Particle sources
Part I:
Electron sources

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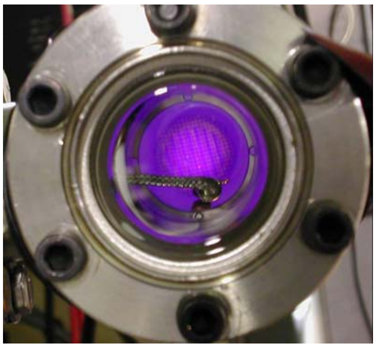
- Electron emission properties and electron sources
  - introduction to some concepts
  - thermal emission
  - field emission
  - photon induced emission
  - secondary electron emission
- Positron source



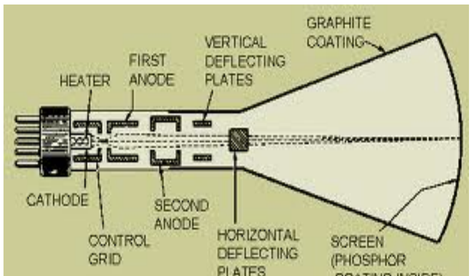
Motivation:

Electron emitter (electron source) is needed for different kind of applications:

- Electron guns: electron **beam** with precise kinetic energy
  - television "tubes", displays
  - electron microscope
  - **particle accelerators**
  - (e-beam) welding
  - charge neutralizer (for space craft for example)
- Electron emission (not a focused beam) for plasma production

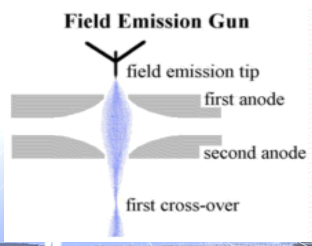
Step 1: electron production (emission)
- different emission mechanism can be used

Step 2: electrons are accelerated for further use (DC or RF)



http://www.tpub.com/neets/book16/71.htm

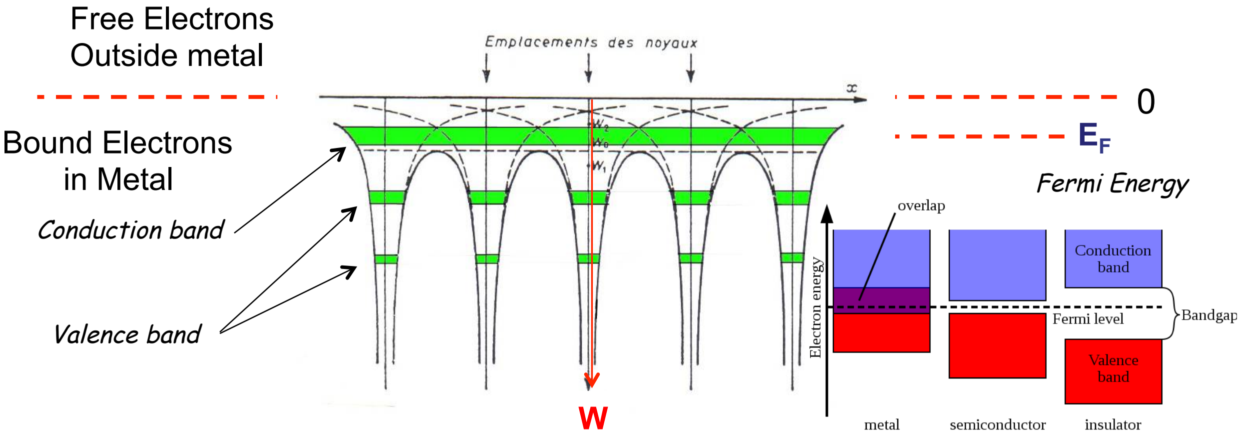
Hot cathode is the main source of electrons in electron guns



http://advressys.com/analytic/sem.htm

Work Function of electrons in metals:

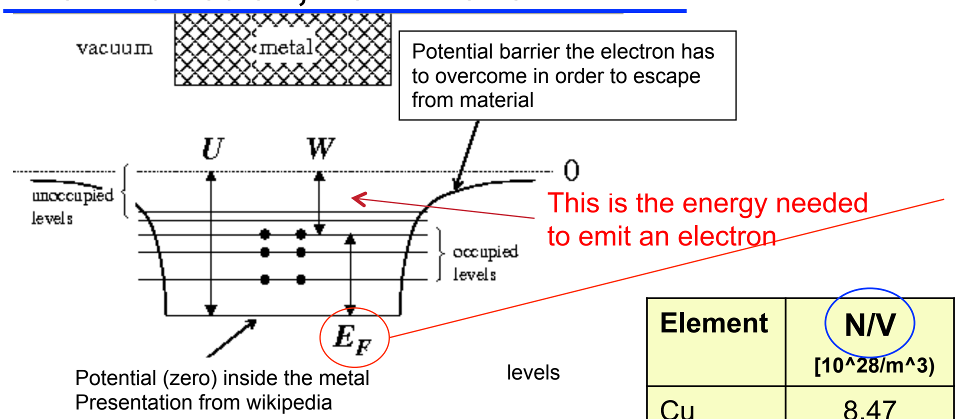
- The **Work Function W** is the minimum energy needed to remove an electron from a solid surface



Drawing Extracted from : J.Arianer lectures

- In a metal, some electrons are populating the conduction band
- The Fermi energy E_F is the energy of electron on the topmost occupied quantum level at T = 0˚K

Work function, Fermi level:



Presentation from wikipedia

$$\varepsilon_F = \frac{h^2}{2m}\left(\frac{3}{8\pi}\frac{N}{V}\right)^{2/3}$$

Element	N/V [10^28/m^3)
Cu	8.47
Ag	5.86
Au	5.90
Be	24.7
Mg	8.61
Fe	17.0
Mn	10.9
Zn	13.2
Al	11.7
Ga	10.4

Fermi energy [eV]	
Cu	7.00
Ag	5.49
Au	5.53
Be	14.3
Mg	7.08
Fe	11.1
Mn	10.9
Zn	9.47
Al	11.7
Ga	10.4

Work function is the energy we have to give to an electron in order get it out from the material! Originally those electrons have an energy called Fermi energy E_F (at 0 K).

Note: 1 eV corresponds to temperature of 11600˚K . Consequently, the normal temperature has quite modest effect on Fermi level (Fermi energy + temperature effect).

Work Function of electrons in metals (wikipedia):

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 (Min)
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: (Max)	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				

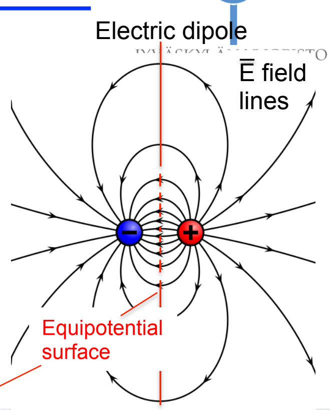
Concept of image charge:

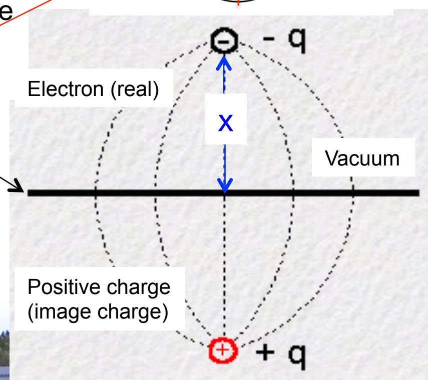
Electrostatic potential and electric field caused by the ***image charge*** is relevant when the charge is close to the surface. Quantum mechanical consideration is needed when the distance between the charge and the surface is of the order of few atomic units or less

Electric field produced by image charge (at the position of electron):

$$\int \bar{E}\cdot\overline{ds} = \frac{q}{\varepsilon_0}$$

$$\Leftrightarrow \bar{E} = \frac{q}{4\pi\varepsilon_0 (2x)^2}$$





Example: Electron close to metal surface.
Distance 10 x Bohr radius (≈ 5E-11 m)

E = 1.4 10^9 V/m

Φ = 0.7 V

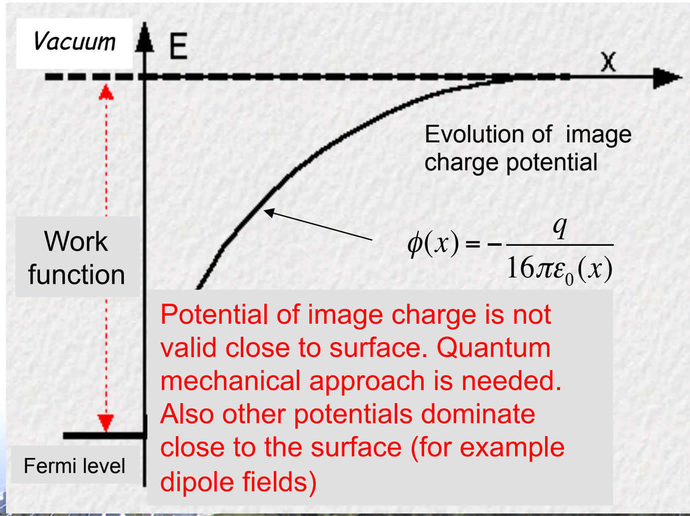
$q\Phi$ = 0.7 eV (potential energy caused by the image charge effect)

As a result of image charge effect: All charges "feel" the metal surface very attractive!

Surface potential: unfortunately not trivial!

The image charge tend to attract the real charge towards the surface. The surface potential, in general, can be very complicated and is beyond the scope of this lecture. ***We just should think that electron has to have enough energy to overcome the surface potential in order to be emitted from the material!***

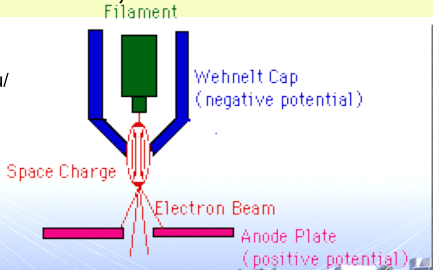
This extra energy can be given by ***thermal heating, photon***,…
the surface potential (also) can be affected by ***external electric field***, the ***work function can be lowered***, etc,.….
As a next step a short review of different electron emissions and concepts…

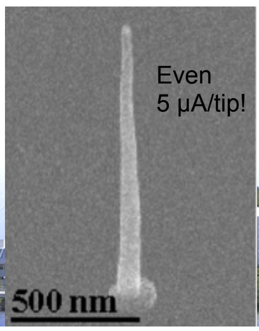


From theory to electron guns:

- The work for “thermal emission” in late 1800’s (for example Edison)
- Identification of electron: 1897, J. Thomson et. al.
- Active experimental (for x-rays for example) and theoretical work for electron emission in 1900-1930: for example Richardson, Lilienfeld, Millikan, Shottky, Nordheim, Fowler,…
- Field electron microscope (FEM): Erwin Muller (1936), basis on field emission, Muller emitters: sharp tips having radius of ≈ 100 nm, high melting point materials are used (such as tungsten).
- Active work in 1950s onwards for development of field emission sources
- Large area field emission sources (1970s): Spindt array
- Presently: development of carbon nanotube based emitters (CNT/CNF), photocathodes,….

http://ncmn.unl.edu/cfem/microscopy/gun.shtml

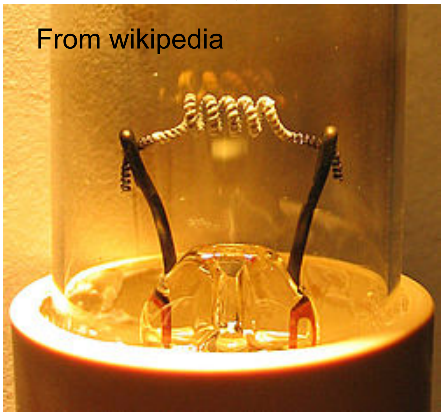


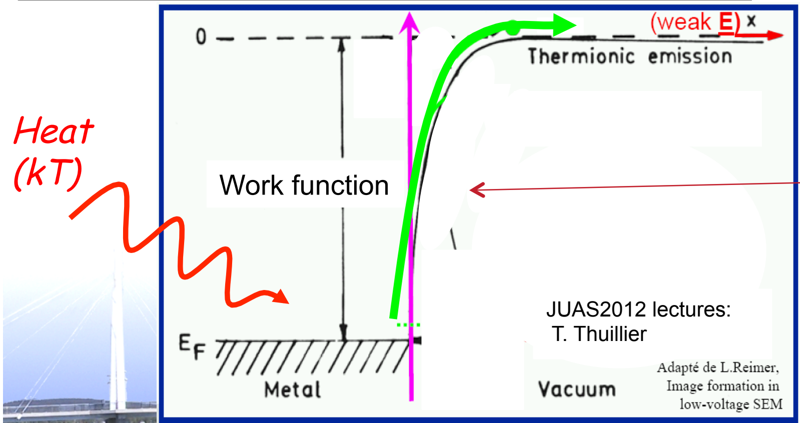


M. A. Guillorn et al., J. Vac. Sci. Technol. B 19(6), Nov/Dec 2001

Thermal (thermionic) emission:

- The most common way to extract/emit electrons from the material is to heat the material to high temperature T (thermionic emission)
- In this heat induced emission the electrons ***(high energy tail of distribution)*** have enough energy to overcome the surface potential barrier (work function)





The extra energy needed for emission is given in this case via heat (i.e. by heating)!

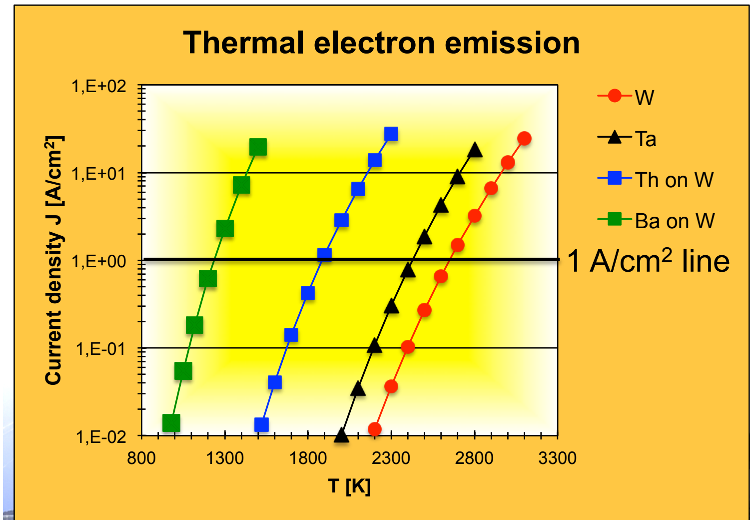
Electron current density of thermionic emission:

The Thermal emission current density is defined by the Richardson (-Dushman) equation

- J current density (A/m^2)
- A_G Richardson constant
- W =q·φ work function

$$J = A_G T^2 e^{\frac{-W}{kT}}, \quad \text{where } A_G = A_0 \lambda_R$$

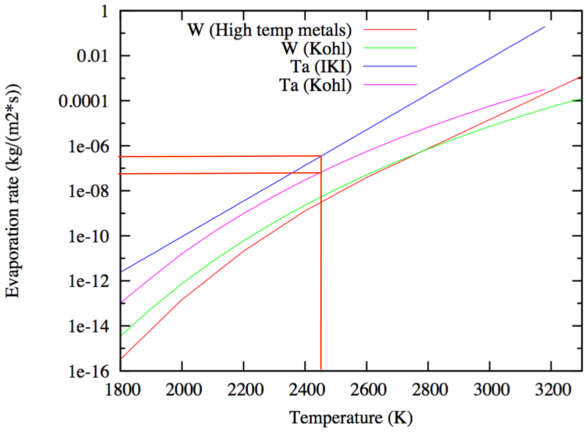
$$A_0 = \frac{4\pi m_e k^2 e}{h^3} = 1.20173 \times 10^6 \ \text{Am}^{-2}\text{K}^{-2}$$



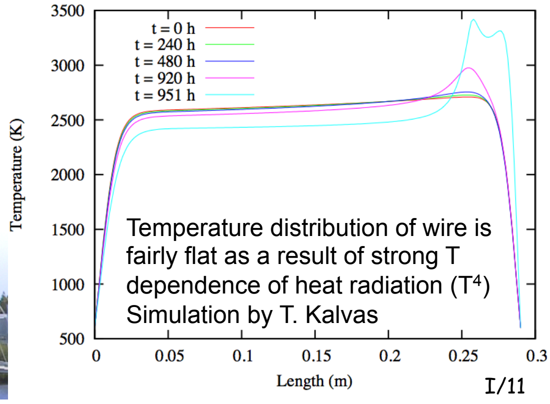
Material	W	λ_R
Molybdenum	4.15	0.46
Nickel	4.61	0.25
Tantalum	4.12	0.50
Tungsten	4.54	0.50
Barium	2.11	0.50
Cesium	1.81	1.33
Iridium	5.4	1.42
Platinum	5.32	0.27
Rhenium	4.85	0.83
Thorium	3.38	0.58
Ba on W	1.56	0.01
Th on W	2.63	0.02
Thoria	2.54	0.02
Cs-oxide	0.75	0.00008
TaC	3.14	0.00
LaB6	2.7	0.24

Problems with filaments (emitting electrons)

Some considerations:
- Evaporation of filament material
- Filament defects: cracks, changes in size
- Chemical reactions, poisoning of filament
- Sudden burning/interruption
- Sputtering



For example JYFL light ion source:
- 2 parallel Ta wires, total filament current ≈ 140 A, diameter 1.5 mm, 80 mm in length
- Emission current ≈ 4 A, corresponds to current density of 1.1 A/cm^2. Richardson-Dushman gives the T estimation of about 2440˚K.
- Estimated evaporation rate ≈ 3.3 mg/day, mass decreases 10 % in 2 months. The operational life-time of this filament is < 2 weeks



Example of a Thermionic Electron Gun:

Electronic Microscope source

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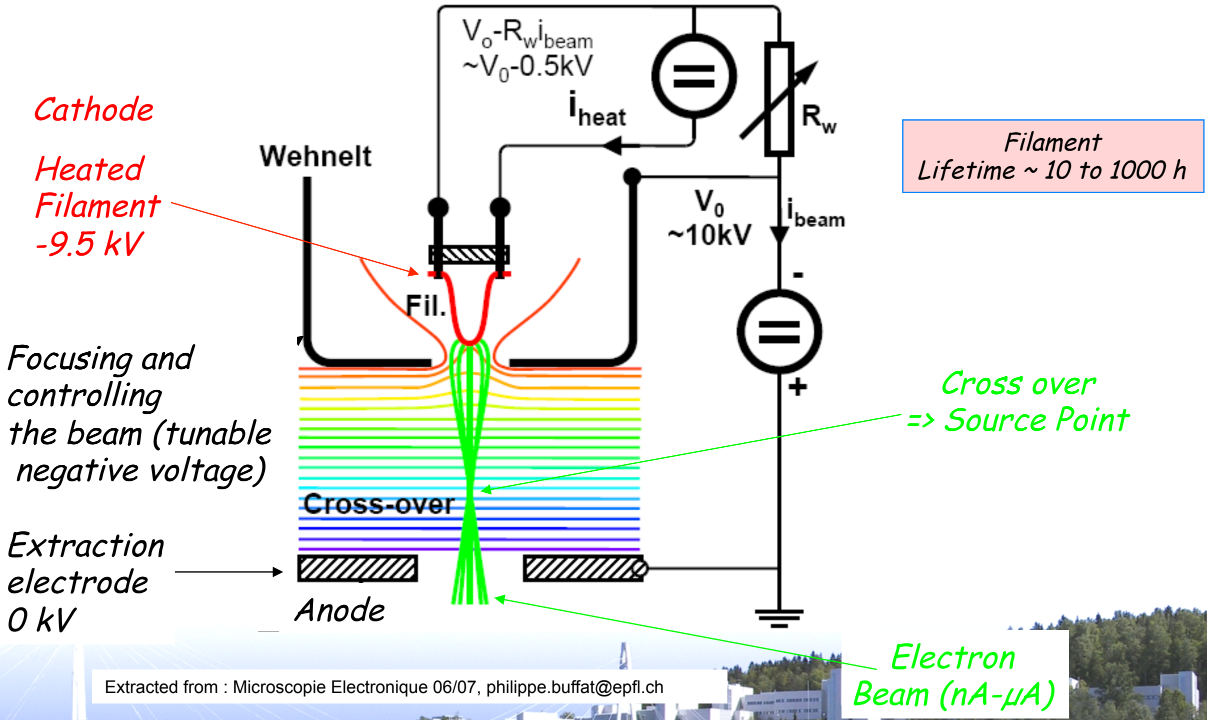


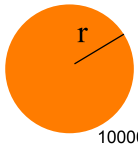
Extracted from : Microscopie Electronique 06/07, philippe.buffat@epfl.ch

Field Electron Emission:

- In the presence of a very strong electric field (E~1 GV/m) , the surface potential barrier is thin enough to allow electron emission through <u>Tunnel Effect</u>
- The associated emission is ruled by the Fowler-Nordheim theory
- It is a cold cathode emission => no metal heating is required

- Lets study how the electric field on the surface of conducting sphere changes with radius.
- Lets also assume that the sphere is far from the ground and its is connected to HV-supply providing the constant voltage of 10 kV.

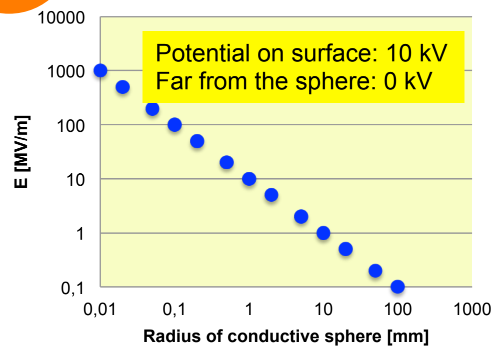
$$V = \phi_{sphere} - \phi_{\infty} = -\int_{r=\infty}^{R} \overline{E} \cdot \overline{dr}$$



$$\int \overline{E} \cdot \overline{ds} = q / \varepsilon_0$$

sphere

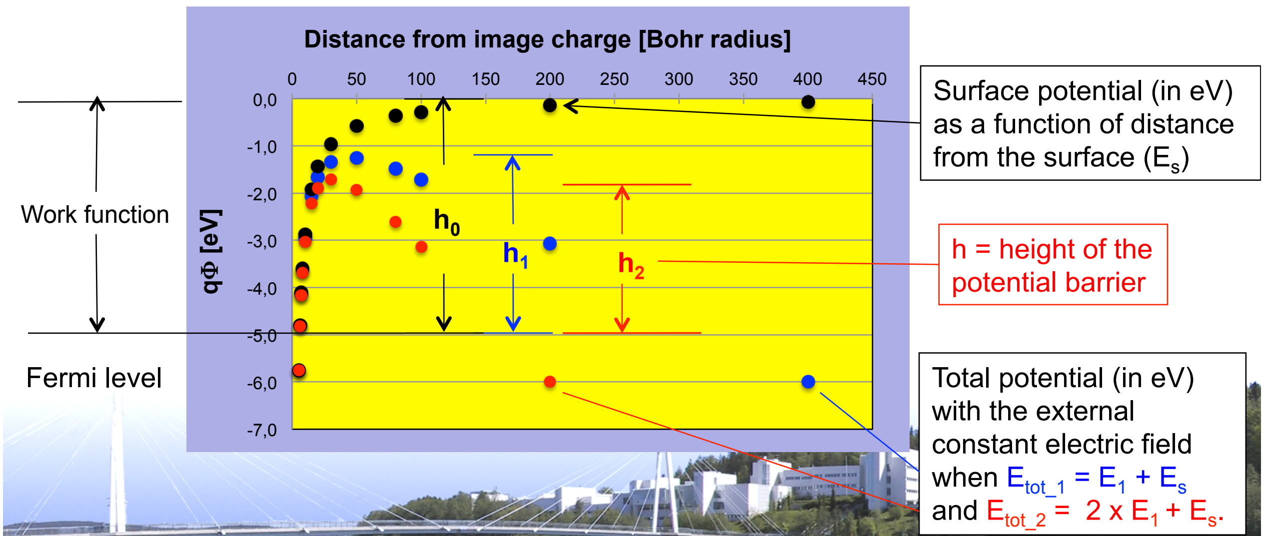
The graph shows E-field on the surface of sphere as a function of the radius of sphere!
As the graph shows very large E-field can be reached with small structures!
This is the idea of field electron (FE) emission and is used in the FE applications!



Potential structure with external electric field:

Note: this is a strongly simplified treatment just to present the concept! In this presentation the image charge potential is used to get nicely behaving potential structure. A constant external electric field is added to image charge field in order to see its effect to total potential structure (presentation in eV)!

Note: surface has surface potential (also without the image charge concept), which binds the electrons and prevents them from escaping from material.



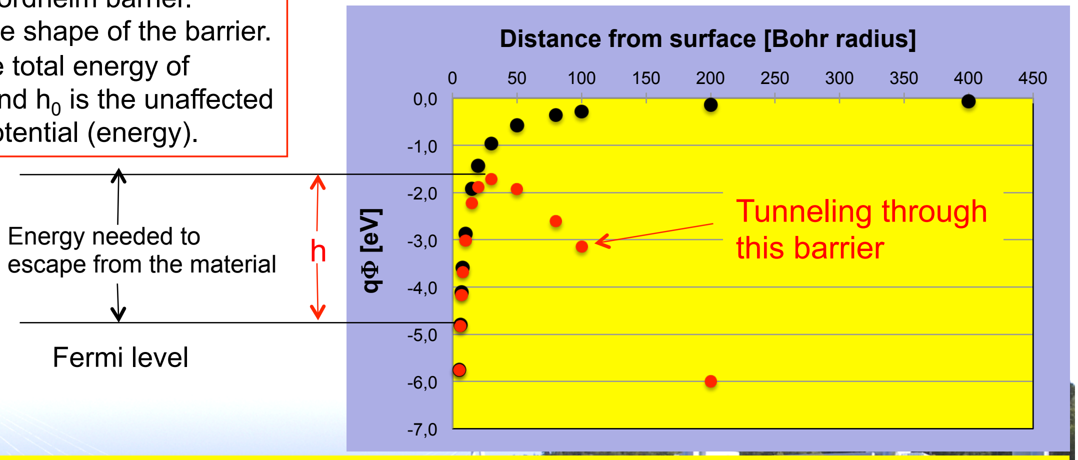
Schottky-Nordheim barrier and tunneling:

Field emission has been explained by quantum tunneling
More realistic barrier (like M(x)) + Schrödinger equation: very difficult, if even possible

An example: Tunneling “speed” and probability depends on the height *h*, which depends on the external electric field E and work function Φ

$M(x) = h_0 - eEx - e^2/(16\pi\varepsilon_0 x)$
Shottky-Nordheim barrier. Defines the shape of the barrier. M(x) is the total energy of electron and h_0 is the unaffected surface potential (energy).

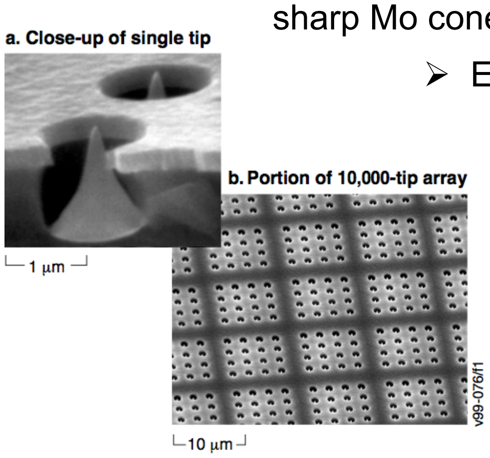
$J \propto E^2 e^{(-\phi^{3/2}/E)}$ Emitted current density



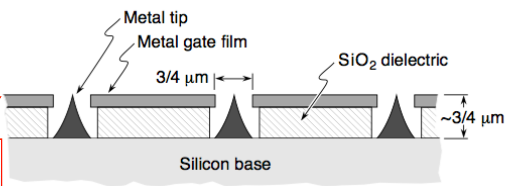
In field emission the surface potential is strongly modified by external electric field!

Spindt Array:

- Field Emitter Array (FEA) consist of large amount of small field electron emitters.
  - The original form of array (Spindt Array) has small, sharp Mo cones
    - Each tip can emit current from nA to mA!
      - Provides mechanism for controlled high current (even above A) with low power.
        - Limitations from heating and space charge effects (check with packing density of up to $5 \cdot 10^7$ tips/cm^2,1 - 100 μA/tip)

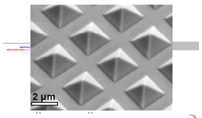


V. M. Aguero and R. C. Adamo, 6th Spacecraft Charging Technology Conference, AFRL-VS-TR-20001578, 1 September 2000

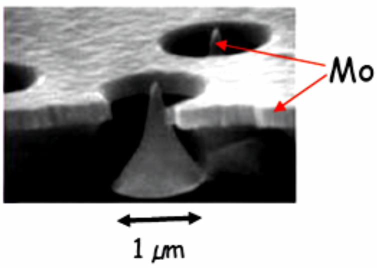


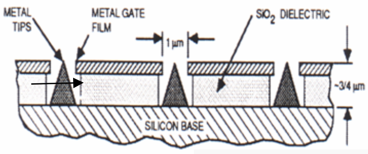
- The emission level is controlled by adjusting the gate voltage (< 100 V)
- Capacity of up to 100 μA/tip has been demonstrated!

Field Emission Array GUN:

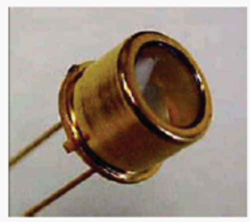


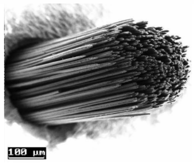
- Built on Si base substrate, using semi-conductor technology
  - small sharp structures generating high electric fields
  - Generation of large surface of Field emission array
  - At PSI: 50000 Mo spikes (tips) on a Ø 1 mm disk
  - Requires ultra high vacuum level

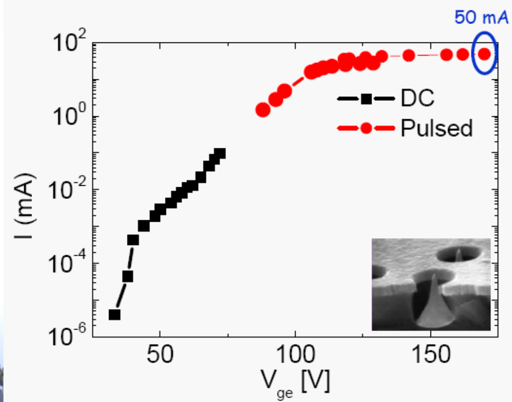




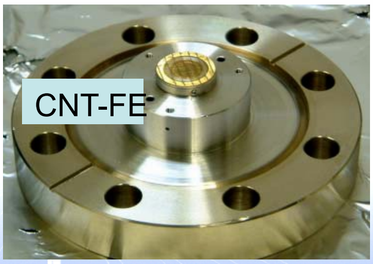
PSI







I-V curves in DC and pulsed regime for a Mo-tip FEA



Extracted from : J.Arianer lectures

A carbon nanotube field emission cathode:

Y. Ohkawa, et. al., The 32nd International Electric Propulsion Conference, Wiesbaden, Germany

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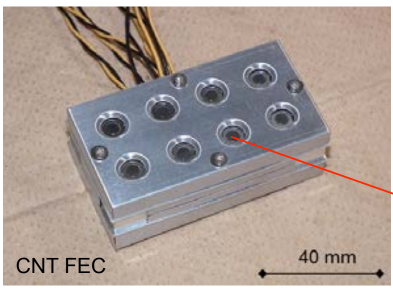
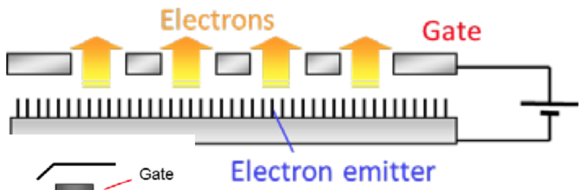
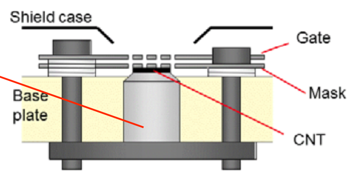
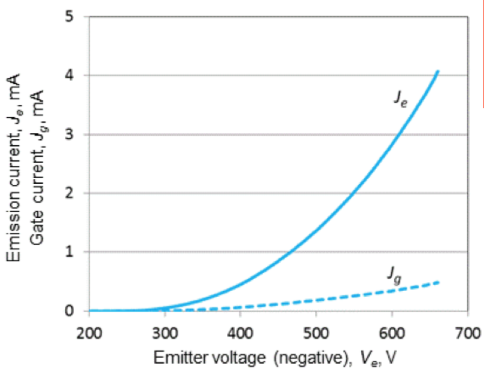


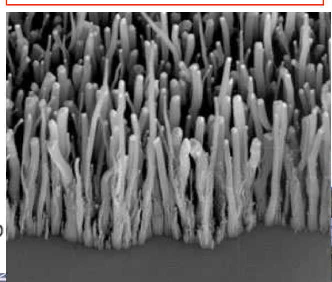




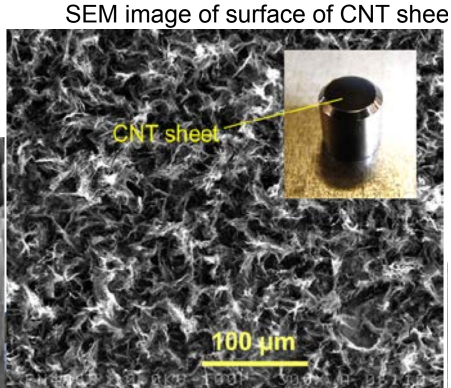
Sharp structures generating strong electric fields



CNT can be used as an electron emitter for several mA/cm²



SEM image of surface of CNT shee



Shottky effect:

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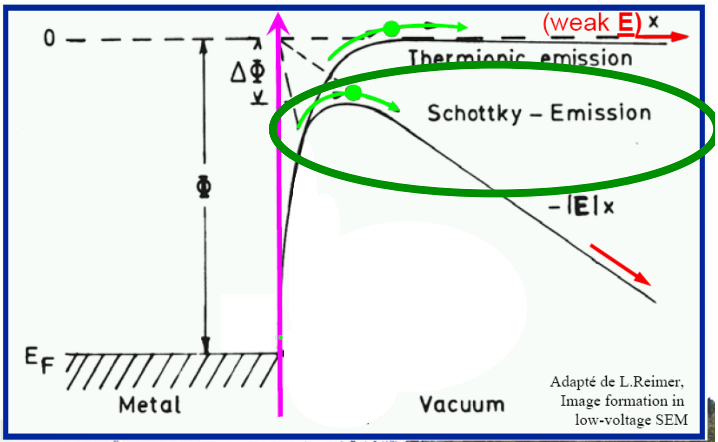
- The hot filament emitting electrons is negatively biased
- This creates an electric field E which accelerates the electrons from filament
- It also lowers the surface barrier by amount of ΔW and consequently increases the emission current. This is known as the Schottky effect.

Modified Richardson equation:

$$J = A_G T^2 e^{\frac{-(W-\Delta W)}{kT}}$$

Note: This expression is quite accurate for electric fields lower than about 10^8 V/m. If higher see section Field Electron Emission.



Photon induced electron emission/Photoelectric effect:

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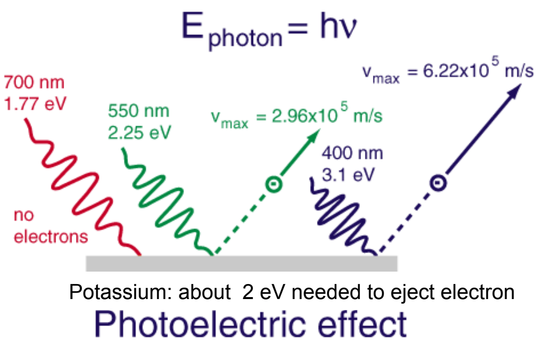
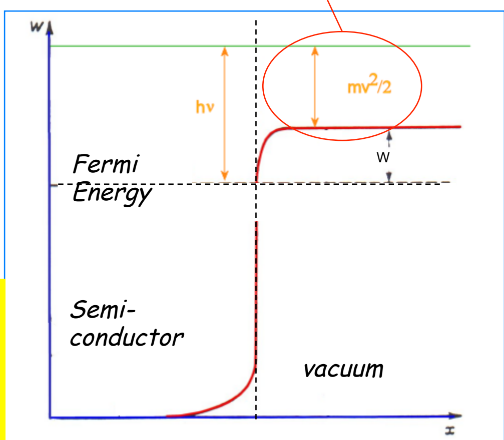
- The energy to emit an electron is given by a photon
  - The energy of photon has to exceed the workfuntion
    - The excess energy is transfered as a kinetic energy of electron

$$E_{kin} = h\upsilon - W$$

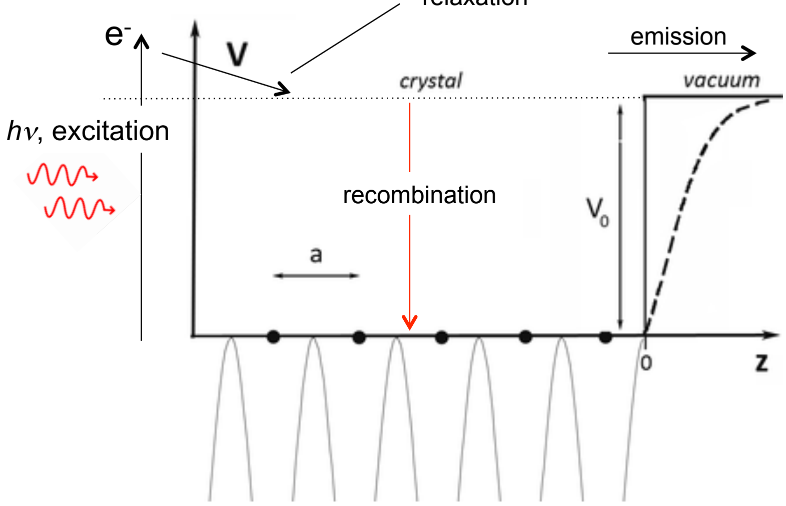


http://hyperphysics.phy-astr.gsu.edu/hbase/mod1.html

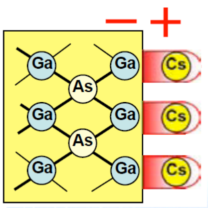


In this case the extra energy needed to get an electron out from the material is given by the photon. Energy of photon has to be at least the work function W

Another simple model….



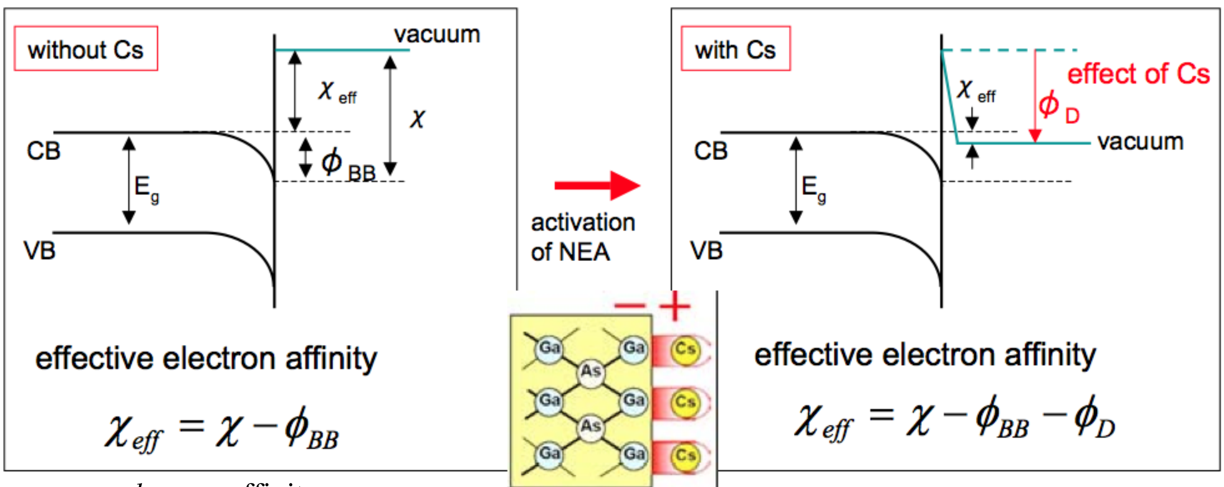
At a real surface the potential is influenced by image charges and the formation of surface dipoles.



Some added elements form dipoles at the surface. This can decrease the vacuum level.

Negative Electron Affinity (NEA) –materials:

- Some materials can have vacuum level below the conduction band (CB) level (typically semiconductors)
- Electrons are excited to the conduction band by photons. In the case of NEA material this state lies above the vacuum level.



χ = *electron* affinity

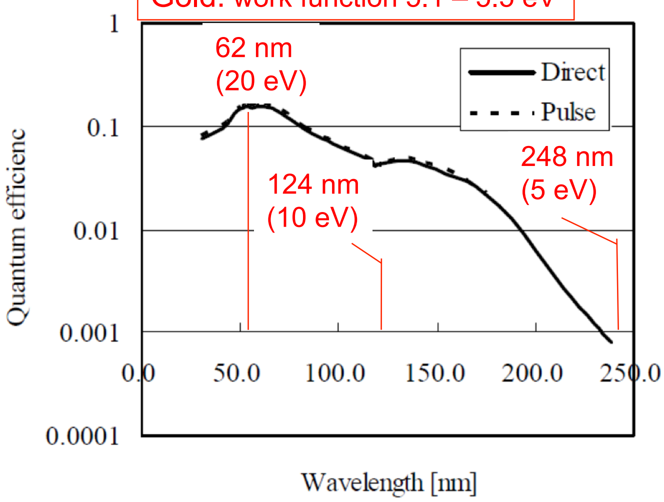
ϕ_{BB} = band bending potential

Quantum efficiency of material:

As soon as the threshold energy (i.e. work function) is exceeded the emission propability is a function of wave length (i.e. the energy of photon)

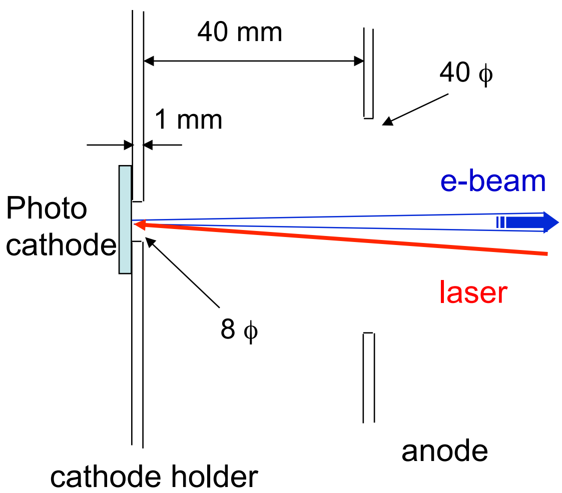
$$E_{photon} = \frac{hc}{\lambda e} \text{ (in eV)}$$

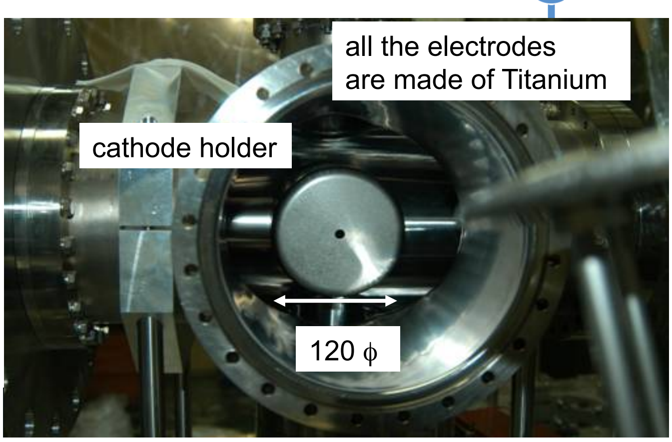
Gold: work function 5.1 – 5.5 eV

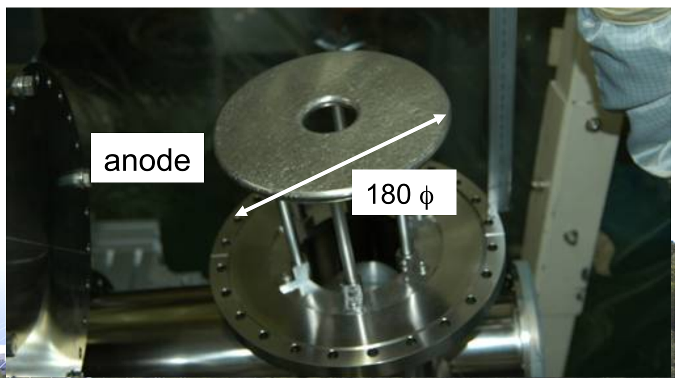


K. Nitta et al., Int. Symp. on Discharges and Electrical Insulation in Vacuum, 2010

Example of a Photocathode DC GUN (JAEA-ERL):







The electric field is 5 MV/m.

Goal is 50 mA DC beam

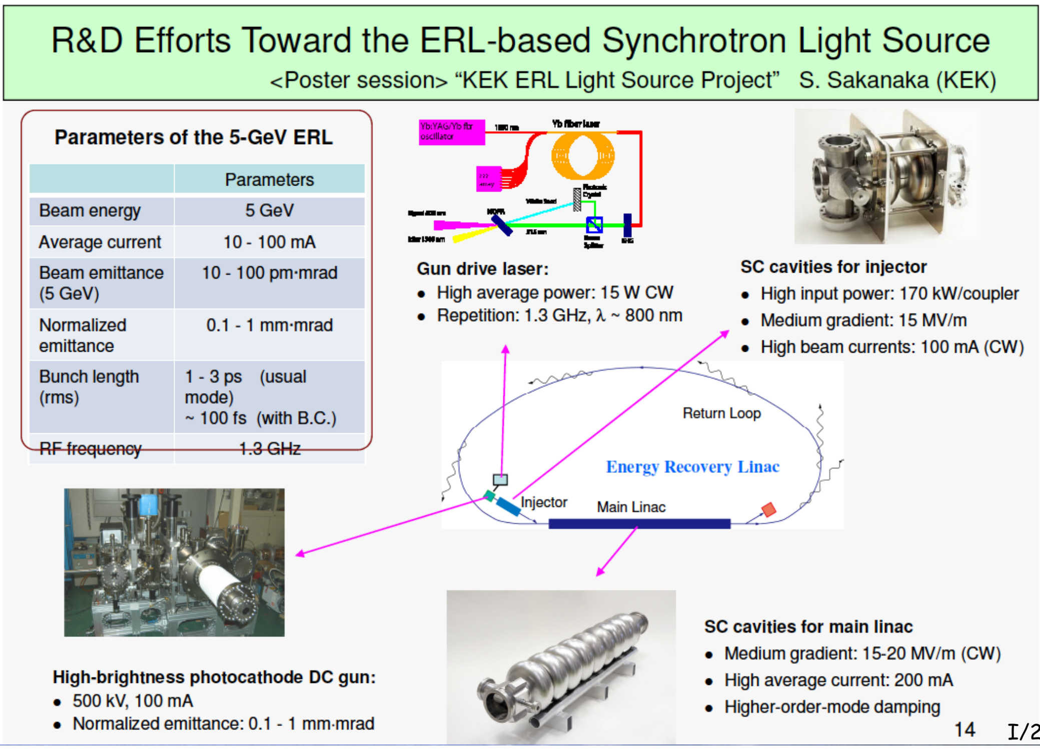
http://indico.cern.ch/getFile.py/access?contribId=10&sessionId=2&resId=0&materialId=paper&confId=15495

Slide is from : N. Nishimori, JAEA, Japan

JAEA-ERL Photocathode DC GUN:

This electron gun is developed for the need of Synchrotron Light Source

Slide from presentation: Hiroshi Kawata, ERL09, 8-12/June/2009, Cornell University



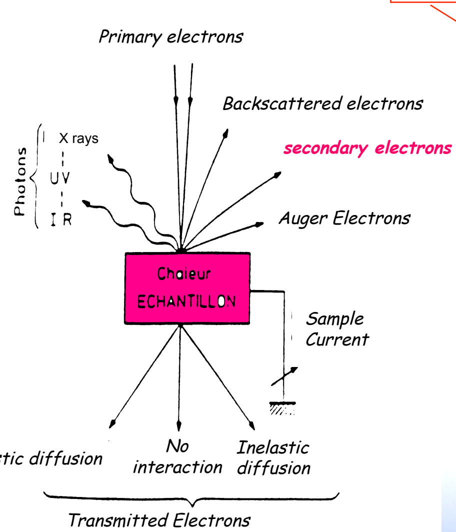
Secondary electron emission:

The incident electron can produce several different effects when interacting with the material surface:

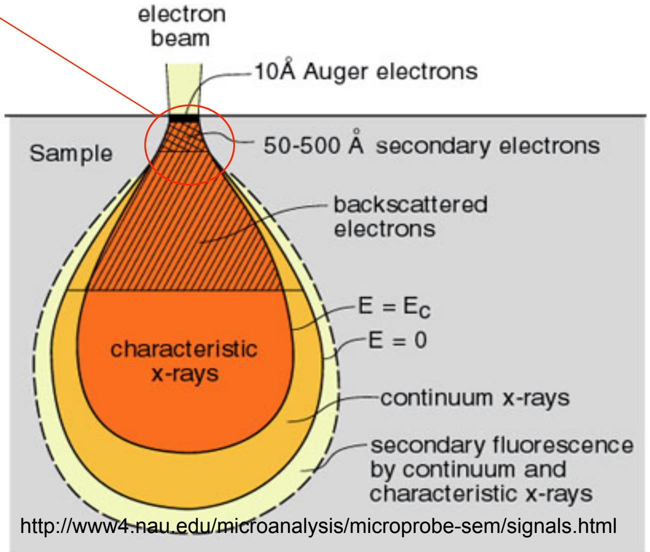
- Secondary electrons
- Backscattered electrons
- X-rays, etc,…

$$x(\mu m)=\frac{0.1E_0^{1.5}}{\rho}$$, penetration depth, E_0 in keV, ρ in g/cm^3

50-500 Å in Al requires electron energy of 0,25 – 1,3 keV

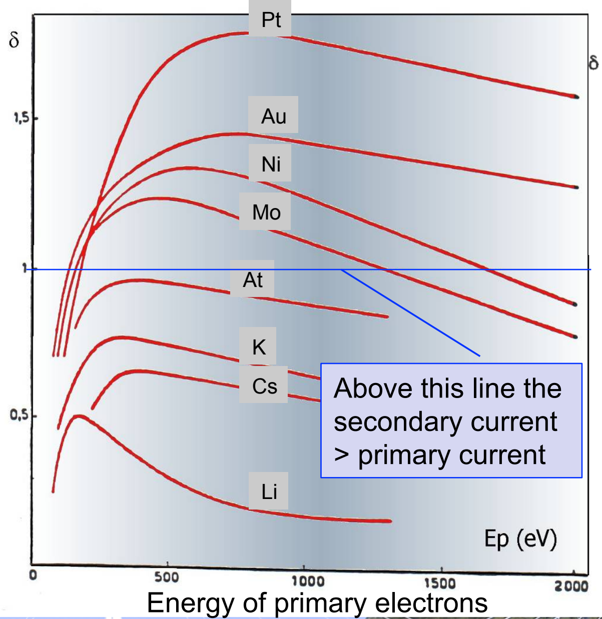


Interaction volume of different effects

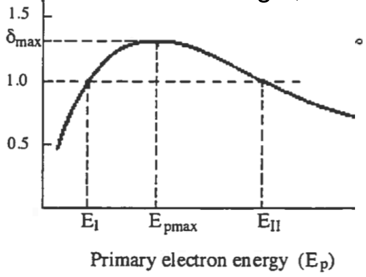


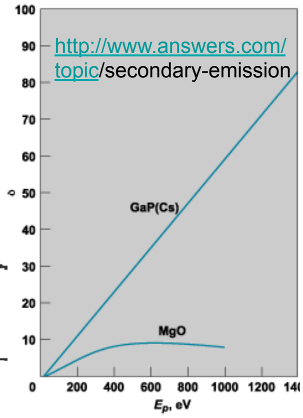
Yield of secondary electron emission:

SE Yield: $\delta = \frac{N_{e_s}}{N_{e_p}}$ $\frac{\textit{Secondary electrons}}{\textit{Primary electrons}}$



Yield depends on:
- Material
- Energy
- Incident angle,…

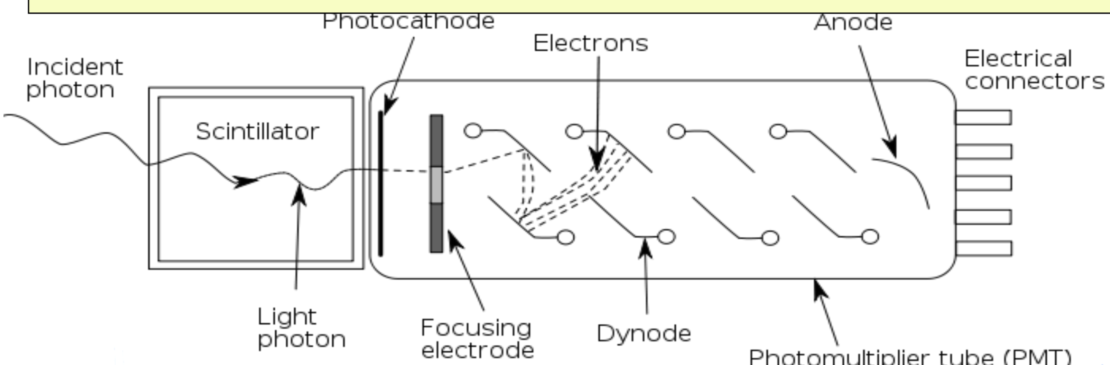




Element	δ_{max}	E_p (eV)	E_I (eV)	E_{II} (eV)
Cu	1.3	600	200	1500
Fe	1.3	600	200	1500
Pt	1.8	700	350	3000
Ta	1.3	600	250	>2000
Compounds	δ_{max}	E_p (eV)		
NaI (crystal)	19	1300		
Al2O3 (layer)	2 to 9			
MgO (crystal)	20 to 25	1500		

Photomultiplier:

- Incident photon strikes the photocathode
- Electron is emitted via photoelectric effect ($E_e \geq$ work function!)
- The electron is accelerated towards the dynode made of material having high yield of secondary electron emission
- These electrons are accelerated towards the second dynode,….
- Exponential increase of current. At the end the current signal is detected from anode



http://en.wikipedia.org/wiki/File:Photomultipliertube.svg

Positron sources:

JYVÄSKYLÄN YLIOPISTO

- Dirac proposed in 1928 that the electron can have a counterpart (antielectron) having positive charge and negative energy
- Positron was observed by D. Skobeltsy in 1929
- Positron is an antiparticle of electron having charge e+ and same mass as electron
- Collision of electron and positron results in two gammas (2 x 511 keV): annihilation
- Positron can be generated by positron emission or by pair production

Positron emission:

- *Nuclear decay (β+) where proton in a nucleus is converted into neutron – reaction releases positron and neutrino*
- *Positron collides immediately with electron resulting in an annihilation. An application: Positron Emission Tomography (for example FDG)*

Pair production:

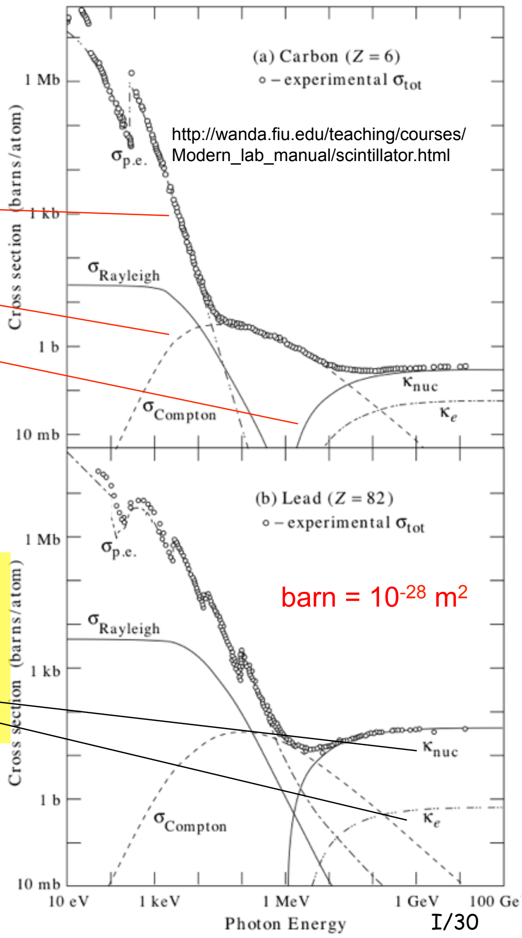
- *Pair production is possible when the photon energy exceeds the combined rest mass of electron and positron, i.e. $h\nu \geq 2 \times m_e c^2$*
- *Reaction:*

$$h\nu \rightarrow e^+ + e^-$$

Pair production (production of positron-electron pair):

Three main photon-material interaction channels:

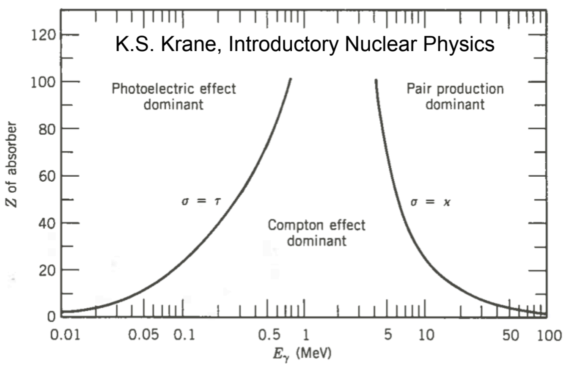
- Photoelectric effect
- Compton scattering
- Pair production



http://wanda.fiu.edu/teaching/courses/Modern_lab_manual/scintillator.html

- Pair production is a dominant process at the energies above some MeV's
- Cross section increases with the atomic number Z

barn = 10^{-28} m^2

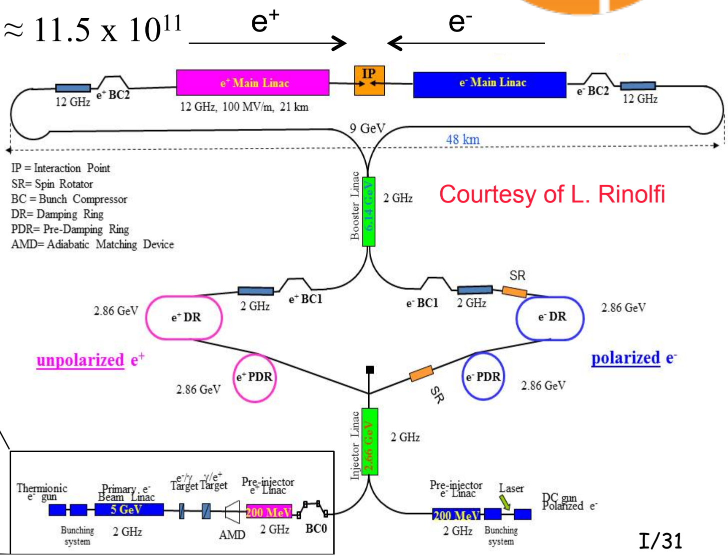


Third body for momentum and energy conservation:

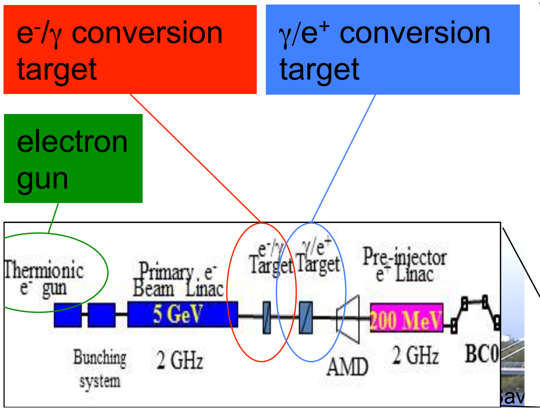
- Nucleus
- Electron

An application using positrons: CLIC

- CLIC (Compact LInear Collider) is a proposed future e^+e^- collider, designed to perform electron-positron collisions
- e^+e^- colliders can be used to determine parameters with a much higher precision than proton colliders (LHC).
- Allows physicists to explore a new energy region in the multi TeV range beyond the capabilities of today's particle accelerators.
- Number of positrons/pulse (at IP) ≈ 11.5 x 10^{11}
  Flux: 1.1 x 10^{14} e+/s



One possible concept



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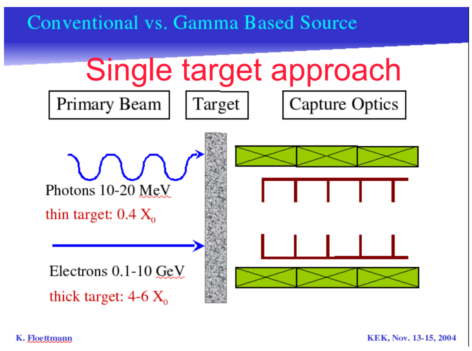
Schemes to produce positrons for CLIC (1/3):

A. Conventional source: e- beam produces Bremsstrahlung which results in pair production (single target/hybrid target)
B. Gamma-based source via undulator-based radiation
C. Gamma-based source via laser backscattering

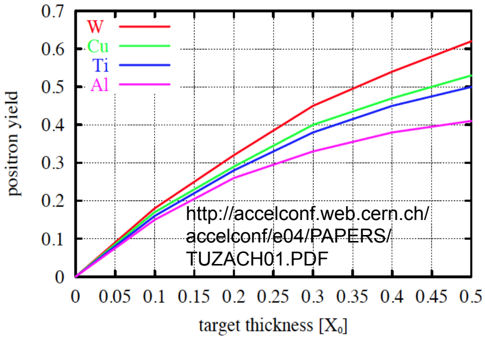
A: Conventional source:

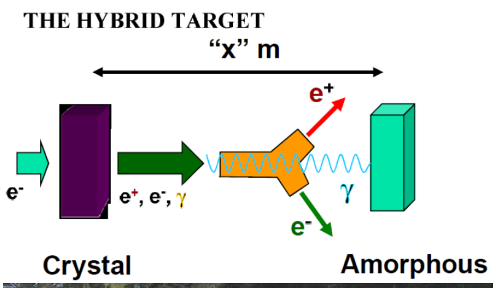
- Single target: Limitation from energy deposition of beam and shock waves
- Hybrid target approach diminishes afore-mentioned problems
- Target material and thickness has to be optimized to maximize the production yield and the escape probability of positron from target surface



$$X_0 = \frac{716 \cdot A}{Z(Z+1)\ln(287/\sqrt{Z})}$$
in (g/cm^2)

X_0: Radiation length





H. Koivisto, JUAS2013,

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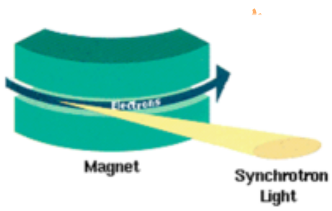
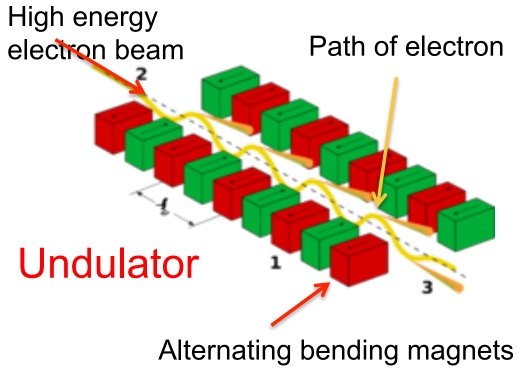
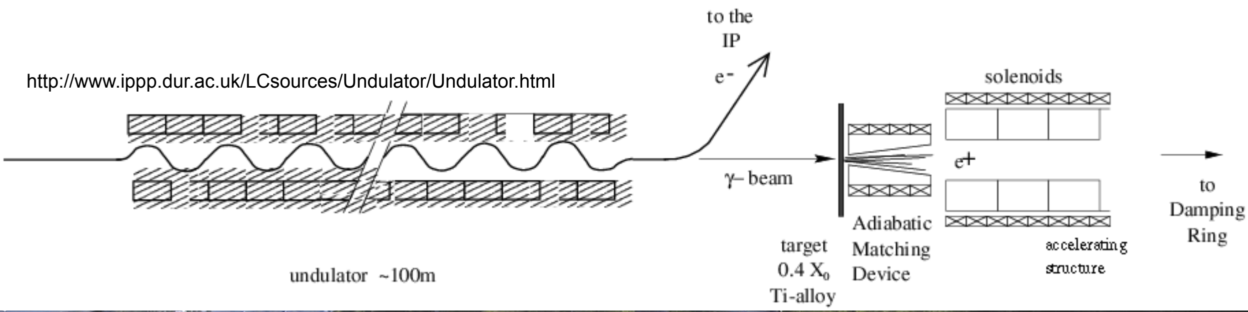
Schemes to produce positrons for CLIC (2/3):



Undulator based γ-radiation: Synchrotron radiation is produced when ultra-relativistic charged particle is radially accelerated in magnetic field B - for example by bending magnet or undulator. Out of those two the undulator can produce orders of magnitudes higher flux than the bending magnet (N2 times higher where N is the number of undulator periods.



http://www.ippp.dur.ac.uk/LCsources/Undulator/Undulator.html



Schemes to produce positrons for CLIC (3/3):

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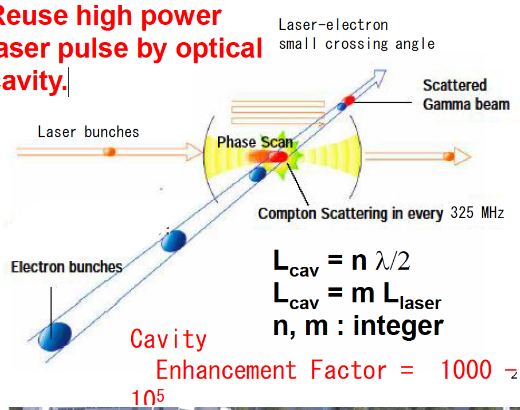
Compton backscattering is the most desirable option for producing positrons for positron-electron collider (both beams are polarized which improves the reaction cross section in the interaction point IP). This scheme includes:

- 1 GeV electron beam which in optical resonator interacts with
- circular polarized laser beam resulting in
- circularly polarized gamma photons via Compton backscattering
- these photons are let to interact with target material producing polarized positrons and electrons via pair production

Reuse high power laser pulse by optical cavity.



Drawback: requires electron bunches and laser pulse intensities that are not, at present, available with the existing technologies. Consequently would require stacking/storage ring.

All three schemes will require strong and active R&D!