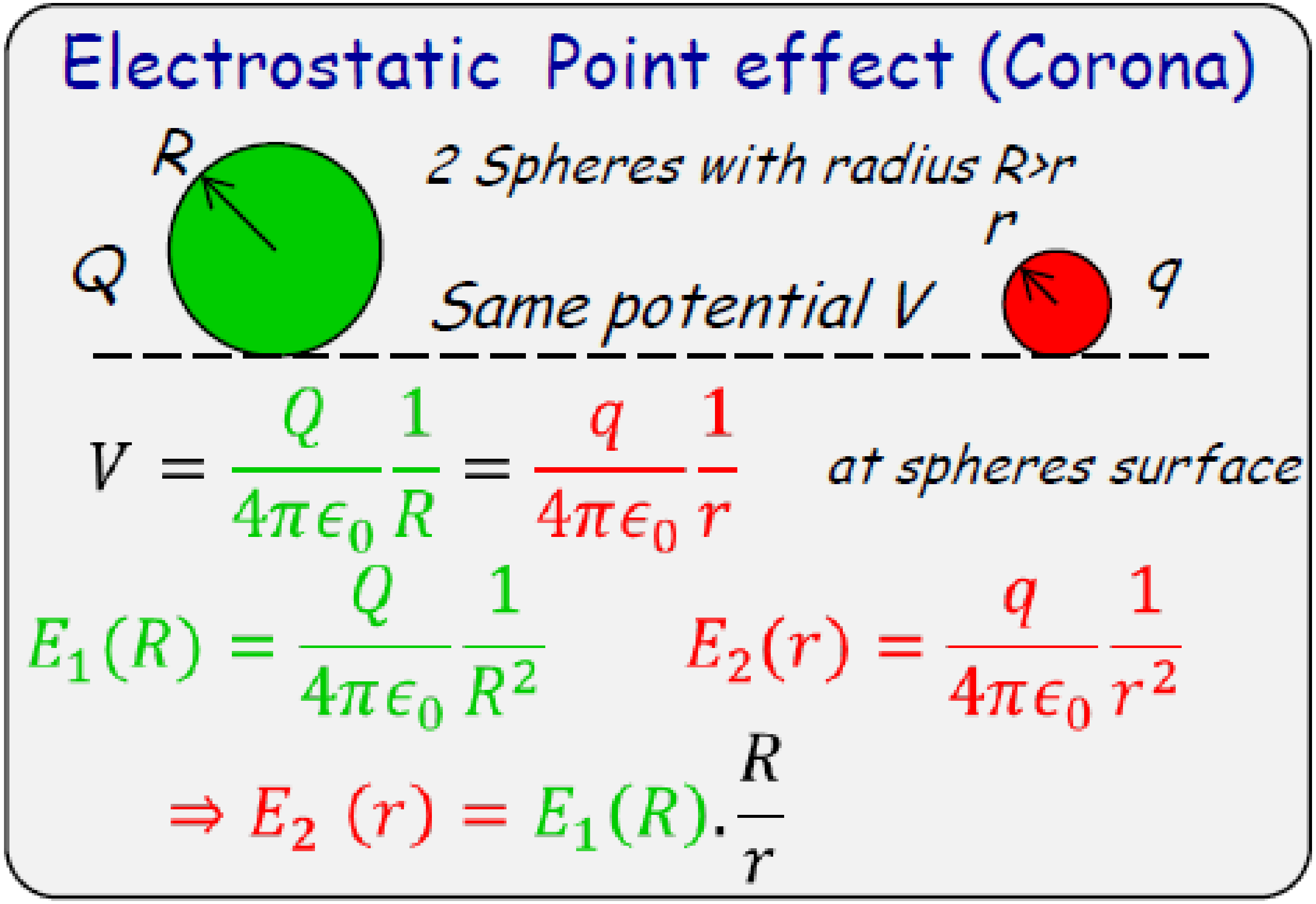
$$\boxed{J_{FN}(E) = A\frac{E^2}{W}e^{\left(-\frac{BW^{3/2}}{E}\right)}} \quad \mathrm{A}/m^2$$

$$A = 1.541 \times 10^{-6}; \quad B = 6.68 \times 10^{7};$$

J_{FN} strongly dependent on electric Field

- More details on FN equation can be found in :
  - Introduction to the Physics of Electron Emission, Kevin L. Jensen John Wiley & Sons, Inc., 2017

Field Emission: Why Sharp Tip?



Electrostatic Point effect (Corona)

2 Spheres with radius R>r

Same potential V

$$V = \frac{Q}{4\pi\epsilon_0}\frac{1}{R} = \frac{q}{4\pi\epsilon_0}\frac{1}{r}$$ at spheres surface

$$E_1(R) = \frac{Q}{4\pi\epsilon_0}\frac{1}{R^2} \qquad E_2(r) = \frac{q}{4\pi\epsilon_0}\frac{1}{r^2}$$

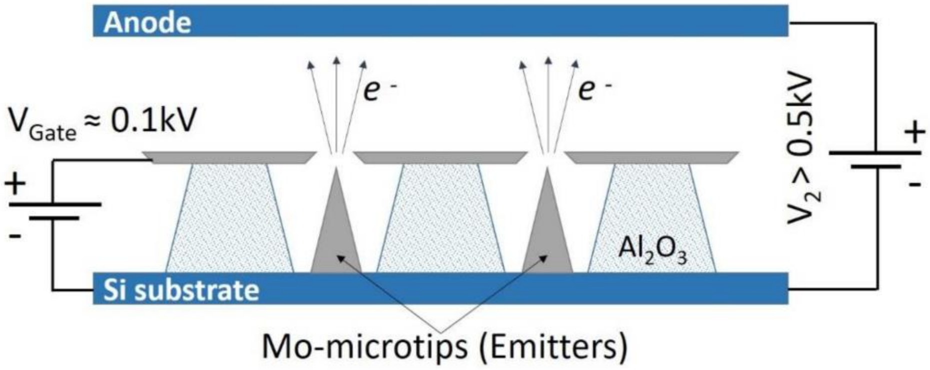
$$\Rightarrow E_2\,(r) = E_1(R).\frac{R}{r}$$

T.Thuillier, JUAS 2012, Particle Sources – Electron Sources

Field Emission Array (FEA)

- FEAs are typically fabricated by means of a lithographic process using an arrangement of individual molybdenum micrometric conical emitters, in gated configuration, on a Si-substrate

- Used extensively for vacuum electronics:
  - X-ray sources
  - Flat panel displays
  - Electron microscopy/lithography

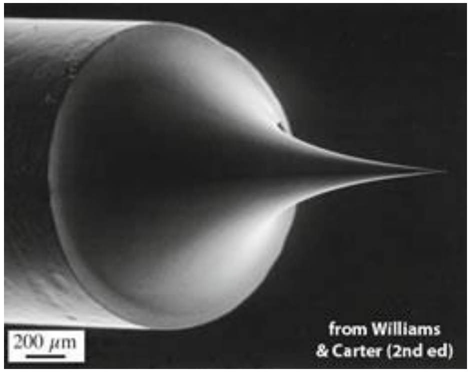


$$Work\ Function\ \ for\ Molybdenum$$

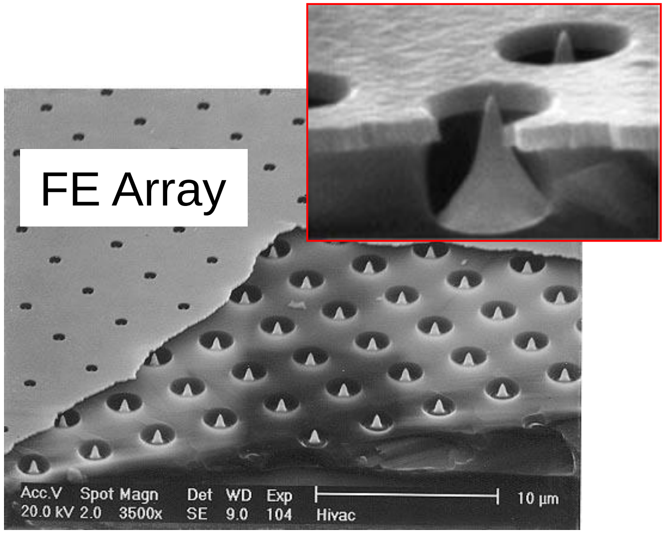
$$\varphi \approx 4.6eV$$

Field (V/m)	Tunnel Width (nm)
3×10^{9}	4.5
3×10^{10}	0.5

Field Emission Tips

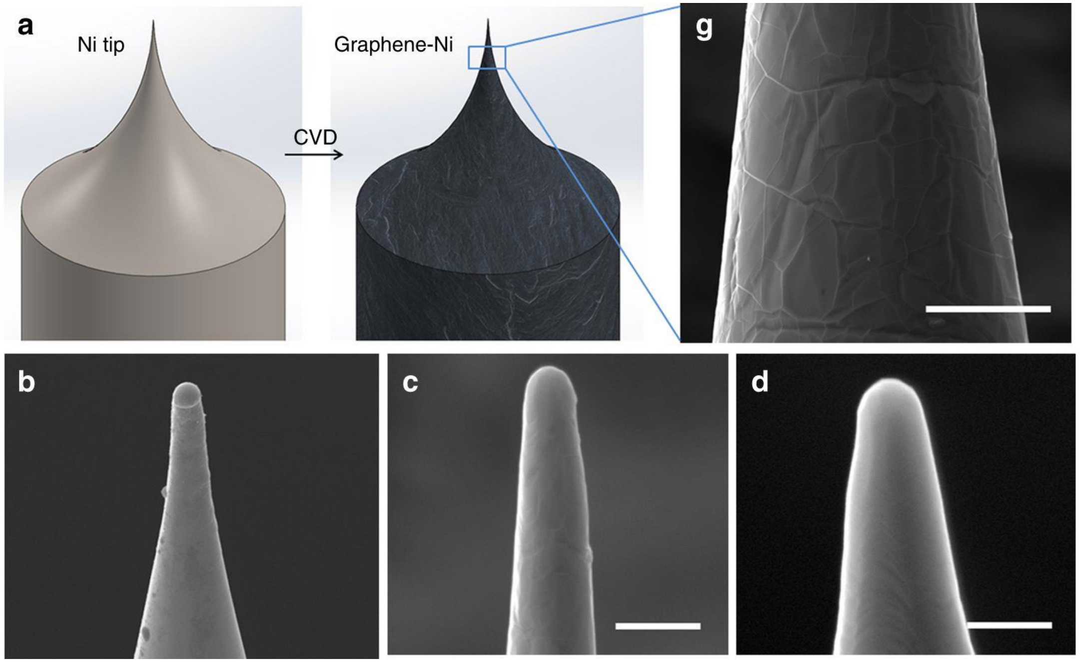


from Williams & Carter (2nd ed)



Courtesy of C. A. Spindt
www.sri.com/psd/microsys/vacuum/

“A high-brightness large-diameter graphene coated point cathode field emission electron source”
Xiuyuan Shao- *Nature Communications (March 2018)*



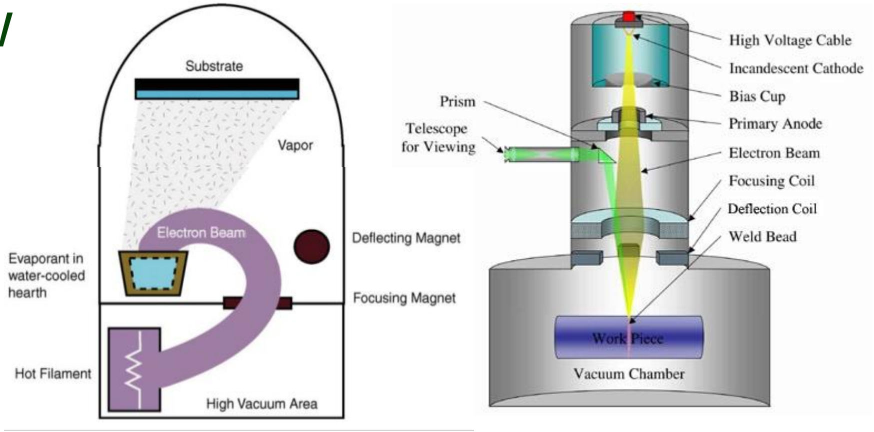
SEM characterization of the Graphene-Ni field emitter. **a** Illustration of the fabrication of a graphene-coated point cathode. **b** SEM images of as-etched Ni tip from electrochemical etching at low magnification showing supporting wire (scale bar, 5 μm), and SEM images of graphene-coated point cathodes of different tip radii: **c** 210 nm, **d** 300 nm. Scale bar (**c**, **d**,) 1 μm. **g** SEM image of the lateral surface of the emitter

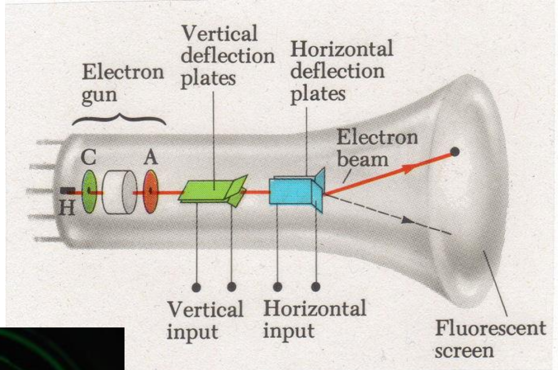
Characteristics of the different electron sources

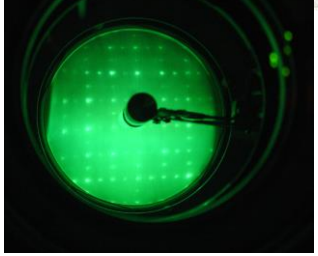
	Units	W	LaB6	FEG
Work Function	eV	4.5	2.4	4.5
Operating Temperature	K	2700	1700	300
Current Density	A/m^2	$5x10^4$	10^6	10^{10}
Total Current	mA	0.1-100s		0.01
Brightness	A/m^2sr	10^9	$5x10^{10}$	10^{13}
Source Size	μm	50	10	<0.01-0.1
Angle	Rad	10^{-3}		10^{-1}
Energy Spread	eV	3	1.5	0.3
Stability	%/hr	<1	<1	5
Vacuum	Torr	10^{-4}	10^{-6}	10^{-10}
Lifetime	hr	100	500	>1000
Handling		Rugged and Cheap	Fragile and delicate	Very fragile

Cathode Applications–Thermionic Guns

- Thermionic guns with relatively low energy are used in a number commercial applications
  - Electron beam welding
  - Electron beam heating, 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
  - Flood guns for charge neutralization
  - Ionization of material for mass spectrometry







Cathode Applications–Electron Microscopes

- Optical microscope resolving power ultimately limited by light wavelength ~100s nm
- Electron wavelength much smaller

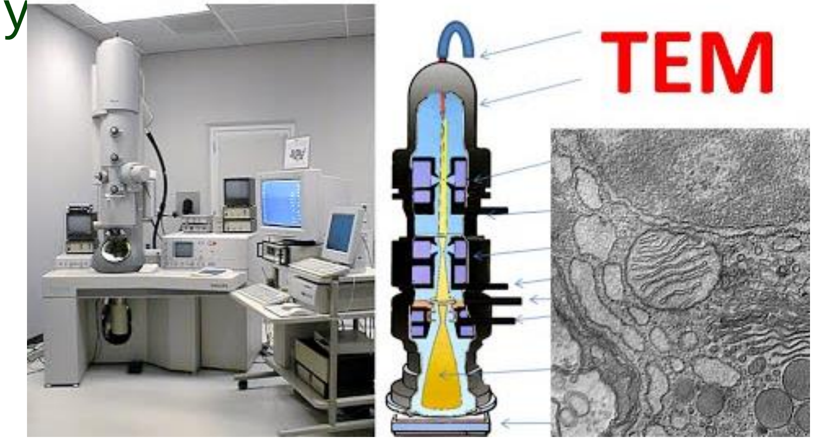
$$\lambda = \frac{h}{p_e} = \frac{h}{\sqrt{2em_eV}}$$

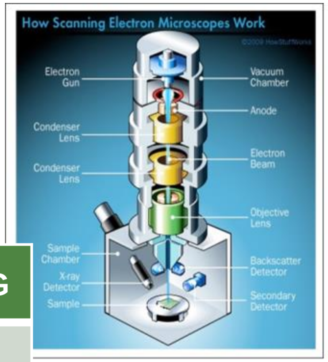
100-300kV $\lambda = 0.03 - 0.01$Å

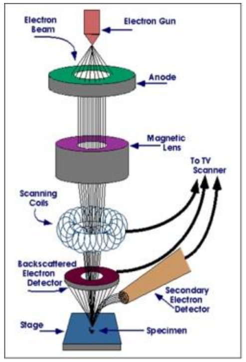
- MicroscopesTypes:
  - Transmission Electron Microscope (TEM)
  - Scanning Electron Microscope (SEM)
  - Scanning Transmission Electron Microscope (STEM)
- Cathode element depends on applications

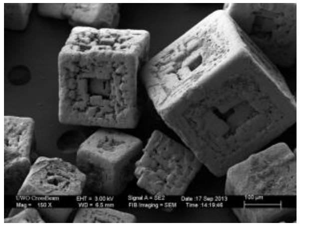
	W Hairpin	LaB6	FEG	Nano FEG
Source Size	50μm	5μm	50Å	5Å
Brightness (A/cm2/str)	10^5	10^6	10^8	10^{10}
Energy Spread (eV)	2.5	1	0.35	

Hitachi High Technologies America, Inc



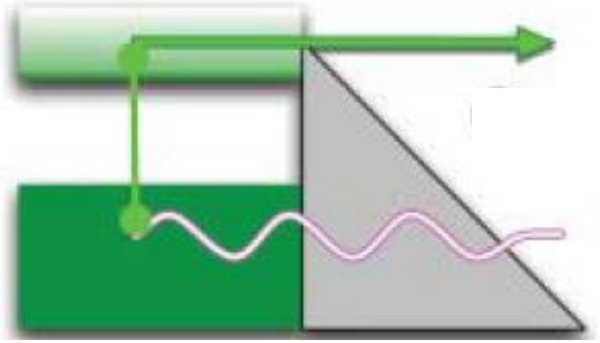






Photoelectric effect

- The energy to emit an electron is given by a photon
- A photocathode is a negatively charged electrode coated with a photosensitive compound. When it is struck by a photon, the absorbed energy causes electron emission due to the photoelectric effect.



$$h\nu = W + \frac{1}{2}mv^2$$

Electron Kinetic Energy

Photon Energy

Work Function of the Photocathode

$$QE = \frac{\# e^-_{emitted}}{\# \gamma_{incident}}$$

$$\boxed{\lambda_{[nm]} = \frac{1234}{W_{[eV]}}}$$

- A photocathode can be made of:
  - Metals
  - Semiconductors

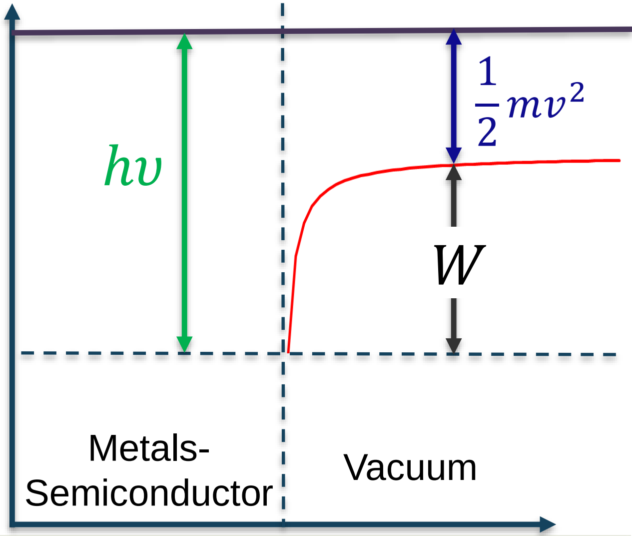
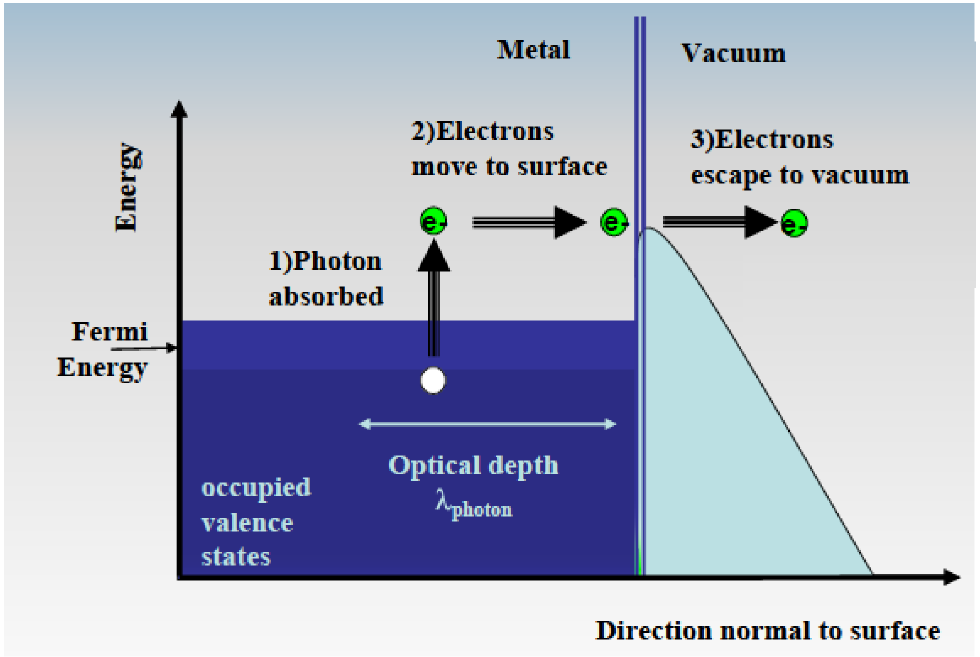


Photo-Electric Emission

- Photoelectric emission from a metal can be described by the three steps :
  1. Photon absorption by the electron
  2. Electron transport to the surface
  3. Escape through the barrier



ABSORPTION of light in bulk material and photo-excitation of electrons

- reflectivity R(ω) — R(w) ~ 40% for metals; R(w)~ 10% for semiconductors
- laser penetration depth δ(ω)

TRANSPORT of photo-excited electrons to surface subject to scattering $f_\lambda(\cos\theta, E)$

- electron energy
- scattering rates (relaxation times)

EMISSION probability D(E)

- Metal:
  Chemical Potential μ, Work Function Φ
  (work function measured from Fermi level)
- Semiconductor:
  barrier height E_a, band gap E_g
  (Electron affinity measured from conduction band minimum)

$$QE = \frac{q}{\hbar\omega}(1-R(\omega))F_{\lambda}(\delta,\tau)P_{FD}(\hbar\omega)$$

Kevin Jensen, 1st Workshop on Photocathode 2009

Metals Photocathodes

- Metal photo cathodes are commonly used in high gradient, high frequency RF guns and used at facilities such as s-band guns.

- Advantages
  - Very Long lifetime (with occasional laser or ion cleaning)
  - Tolerant of poor (nTorr) vacuum
  - Prompt response time (fs)
  - Low field emission
- Disadvantages
  - Require UV photons (>3.5 eV)
  - $<10^{-4}$ quantum efficiency ! Not suitable for high intensity injectors (mA)
  - Short penetration depth (~14 nm)
  - No polarization of electrons

Metal Cathodes	Wavelength (nm) & Energy (eV)	Quantum Efficiency (QE)	Work Function (eV)
Bare Metal			
Cu	250, 4.96	1.4×10^{-4}	4.6
Mg	266, 4.66	6.4×10^{-4}	3.6
Pb	250, 4.96	6.9×10^{-4}	4.0
Nb	250, 4.96	$\sim 2\times10^{-5}$	4.38
Coated Metal			
CsBr:Cu	250, 4.96	7×10^{-3}	~2.5
CsBr:Nb	250, 4.96	7×10^{-3}	~2.5

Semiconductors Photocathodes

- Semiconductor photocathodes
  - Material:
    - GaAs (Cs)
    - Alkali-based: K_3Sb, K_2CsSb, Cs_2Te,
- Advantages
  - Can work in visible light
  - 1% - 10% quantum efficiency
  - Can generate polarized electron
  - Long penetration depth (~mm)
  - Can have delayed electron emission (GaAs)
- Disadvantages
  - Require UHV (<0.1 nTorr)
  - Limited Lifetime (100's hours)
  - Slow Response time
  - Complicated

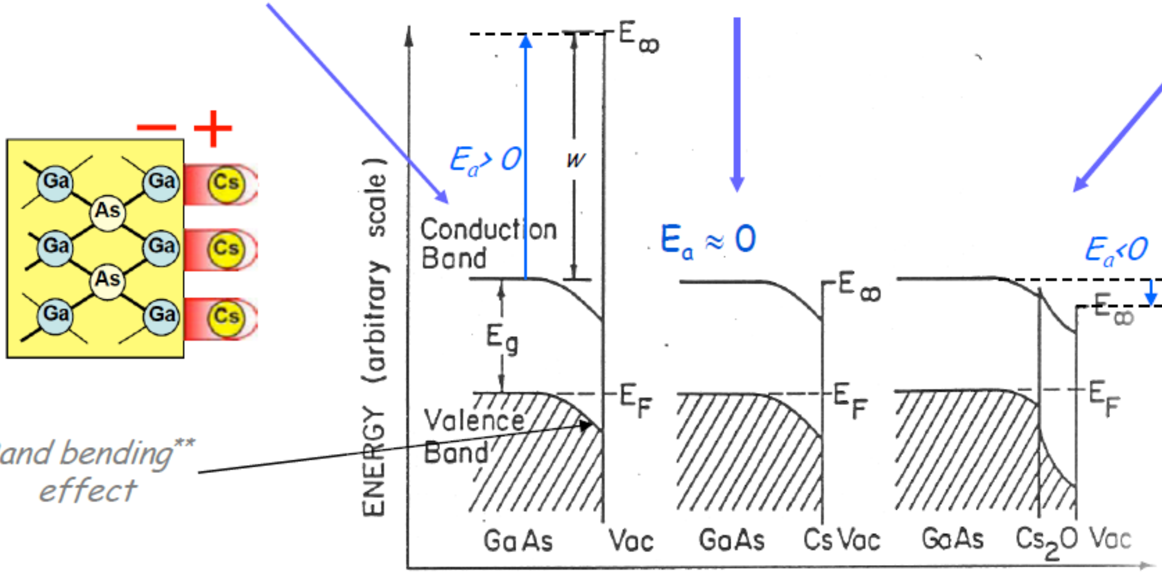
Material	QE (%)	λ (nm)
K_2CsSb	29	590
Cs_2Te	12.4	350
GaAs:Cs	17	225

Photoemission Enhancement from GaAs with Cs or Cs-X coating

Bare GaAs surface;
Large work function.
No electrons

Alkali (Cs) coating
reduces work function.
Some electrons.

Cesium + Oxidant (O or NF3)
"Negative Electron Affinity".
Many electrons



*Band bending*** *effect*

Coating is Very fragile.
Any chemical contamination can damage it.
=> Excellent ultra high vacuum level is necessary

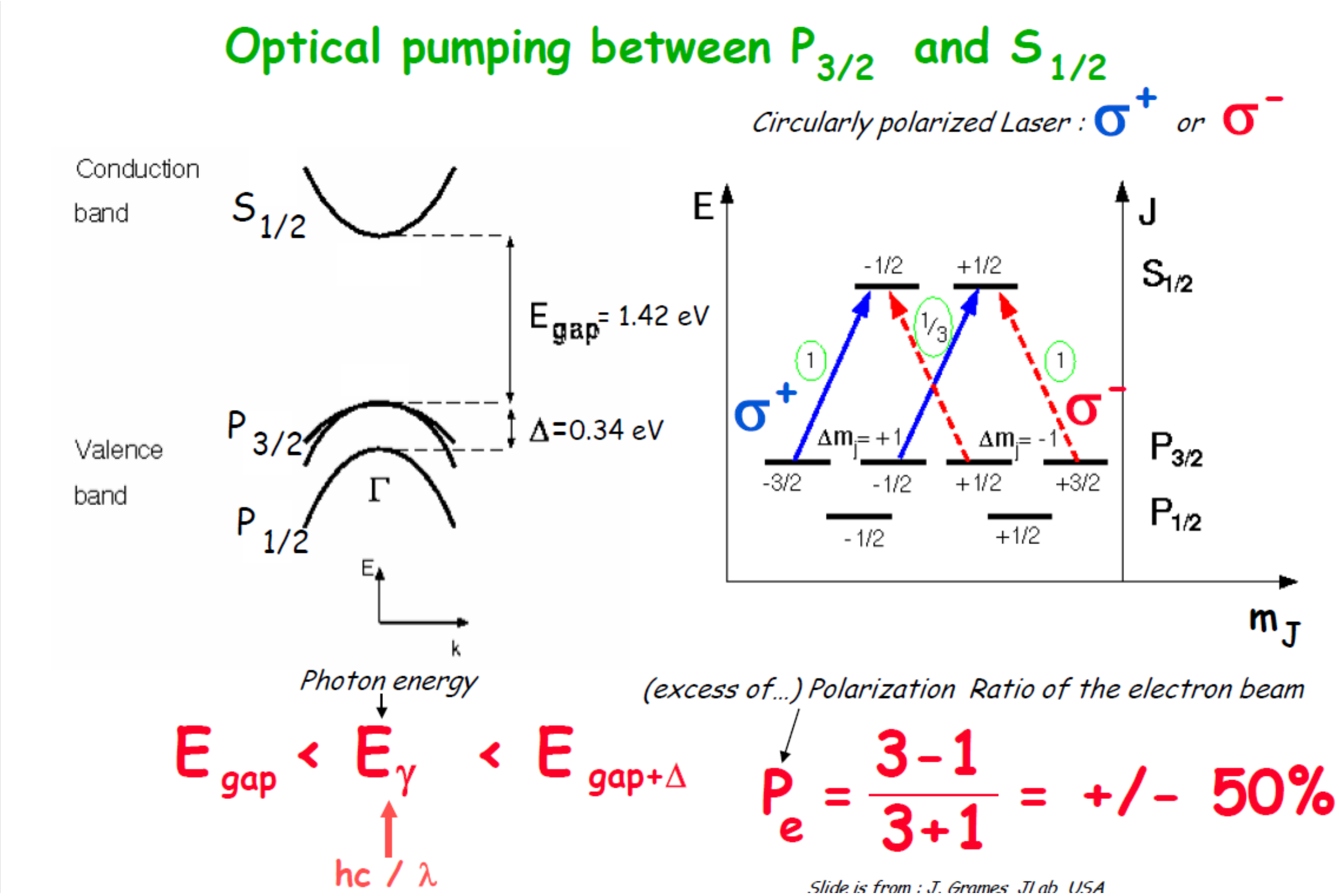
*Electron Affinity** : $E_a > 0$ $E_a \approx 0$ $E_a < 0$

Extracted from slides :
J. Grames, JLab, USA
N. Nishimori, JAEA, Japan

**In solids, the Electron Affinity is the energy difference between the vacuum energy and the conduction band minimum.*

***Band bending refers to the local change in energy of electrons at a semiconductor junction due to space charge effects. The degree of band bending between two layers depends on the relative Fermi levels and carrier concentrations of the materials forming the junction.*

Polarization of electron Beam



Optical pumping between $P_{3/2}$ and $S_{1/2}$

Circularly polarized Laser : σ^+ *or* σ^-

Photon energy

$$E_{gap} < E_\gamma < E_{gap+\Delta}$$

hc / λ

(excess of...) Polarization Ratio of the electron beam

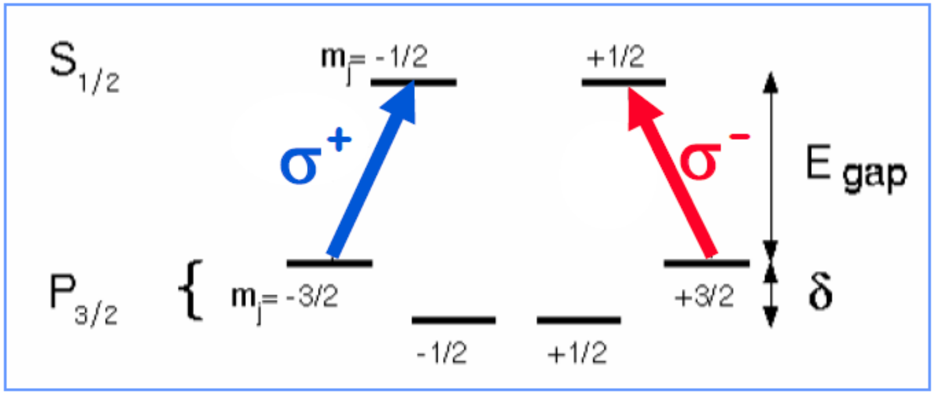
$$P_e = \frac{3-1}{3+1} = +/-\ 50\%$$

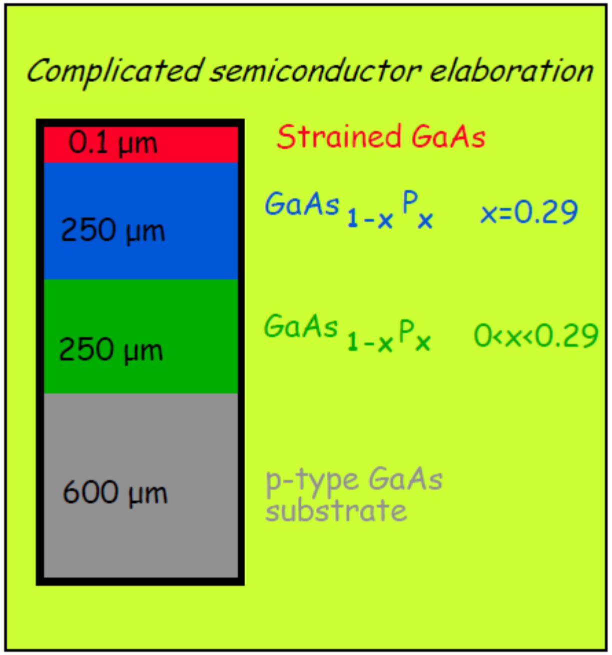
Slide is from : J. Grames, JLab, USA

High Polarization : Optical Pumping of strained GaAs

Split degeneracy of $P_{3/2}$

& optical pumping between $P_{3/2}$ and $S_{1/2}$





theoritical

$$P_e = +/-\ 100\%,\ \text{with } E_{gap} < E_\gamma < E_{gap+\delta}$$

Experimentaly ~85%

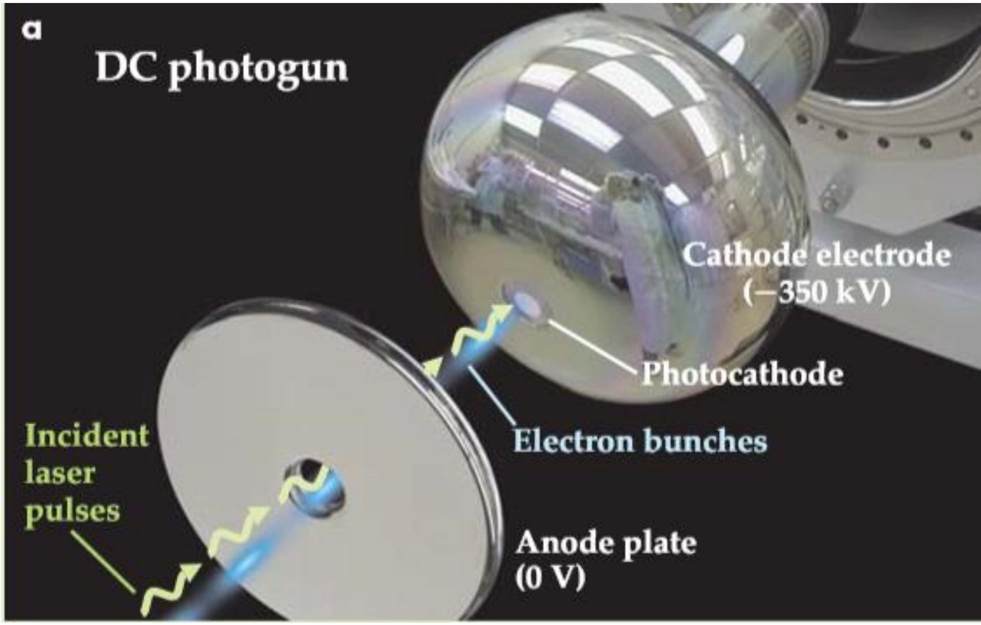
Slide is from : J. Grames, JLab, USA

Type of Gun Technologies

- DC Guns
- Super Conducting RF Guns
- Normal Conducting RF Guns (Low Frequency <700MHz)
- Normal Conducting RF Guns (High Frequency > 1GHz)

State of the Art Photoemission electron source: DC Photoguns

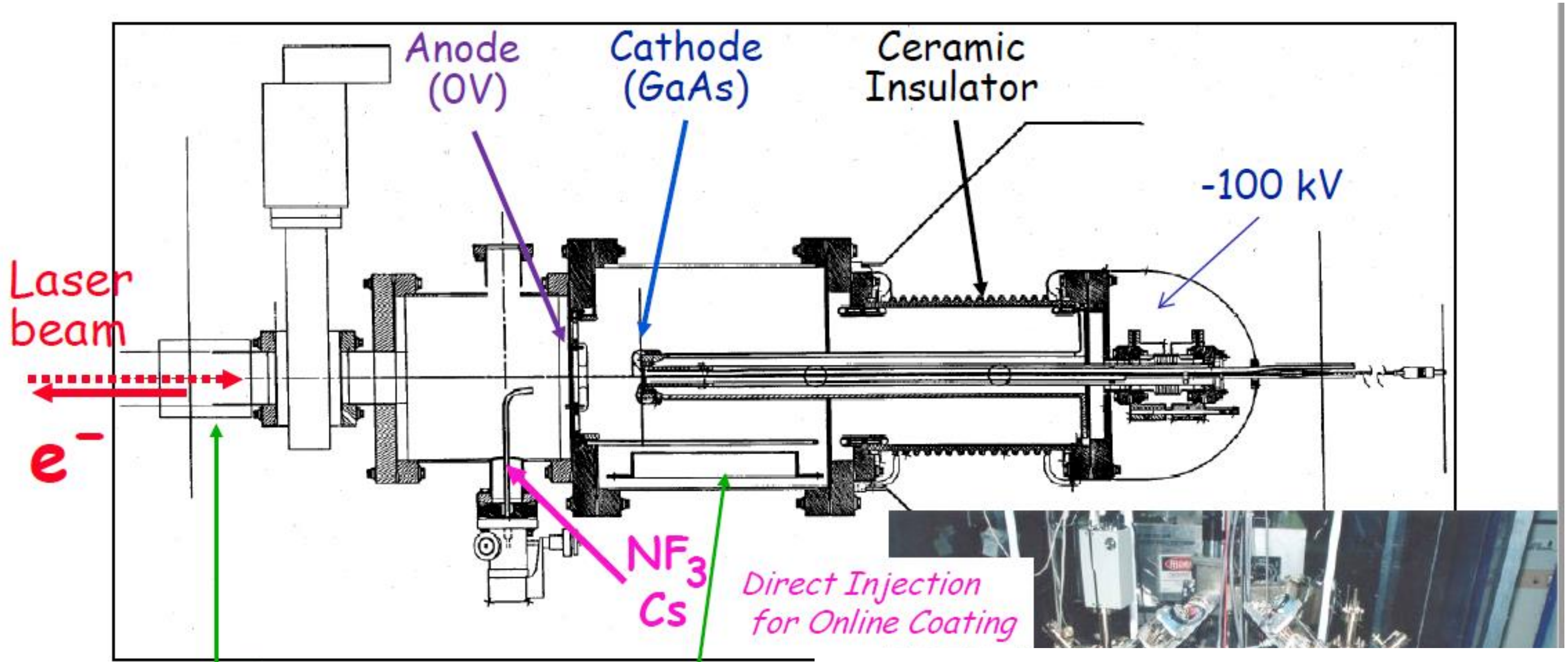
- High-voltage photoguns were first developed at SLAC to deliver polarized electron beams for high-energy physics experiments.
  - The high polarization photogun at JLAB-CEBAF has among the longest lifetimes, measured at 550 beam hours at an average current of 100 μA (10^{-11} Torr)



- Pros
  - DC guns reliably operated at 350 kV (JLAB) for many years, ongoing
  - Excellent vacuum performance
  - Compatible with most photo-cathodes (Only one used with GaAs).
  - Preferred of high average current

- Challenges
  - Difficulty to scale to higher average current (100mA) due to lifetime issue
  - Difficulty to meet brightness and high charge bunch with DC voltage (field emission)

CEBAF (Jlab) Polarized DC Photoinjector



NEG coated
beampipe

Non evaporable getter pumps (NEG)
4,000 liter/s pump speed ⇒ ~410^{-12} mbar

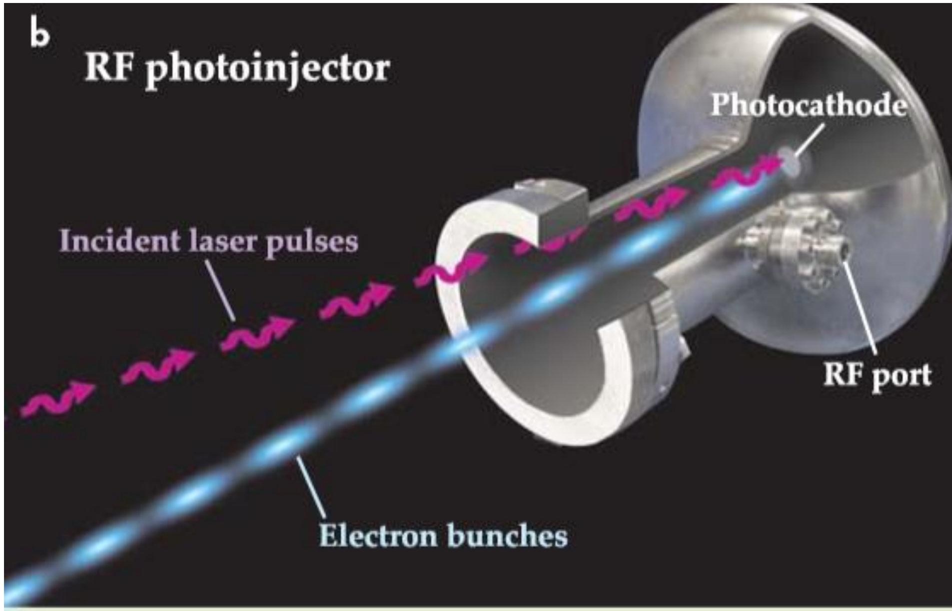
↑

Mandatory to prevent Photocathode early aging

Polarized injector for CEBAF
Design – DC
DC Voltage – 250 kV
Cathode material – GaAs
Typical electron beam current – 150 μA
Beam structure – 499 MHz, pulsed or CW
Spin polarization > 70%

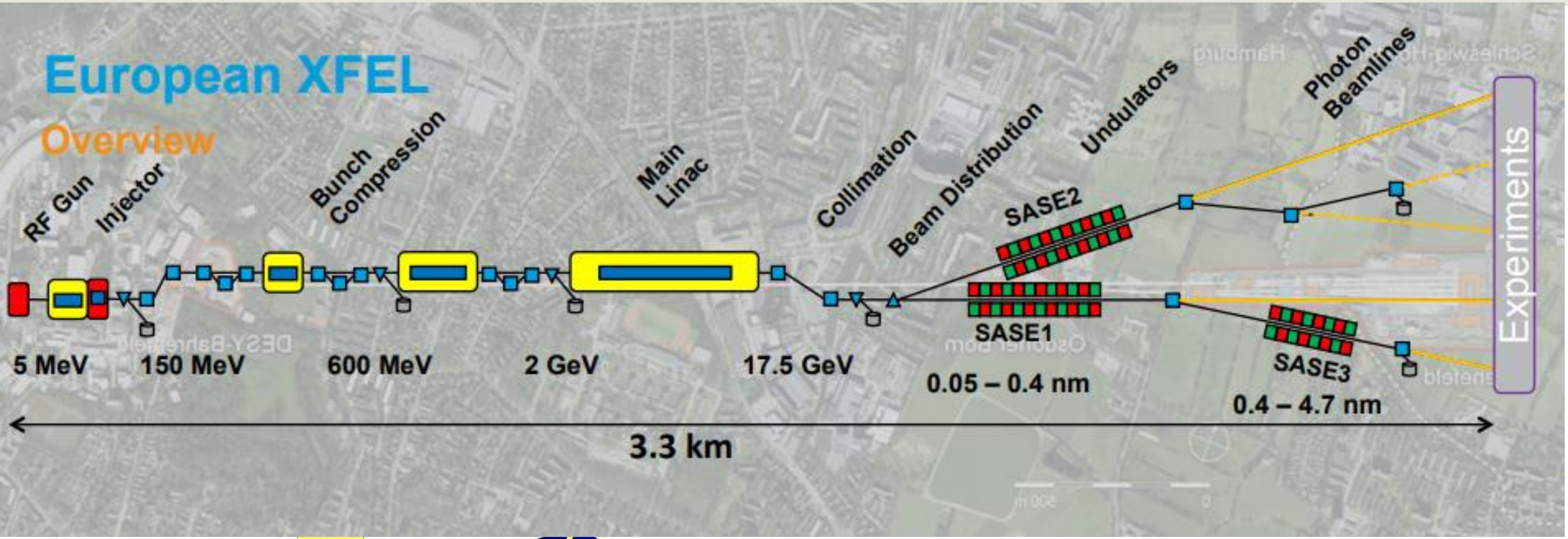
State of the Art Photoemission electron source: RF photo-injectors

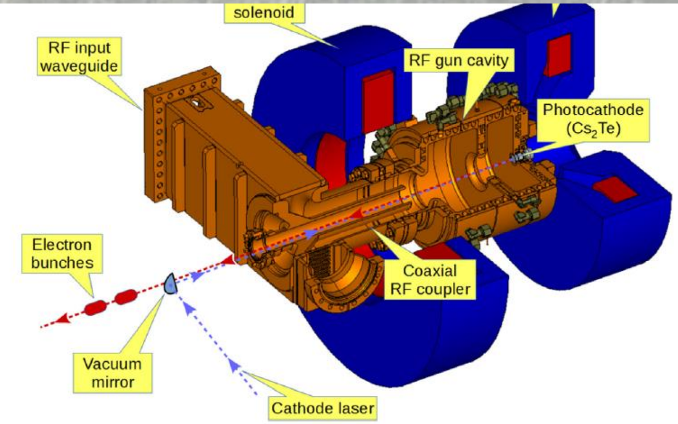
- Two technology either normal-metal or superconducting cavities to generate electron beams.
- RF photo-injectors, typically chosen to generate much higher bunch charge than is achievable through DC photo-guns, also have less stringent vacuum requirements.
  - copper and magnesium are the predominant technology (at low duty factors) for light sources requiring high peak brightness.
- The high accelerating gradient in normal-metal RF photo-injectors produces a low-emittance beam



- Challenges
  - Difficulty to reach high average current
  - Getting sufficient RF power into the photo-injector accelerating cavities without overheating and damaging the system

DESY-XFEL





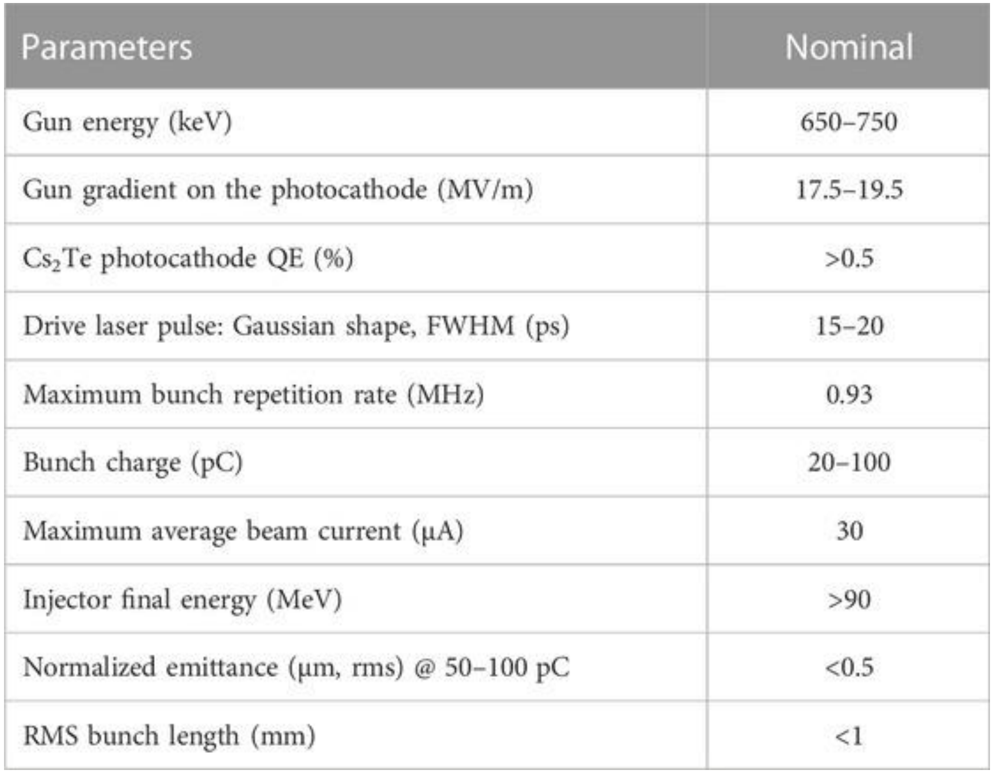
10 years of pioneering X-ray science at the Free-Electron Laser FLASH at DESY

Jörg Rossbach, Jochen R. Schneider, Wilfried Wurth

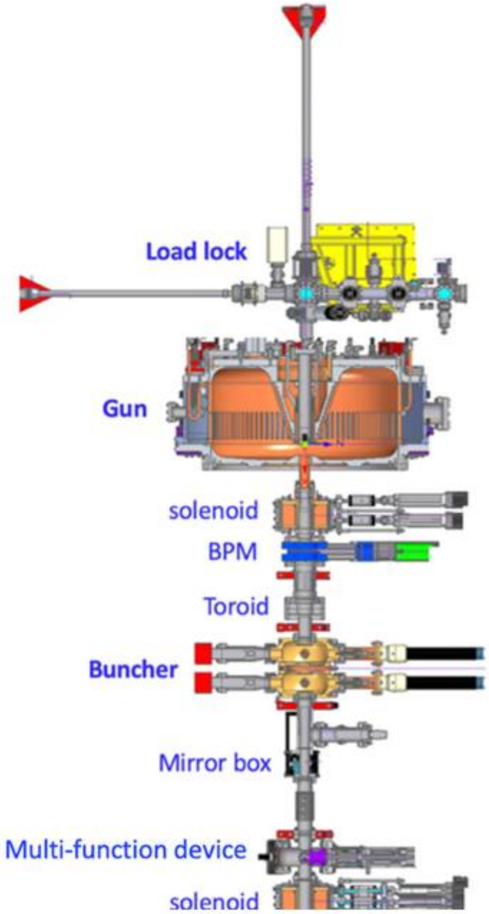
Physics Reports 808 (2019) 1–74

LCLS-II Photocathode

- Normal Conducting RF Gun operation at 185.7 MHz



Parameters	Nominal
Gun energy (keV)	650–750
Gun gradient on the photocathode (MV/m)	17.5–19.5
Cs_2Te photocathode QE (%)	>0.5
Drive laser pulse: Gaussian shape, FWHM (ps)	15–20
Maximum bunch repetition rate (MHz)	0.93
Bunch charge (pC)	20–100
Maximum average beam current (μA)	30
Injector final energy (MeV)	>90
Normalized emittance (μm, rms) @ 50–100 pC	<0.5
RMS bunch length (mm)	<1



Future of electron Sources

- https://science.energy.gov/~/media/bes/pdf/reports/2017/Future_Electron_Source_Worskhop_Report.pdf
- Content includes:
  - Scientific needs for electron sources
  - Science and Technology of electron Generation
  - CW Electron Sources
  - Pulsed RF Photocathodes
  - Novel Electron Sources

FUTURE OF
ELECTRON
SOURCES

Report of the Basic Energy
Sciences Workshop on the
Future of Electron Sources

September 8-9, 2016
SLAC National Accelerator Laboratory
Menlo Park, CA 94025

U.S. DEPARTMENT OF
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