JOINT UNIVERSITY ACCELERATOR SCHOOL

PARTICLE SOURCES

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OUTLINE

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    - Field Emission electron source
    - Photo emission electron source
    - Radio-frequency gun
- **POSITRON SOURCES**
- **ION SOURCES**
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    - Surface ion source
    - Laser induced ion source
    - Electron Cyclotron Resonance ion source (ECRIS)
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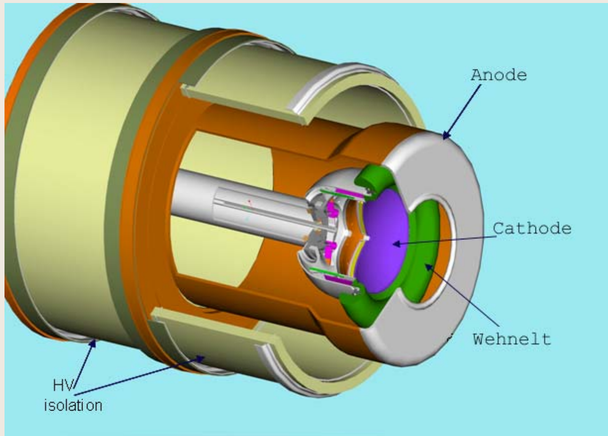
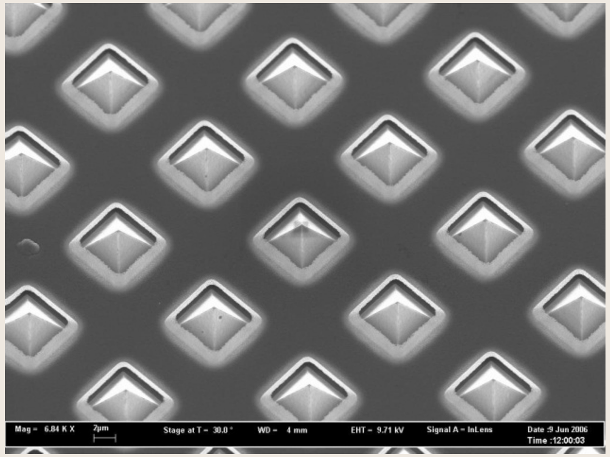
  - Negative Ion source
  - Multicharged ion source
    - Laser ion source
    - Electron Beam Ion Source
    - Electron Cyclotron Resonance Ion Source
- **RADIOACTIVE ION SOURCE**
  - Radioactive 1+ Ion sources
  - Radioactive charge breeder
- **TUTORIAL**

- **ADD-ON**
  - Beam Extraction from an ion source
  - Ion Beam Emittance
  - Low Enery Beam line Transfer

PARTICULE SOURCES

- Particle source activity requires both Physics and Engineering skills on many transversal topics
  - High voltage, magnetism, thermodynamics, chemistry, vacuum, condensed matter physics, plasma physics, atomic physics…
- Particule sources are legions!
  - There are as many particle sources as accelerators
  - Each of them would justify a one hour lecture…
- So…It is **IMPOSSIBLE** to give a detailed overview of the topic within a day lecture
  - Please consider this lecture as an introduction to the topic
- The philosophy of this lecture is to present shortly commonly used sources of particle and introduce the physics behind



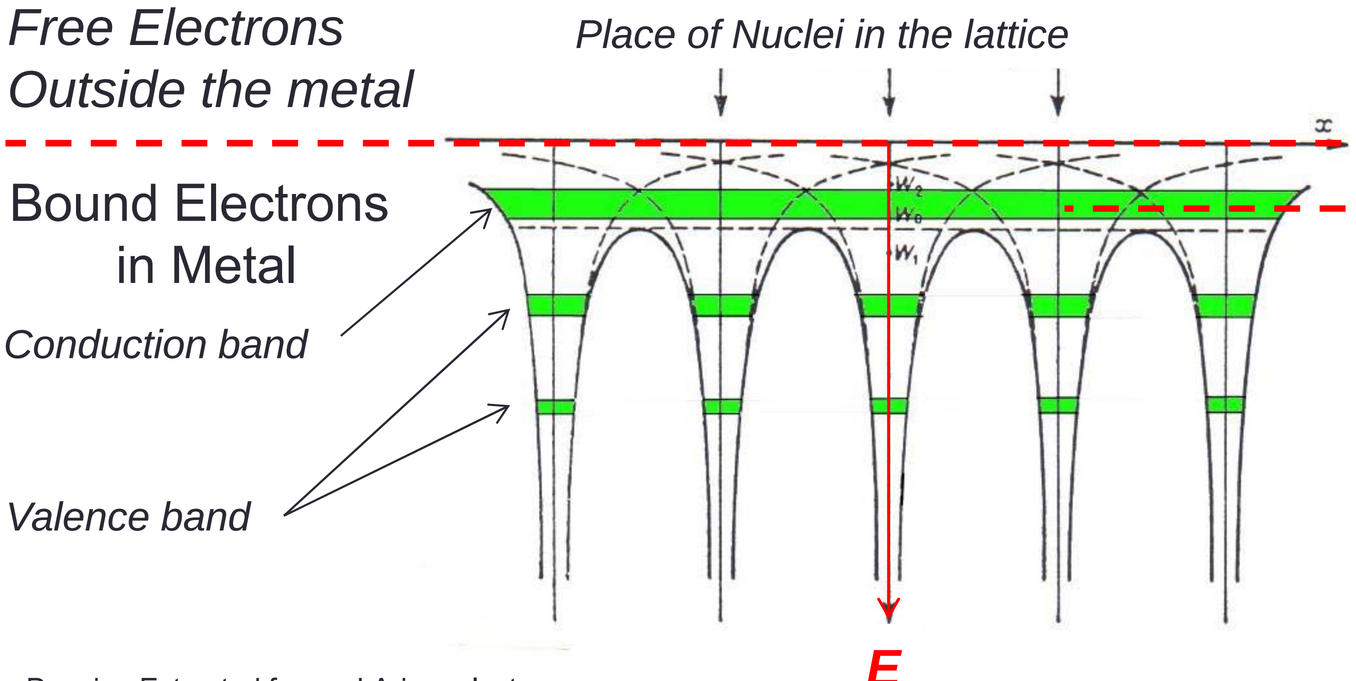


ELECTRON SOURCES

An introduction

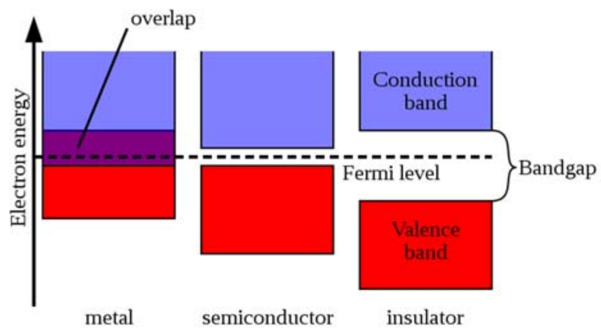
Work Function of electrons in metals

- The **Work Function W** is the minimum energy needed to remove an electron from a solid to a point immediately outside of the solid surface
  - In a metal, some electrons are populating the Conduction Band
    - electrons shared by the lattice
  - The maximum binding energy of electrons in metal corresponds to the Fermi Energy: $W=E_F$ (whenT=0 Kelvin). So $W<E_F$ *when T>0.*



Drawing Extracted from : J.Arianer lectures

Binding energies of electrons in a metal



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.

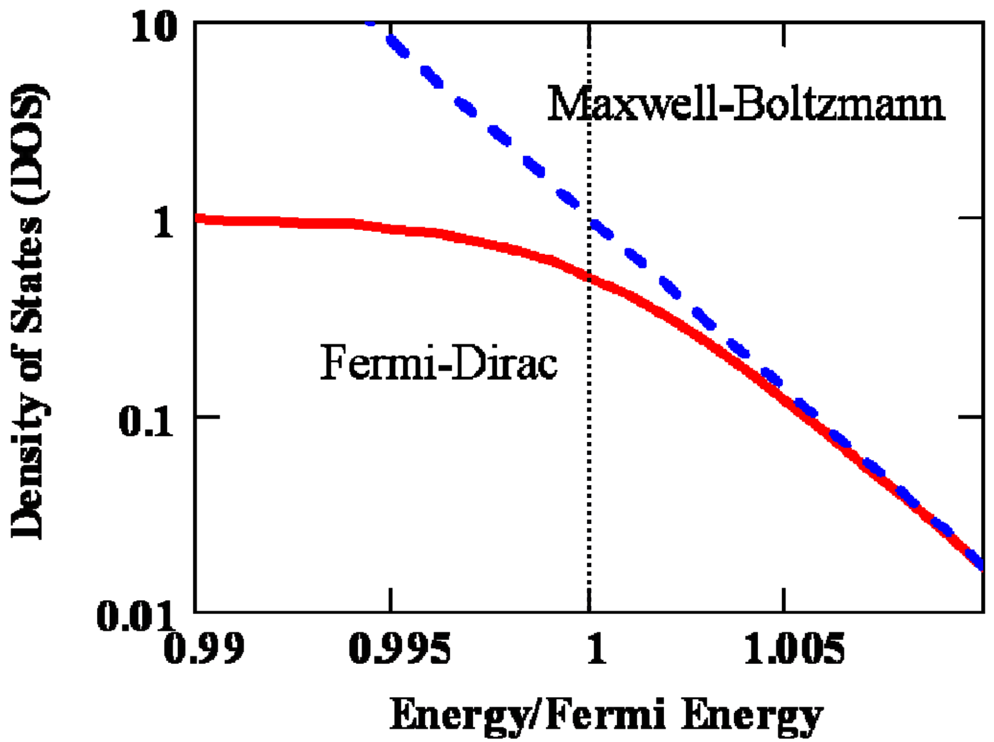
Element	eV	Element	eV	Element	eV	Element	eV	Element	eV
Ag:	4.52-4.74	Al:	4.06-4.26	As:	3.75	Au:	5.1-5.47	B:	~4.45
Ba:	2.52-2.7	Be:	4.98	Bi:	4.34	C:	~5	Ca:	2.87
Cd:	4.08	Ce:	2.9	Co:	5	Cr:	4.5	Cs:	2.14
Cu:	4.53-5.10	Eu:	2.5	Fe:	4.67-4.81	Ga:	4.32	Gd:	2.90
Hf:	3.9	Hg:	4.475	In:	4.09	Ir:	5.00-5.67	K:	2.29
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. (Cs: 2.14)

Max. (Os: 5.93)

Electron statistics and energy distribution function

- Electron, being fermions, follow the Fermi-Dirac statistics :
  - $f_{FM}(E) = \frac{1}{1+e^{\frac{E-E_F}{kT}}}$
    - E_F Fermi Energy
    - T electron temperature
- On the other hand, bosons obey the Maxwell-Boltzmann statistics:
  - $f_{MB}(E) = e^{-\frac{E}{kT}}$
- Practically, when $(E > 1.005\ E_F)$:
  - $f_{FM}(E) \cong e^{-\frac{E}{kT}}$
  - This approximation will be of interest to derive electron current densities



See USPAS site : http://uspas.fnal.gov/materials/10MIT/Lecture2_EmissionStatisticsCathodeEmittance_text.pdf

Distorsion of the electric potential near to a metallic surface

- When an electron is emitted from a material, the **image charge effect** changes the electric potential profile near to the surface:

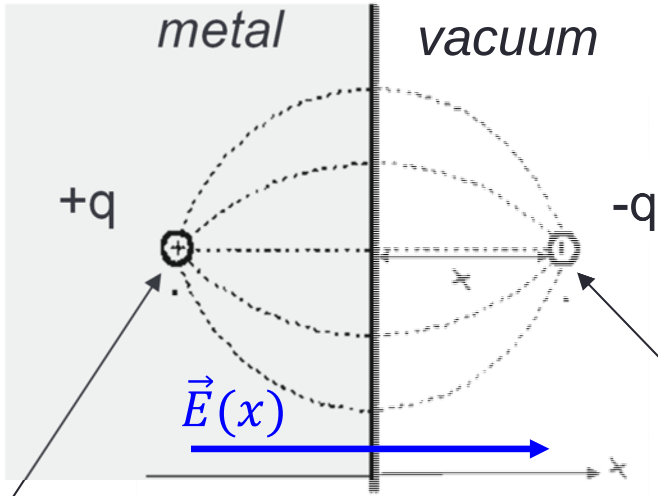
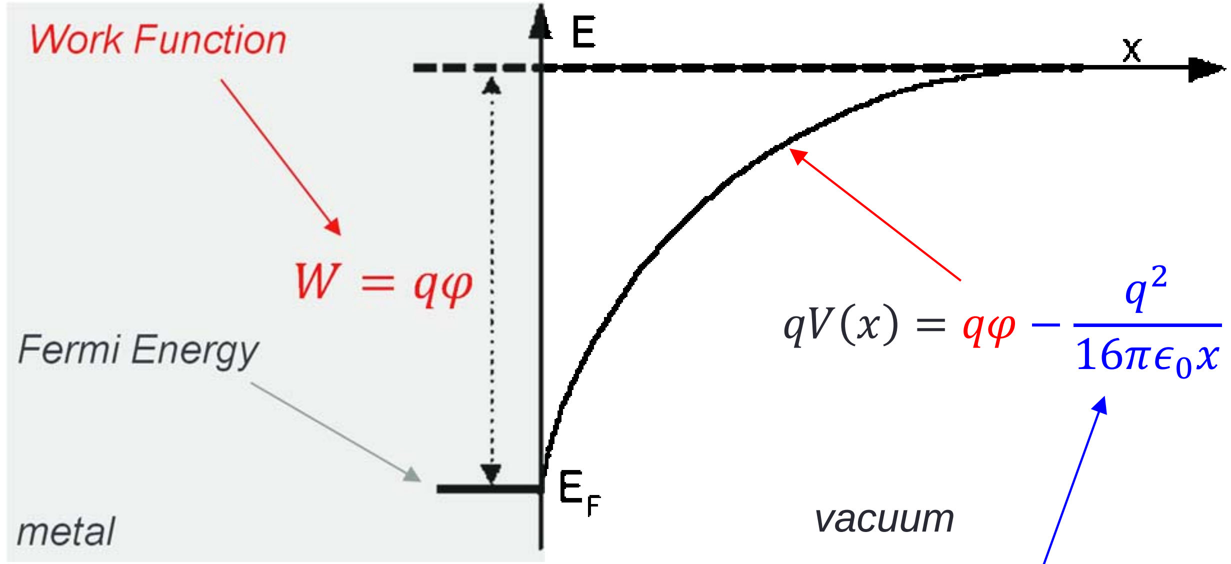


Image Charge (positive hole)

Electron extracted From the metal



$$qV(x) = q\varphi - \frac{q^2}{16\pi\epsilon_0 x}$$

IMAGE CHARGE TERM

$$E(x) = \frac{q}{4\pi\epsilon_0 (2x)^2}$$

$$V_{CI}(x) = -\frac{q}{16\pi\epsilon_0}\frac{1}{x}$$

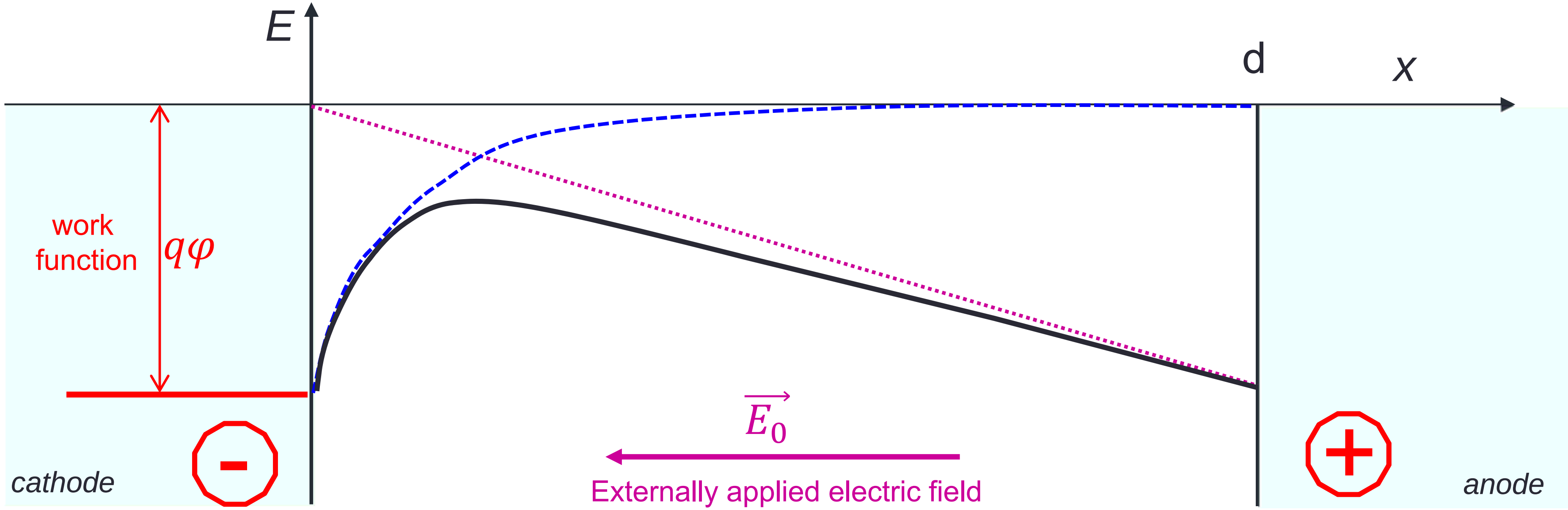
Electric potential energy as a function of distance near to a cathode with an externally applied electric field

$$qV(x) = q\varphi - \frac{e^2}{16\pi\epsilon_0 x} - E_0 x$$

Externally applied electric field

Image charge

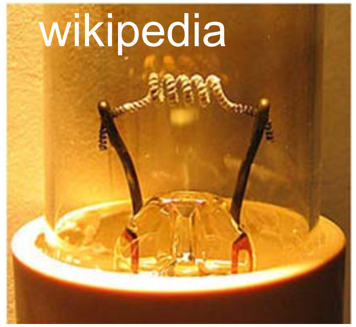
E=V/d



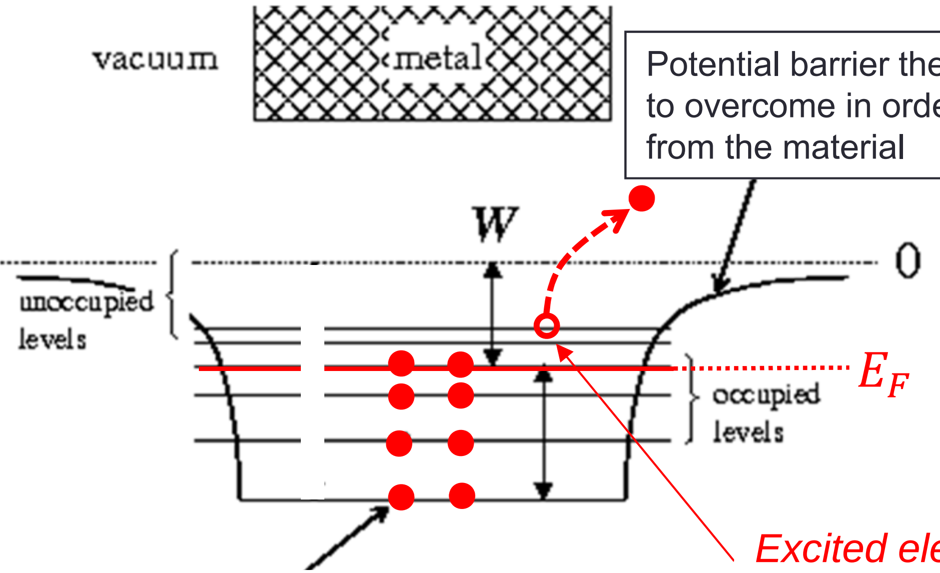
V(0)<0

V(d)=0

Thermionic emission of electrons



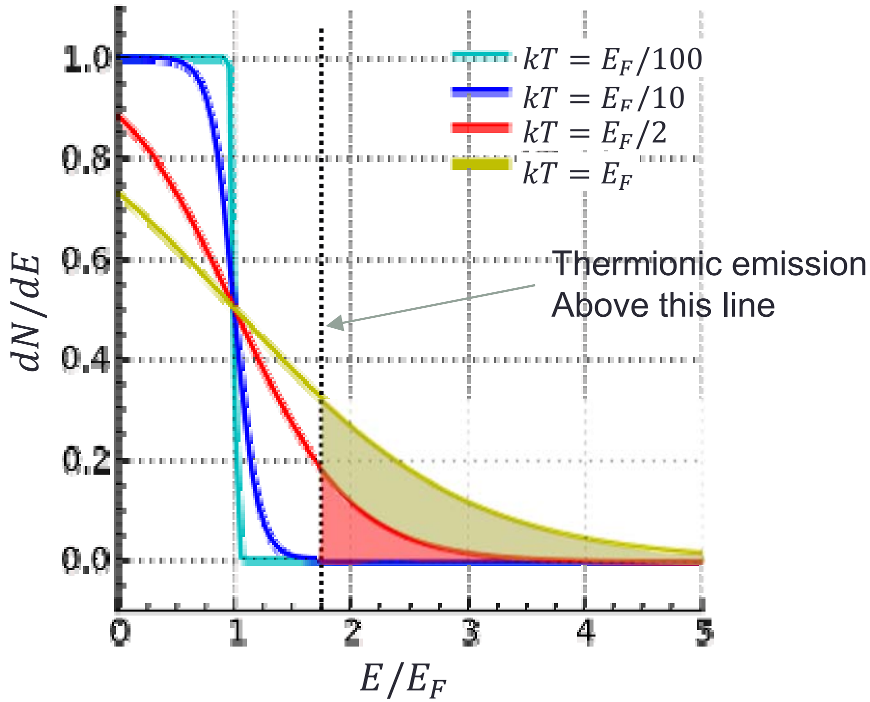
- A first way to extract electrons is to heat a material to a high temperature
  - When the material is heated, the thermal vibrations of the atoms are partially transferred to the electrons (E~kT_e) which can populate excited states above the Fermi level
  - Electrons are finally kicked out of the metal when their final energy **E** is higher than the Work Function **W** : **E > W**
- **The thermionic emission** is the resulting flow of electrons extracted from the heated material
- The application of a negative voltage (weak Electric field) helps to extract electrons from the metal surface (and accelerates them)



Potential barrier the electron has to overcome in order to escape from the material

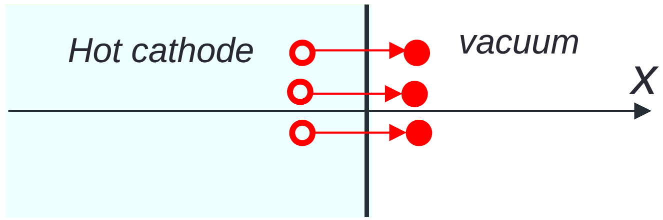
Excited electrons Above the Fermi level

Potential (zero) inside the metal (*Wikipedia*)



Fermi-Dirac function

Thermionic emission of electrons : current density



- Electron kinetic energy:
  - $\frac{1}{2}m_e{v_x}^2 > e\varphi$
- Electron current density:
  - $j_{thermionic} = n_e e\langle v_x\rangle = \iiint_{v_x>\sqrt{2e\varphi/m_e}} v_x g(v) f_{FD}(v) dv_x dv_y dv_z$
  - $j_{thermionic} = n_e e \iiint_{v_x>\sqrt{2e\varphi/m_e}} v_x \frac{2m}{h^3} e^{-\frac{m}{2kT}(v_x^2+v_y^2+v_z^2)} dv_x dv_y dv_z$
  - Calculations → $j_{thermionic} = \frac{4\pi m_e k^2 e}{h^3} T^2 e^{-\frac{e\phi}{kT}}$

density of states function

Fermi-Dirac distribution function

Maxwell-Boltzmann approximation

- This is known as the Richardson-Dushman equation

Current density of Thermionic emission

- The experimental Thermionic emission flow is ruled by the Richardson-Dushman formula:
  - **J** current density (A/m²)
  - **A** Richardson constant
  - **W** =q.φ work function
  - **T** temperature

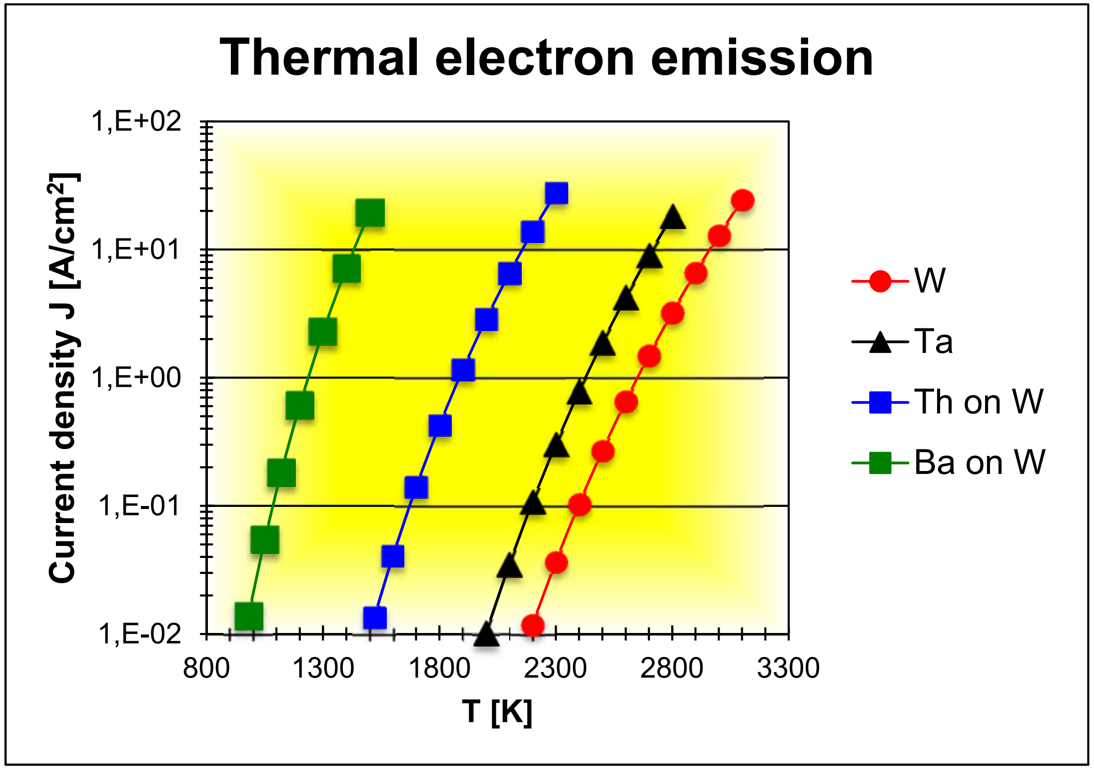
$$J = AT^2 e^{\frac{-W}{kT}} \quad , with\ A = A_0 \lambda_R$$

$$A_0 = \frac{4\pi m_e k^2 e}{h^3} = 1{,}20173 \times 10^6 A\, m^{-2} K^{-2}$$

- Order of magnitudes :
  - Wolfram : W_w~4.5 eV ; Tw~2900 K → J~10 A/cm²
  - LaB_6 : W_{LaB6}~2.4 eV ; $TLaB_6$~2100 K → J~10² A/cm²

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	2.4	0.24

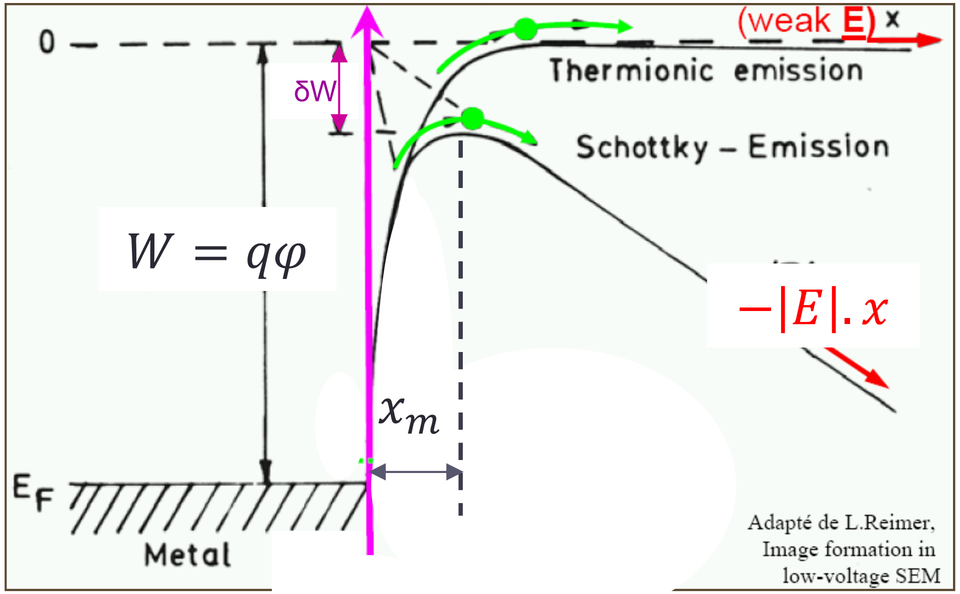
Source: H. Koivisto, JUAS 2013
J. Arianer, IN2P3 Lecture



The Schottky effect

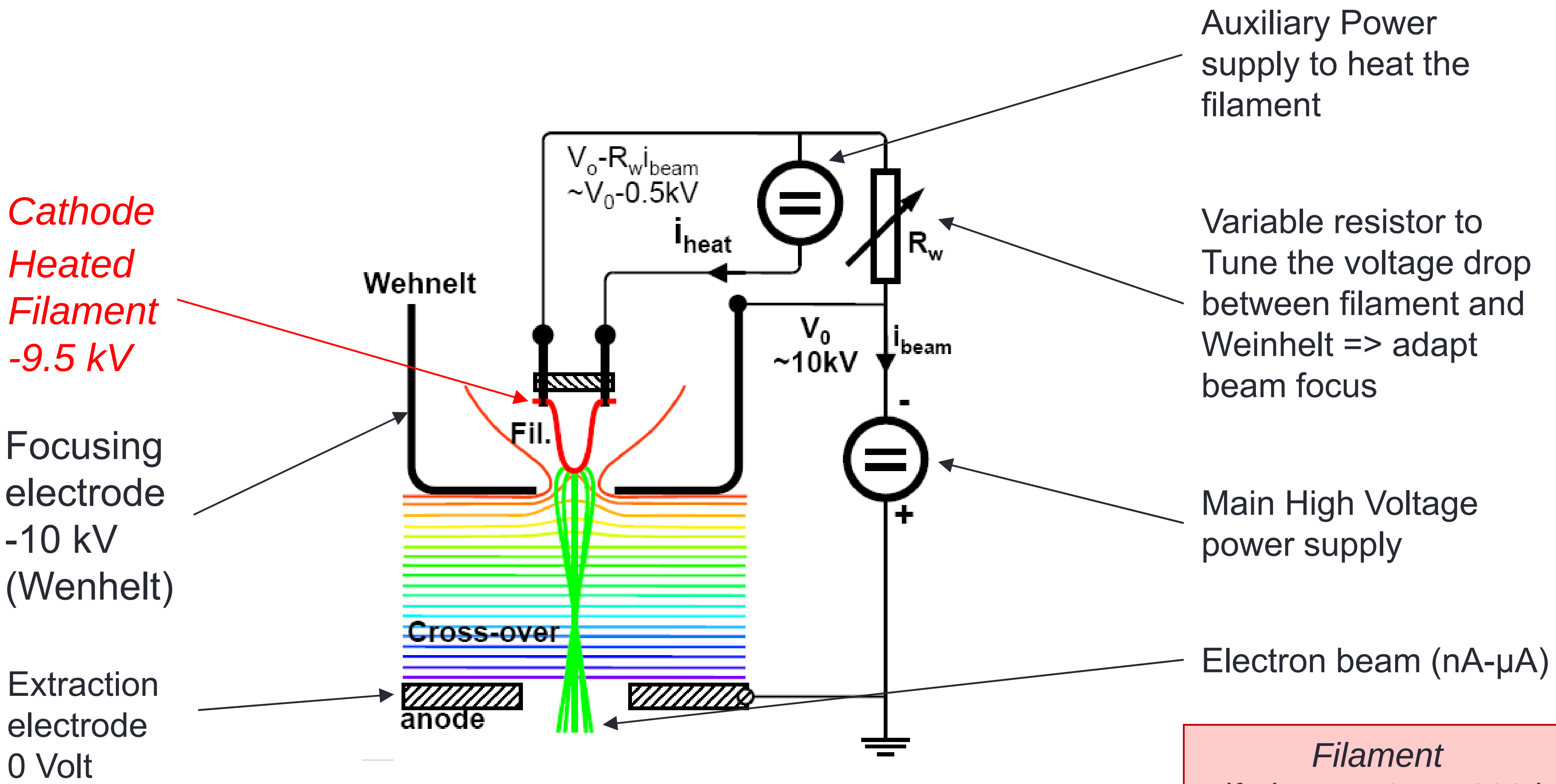
- The Schottky effect is the reduction of the electron work function when a strong external electric field E is applied to the hot cathode
  - This is the case for thermionic guns since cathodes are negatively biased
  - $qV_S(x) = q\varphi - \frac{q^2}{16\pi\epsilon_0 x} - qE.x$

    Modified potential — Work function — Image charge (slide 7)
  - The work function is reduced by $\delta W = \sqrt{\frac{q^3 E}{4\pi\varepsilon_0}}$
  - The distance to the peak potential is $x_m = \sqrt{\frac{q}{16\pi\epsilon_0 E}}$
- Modified Richardson-Dushman formula:
  - $J = AT^2 e^{\frac{-(W-\delta W)}{kT}}$
- Shottky effect is usually of second order :
  - $E = 10\frac{kV}{cm} \rightarrow \delta W = 30\ meV$ and $x_m \sim 190\ \dot{A}$
  - $E = 100\frac{kV}{cm} \rightarrow \delta W = 100\ meV\ and\ x_m \sim 60\ \dot{A}$
  - Schottky Effect valid up to $E \sim 1\frac{MV}{cm} \rightarrow \delta W = 0.3\ eV\ and\ x_m \sim 19\ \dot{A}$



The Thermionic Electron Source

- A very common electron source used in industry and research
  - klystron, TV tubes, electronic microscope, accelerators…
- Example of an electronic microscope source:

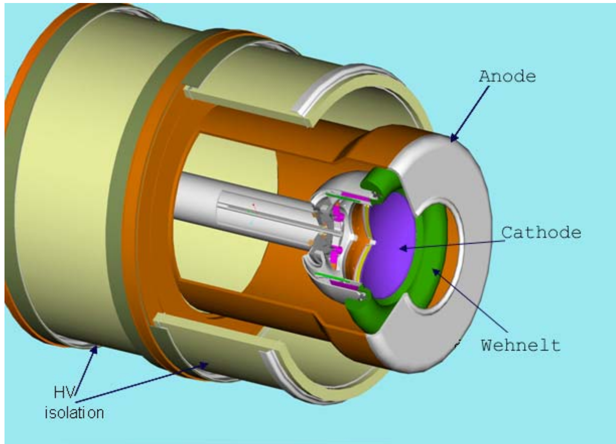


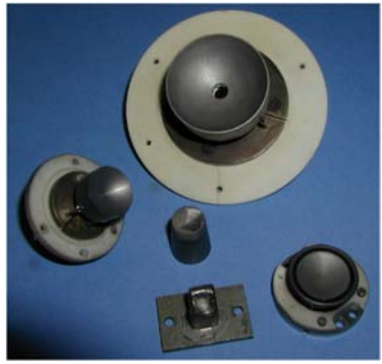
Filament
Lifetime ~ 10 to 1000 h

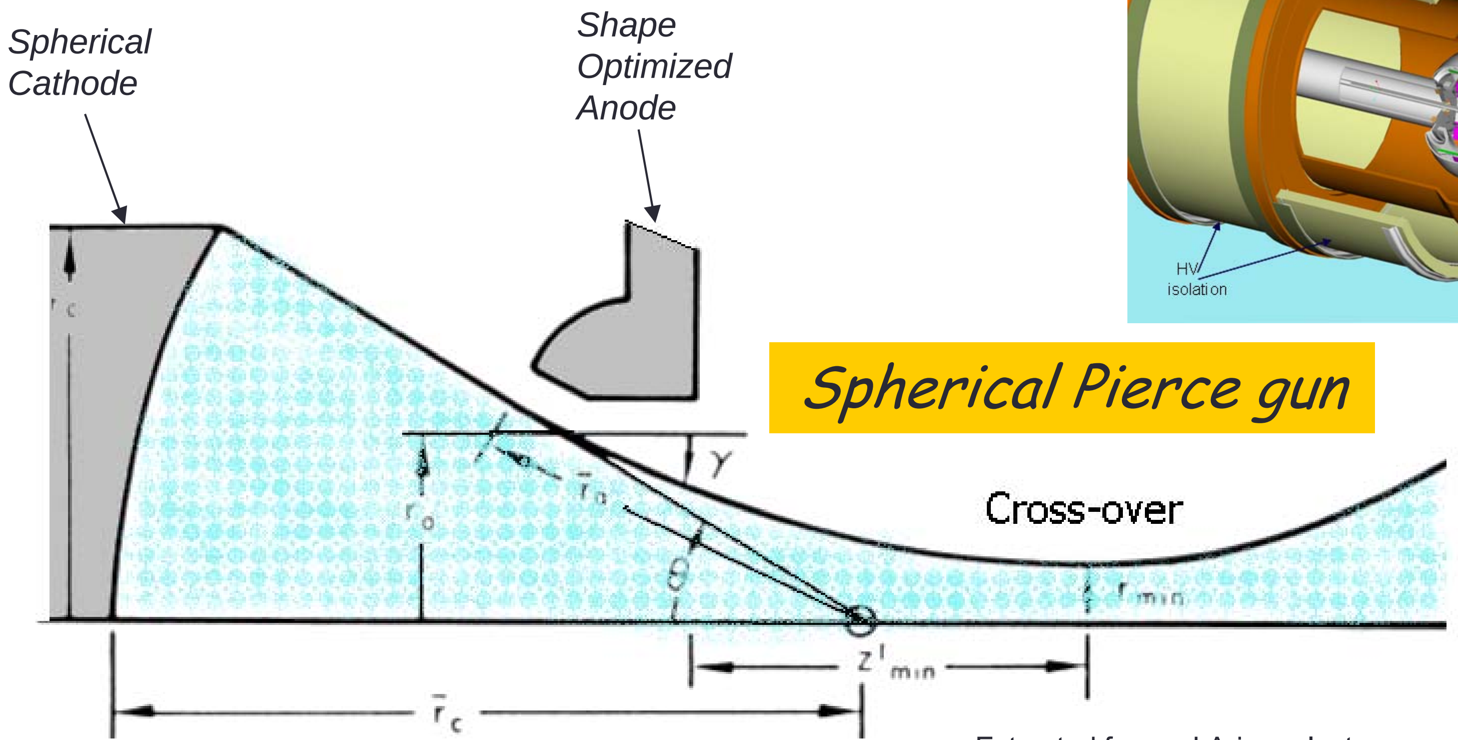
Extracted from : Microscopie Electronique 06/07, philippe.buffat@epfl.ch

High Intensity Thermionic Electron Gun

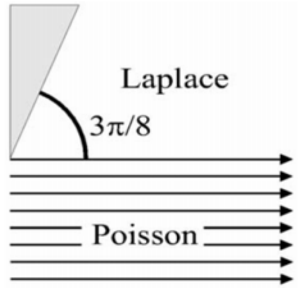
- The electronic current is increased by increasing the cathod surface
  - Depending on the design, the beam intensities span from ~µA to ~100 A
- « Pierce design » At high current, the electron beam space charge (which inflates the beam) is compensated by a careful design of the electrodes (which generate a focusing effect)




Example of cathodes



Spherical Pierce gun



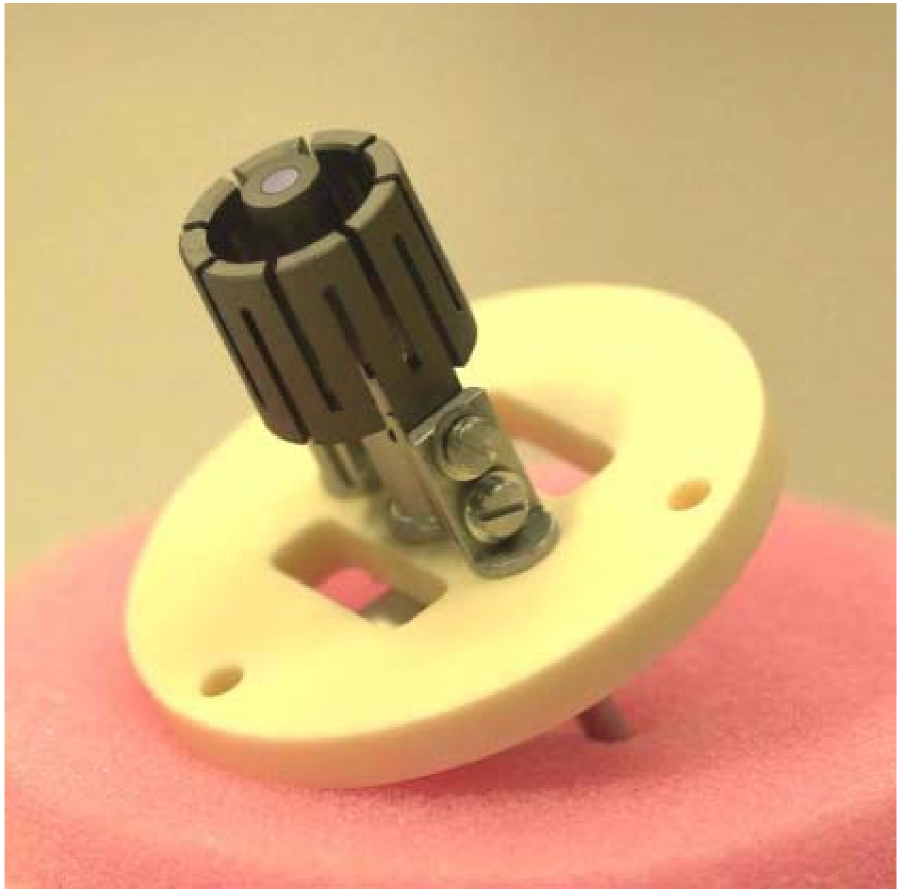
Pierce Angle For a flat gun

Extracted from : J.Arianer lectures

Example of a modern accelerator thermionic gun

- Spring8 CeB6 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]



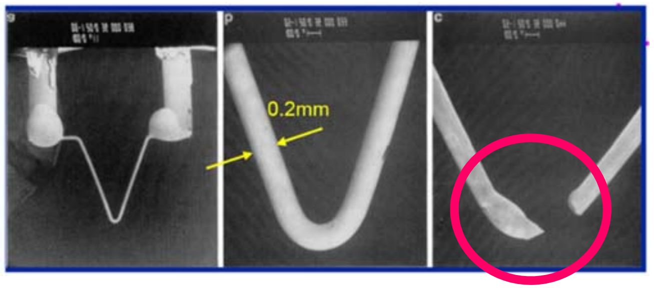
*K. Togawa et al., PAC03, 3332; NIMA **528** (2004) 312*
H. Tanaka et al., FEL06, 769

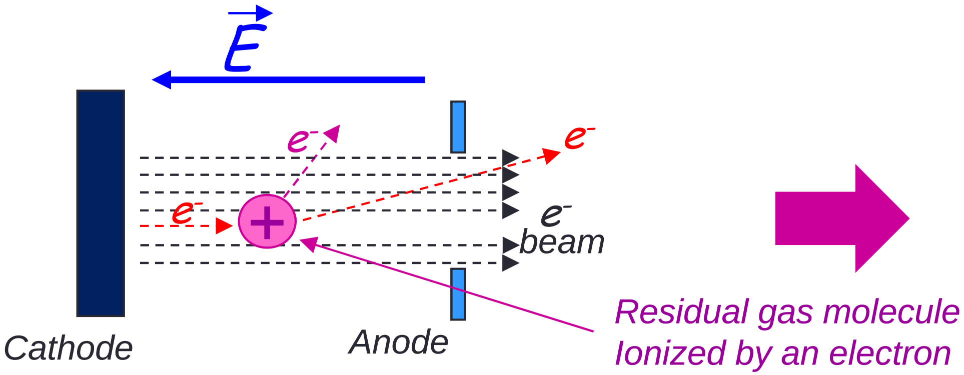
Slide extracted from Brookhaven lecture on cathode physics, M. Poelkerand and J. Smedley

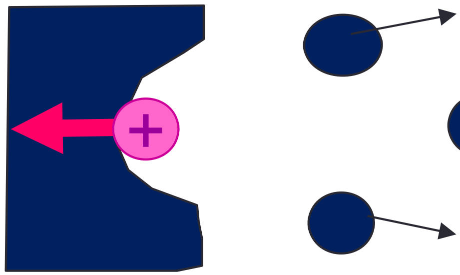
Cathode and filament aging

- The lifetime of a cathode/filament strongly depends on the condition of operation
  - Cathode shape
    - a massive cathode will last much longer
  - Residual vacuum pressure
    - Electrons collide with the residual gas and generate ions which are accelerated toward the cathode => cathode sputtering
  - High Temperature:
    - Atom evaporation
    - chemical reaction induced by neighbor materials or gas
    - Thermal cycling generating cracks
    - Sudden burning, interruptions…
- Typical filament/cathode lifetime is 10^2~10^4 hours

cathodes damaged by sputtering



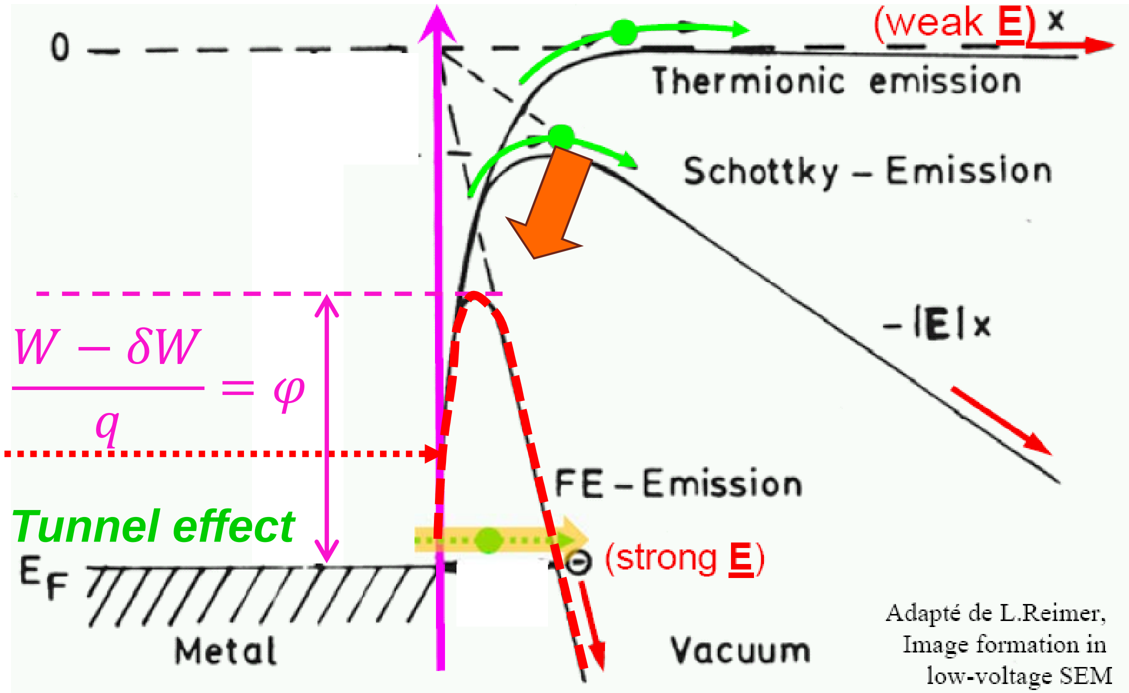




Electron Field Emission

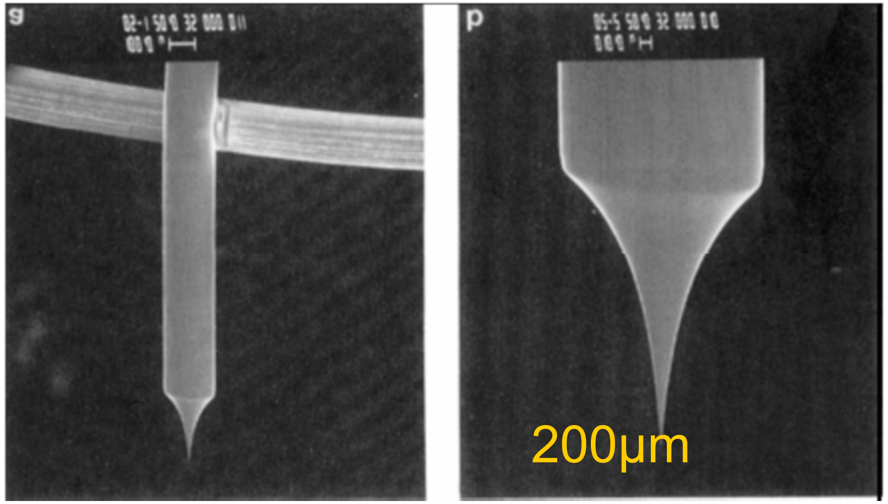
- In the presence of a very strong electric field (E>10 MV/cm) , the working barrier is thin enough to allow electron emission through **Tunnel Effect**
- The associated emission is ruled by the Fowler-Nordheim theory (quantum physics)
- It is a **cold cathode emission** => no metal heating is required
- $J \approx \frac{k_1 E^2}{\varphi} e^{-\left(\frac{k_2 \varphi^{3/2}}{E}\right)} A/m^2$
  - $k_1 = 1.4\ 10^{-6} (SI)$
  - $k_2 = 6.87\ 10^{7} (SI)$
- *J~1 MA/cm² !*

Field Emission (cold cathode)



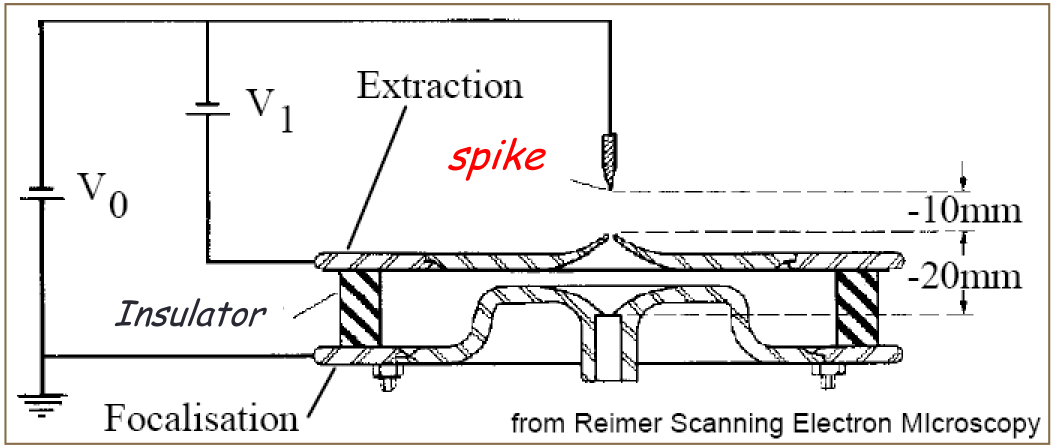
Field Emission Electron Source (electronic microscopy)

Example of a tip which concentrates the Electric field



The lower the radius of the tip, the higher the electric field

(from J. Goldstein, Scanning electron microscopy)



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

Electrostatic Point effect (Corona)

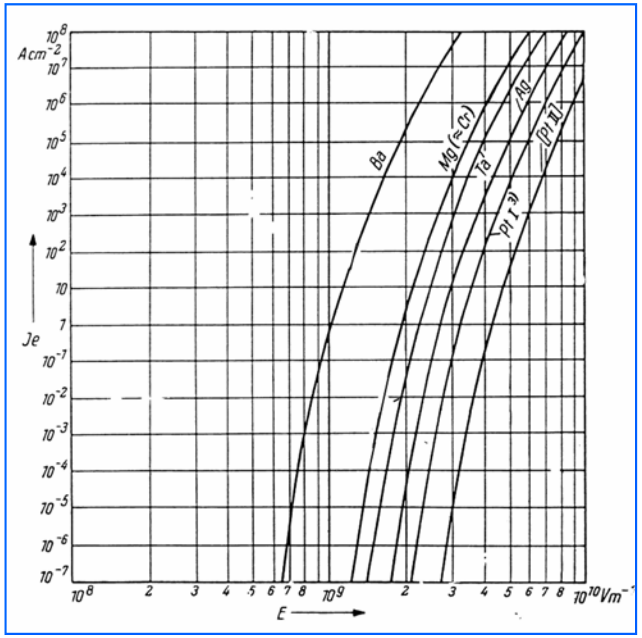
R, Q — 2 Spheres with radius R>r — r, q

Same potential V

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

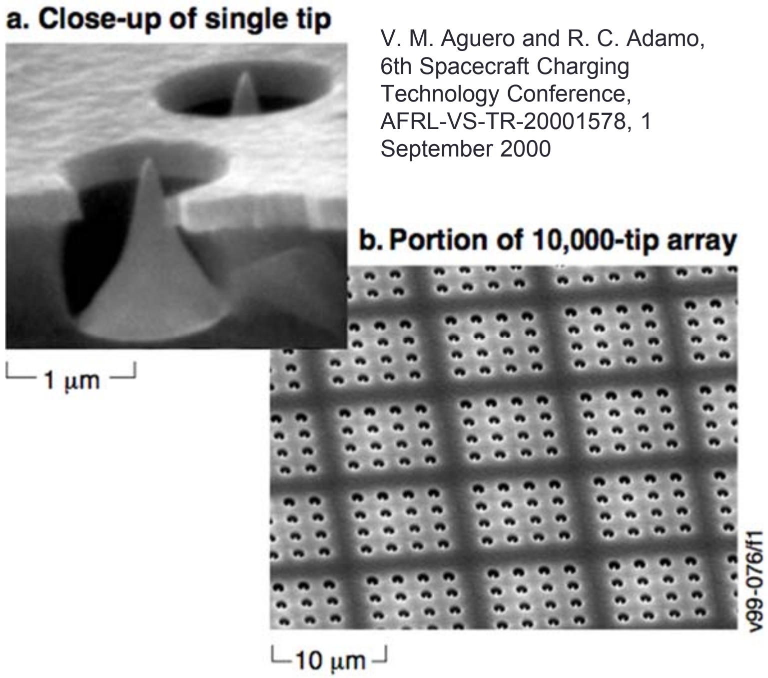
$$E_1(R) = \frac{Q}{4\pi\epsilon_0}\frac{1}{R^2} \qquad E_2(r) = \frac{q}{4\pi\epsilon_0}\frac{1}{r^2}$$

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

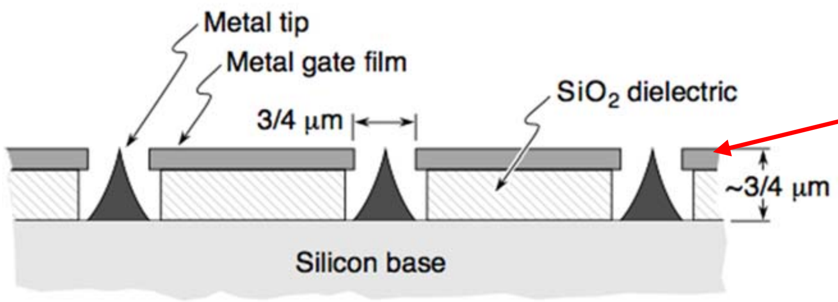


The Spindt Array

- Field Emitter Array (FEA) consists of a 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 parasitic heating and space charge effects



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 electron current up to 100 µA/tip has been demonstrated

Slide adapted from H . Koivisto

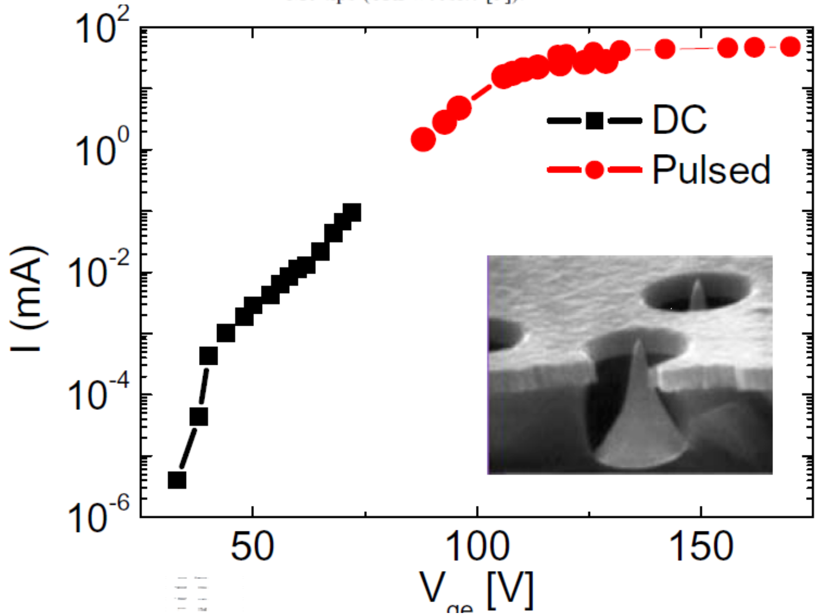
Field Emission Array Electron Source

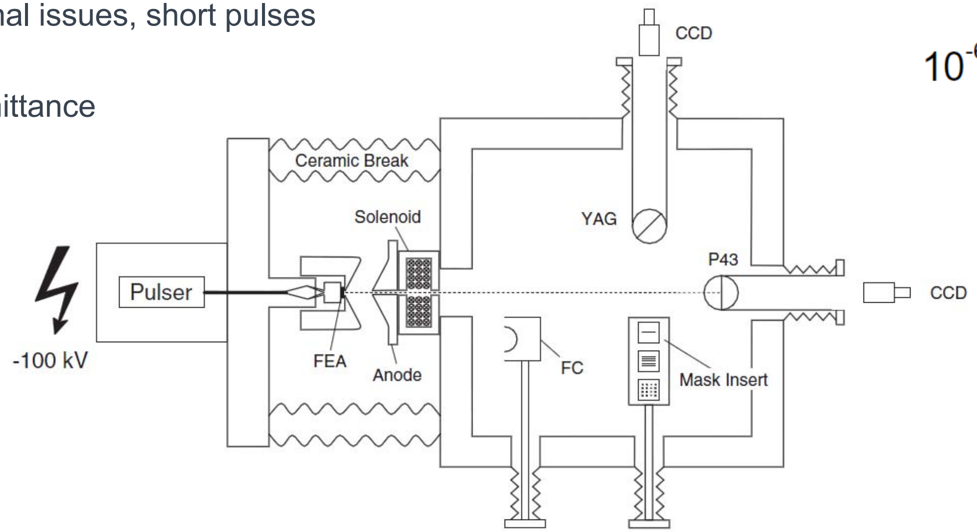
PAUL SCHERRER INSTITUT

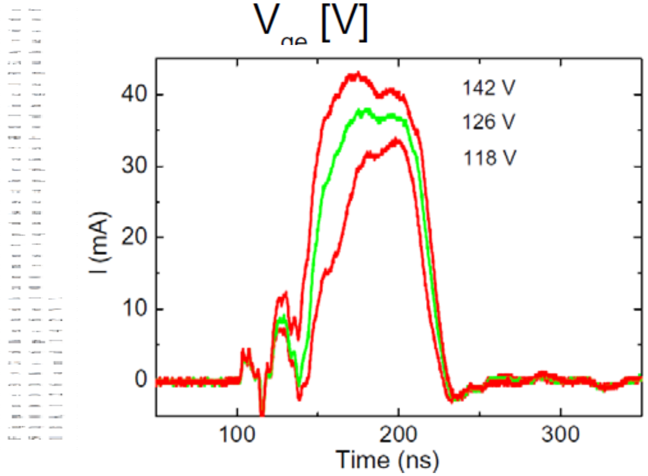
Tests performed at PSI

- Several Companies developed Field Array emission gun (SRI Inc. , XDI Inc…) using the Spindt method
  - Array Built on Si base substrate, using semi-conductor technology
  - Generation of large Field emission array surface
    - 50000 Mo spikes (tips) on a Ø 1 mm disk for SRI Inc.
- The DC operation is subject to fluctuation and is limited to a few 100 μA, due to:
  - Thermal desorption of atoms inducing contamination, sputtering, parasitic discharges
  - Even destructive arcing if the pressure degrades too much
- **The pulsed operation is very promising**
  - Stable operation, no thermal issues, short pulses
  - High current density
  - Small intrinsic cathode emittance

Figure 2: Current-voltage characteristic in DC and pulsed regime for a SRI Inc. FEA (1 μm diameter, 50,000 Mo tips) Insert: SEM picture of some conical Mo tips (SRI website [3]).





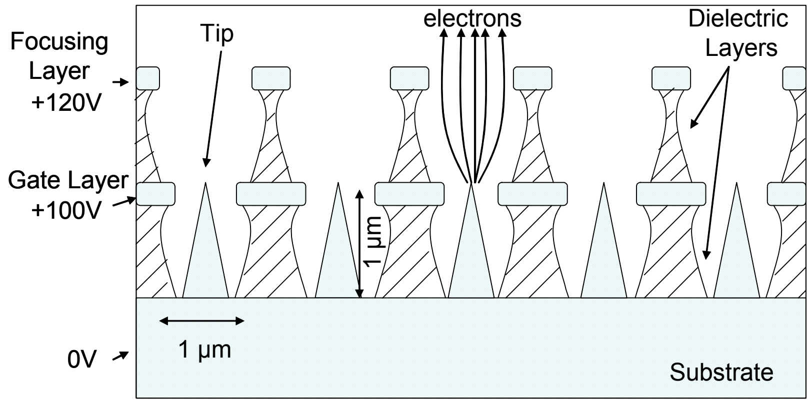


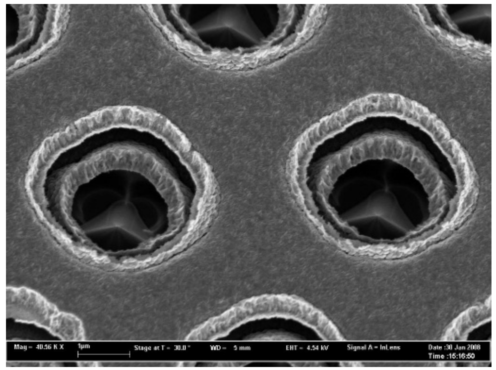
Ultra Low Emittance Electron Gun Project for FEL Application THP27, Proceedings of LINAC 2004, Lübeck, Germany, www.jacow.org

FIG. 1. Schematic overview of the 100 keV gun test stand (not to scale).

Double Gated Field Array Source – PSI R&D

- The goal is the design of a high intensity, low emittance electron source for a free electron Laser facility





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

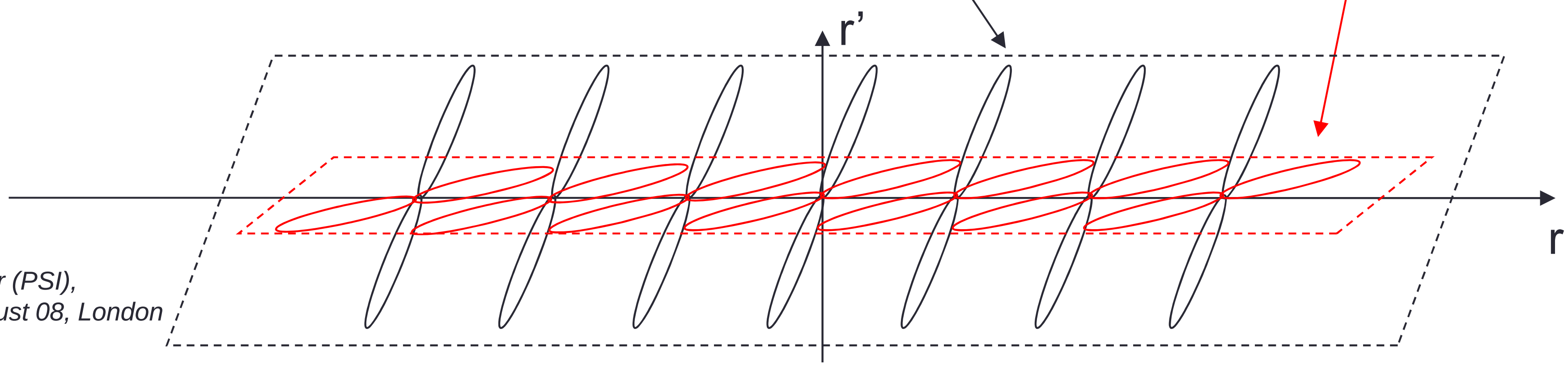
$\beta\gamma.\vartheta = 5mrad$ n=100; δx=2µm

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

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

Initially
$\varepsilon_n \sim 2$ mm.mrad

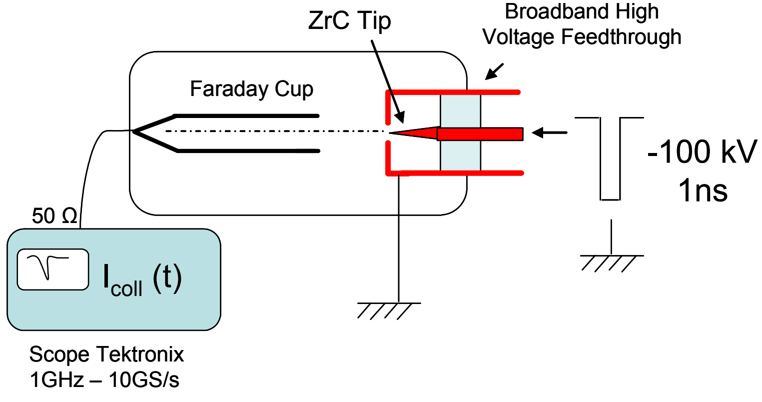
After Focusing
$\varepsilon_n < 0.1$ mm.mrad



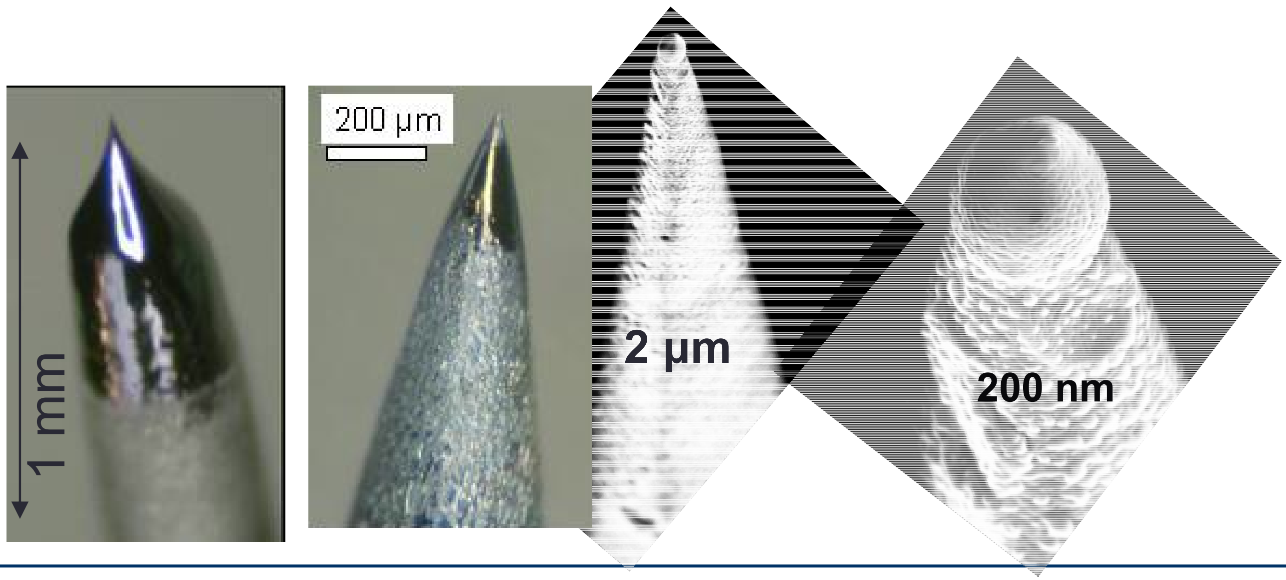
Slide: R. Ganter (PSI), IVESC08, August 08, London

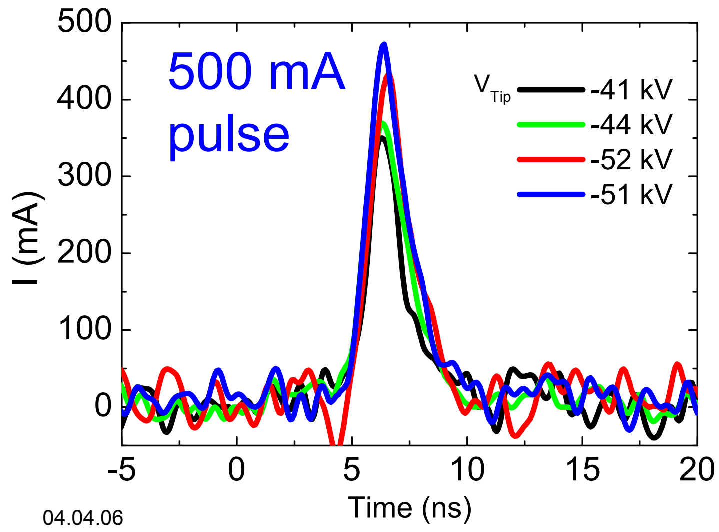
Needle Cathode Electron Source (PSI R&D)

- The cathode consists of a single ZrC needle
  - W_{ZrC}=3.5 eV
- Pulsed operation:
  - A 1 ns High Voltage pulse is applied to the needle
  - Peak intensity measured up to 500 mA

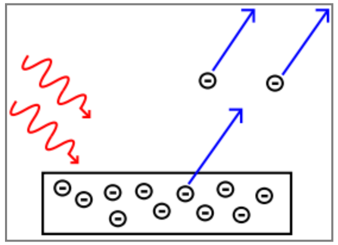


Commercial Devices from A. P. Tech Inc.





Photoelectric Effect



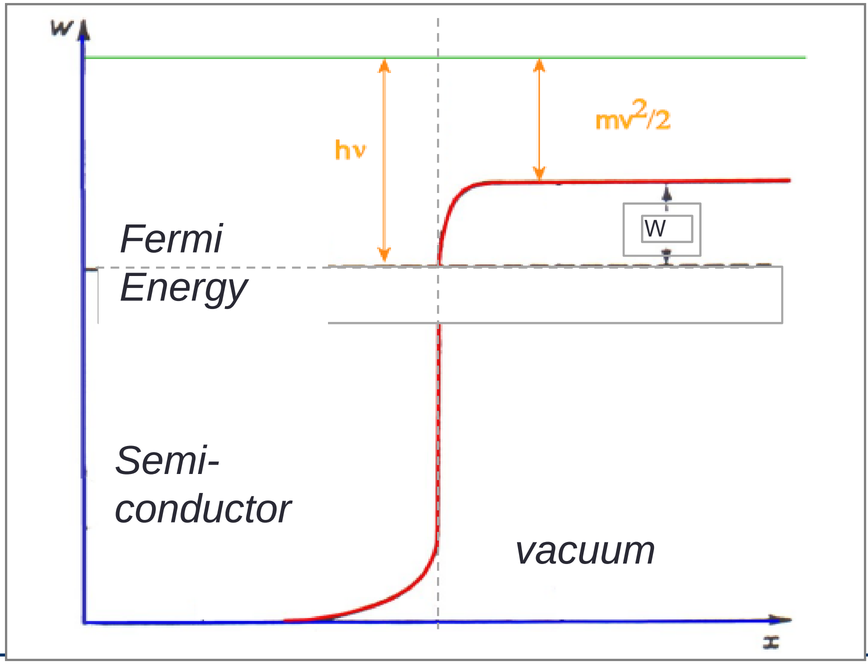
- The energy to emit an electron is given by a photon
  - A photocathode is a negatively charged electrode coated with a photosensitive compound. When it is struck by a photon, the absorbed energy causes electron emission due to the photoelectric effect.
  - A photocathode is usually composed of alkali metals with very low work functions (e.g. Cesium).

Photon energy

Electron kinetic energy

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

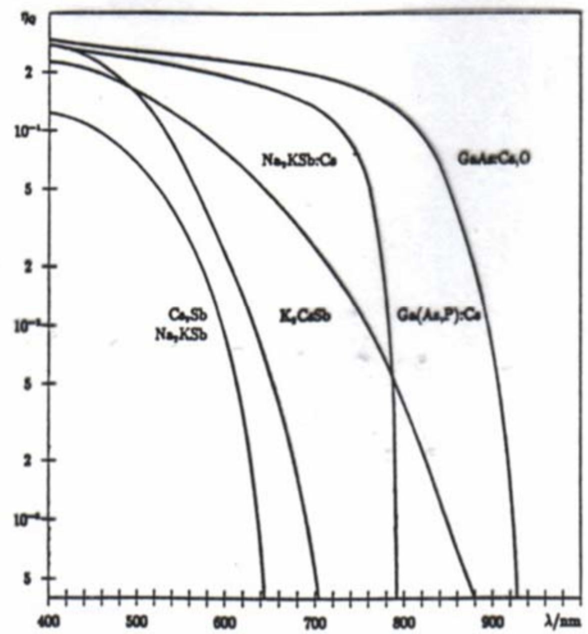
W = photocathode Work function



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

Material	ΔE [eV]	λ_0 [nm]
Cs_3Sb	1.95	640
K_2CsSb	1.8	700
$Na_2KSb:Cs$	1.4	890
GaAs:Cs,O	1.35	930

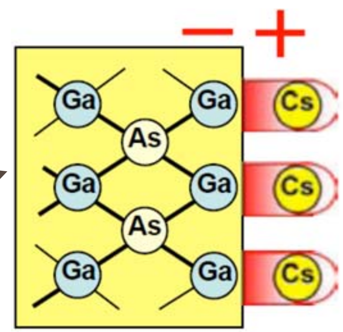
Photocathodes Quantum efficiencies (semi conductors)



Negative Electron Affinity

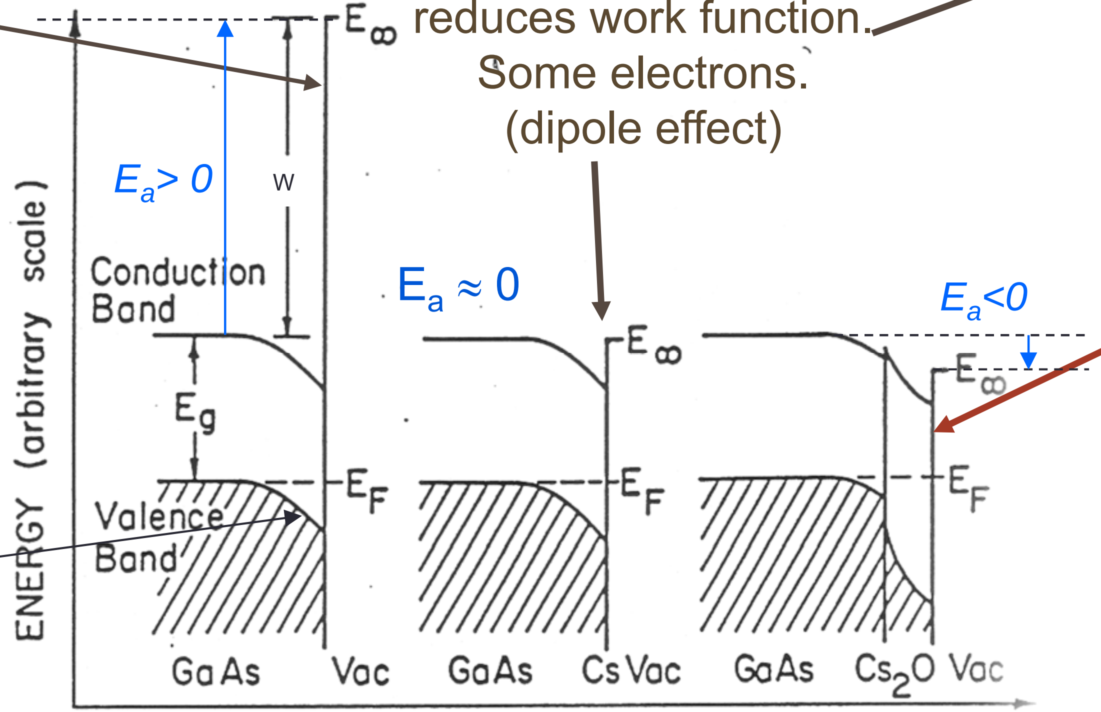
Bare GaAs surface;
Large work function.
No electrons

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



Cesium + Oxidant (O or NF3)
"**N**egative **E**lectron **A**ffinity".
Many electrons

Band bending[**]
effect



- NEA coating is deposited **directly on site** under ultra low vacuum (~10^{-12} mbar)
- NEA helps A LOT extracting electrons
- NEA coating is fragile, sensitive to contamination and sputtering
- Automatic coating on guns, see next slides

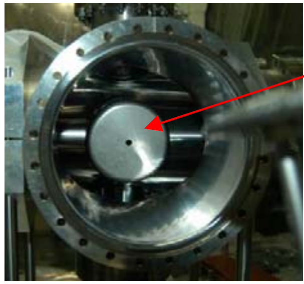
Electron Affinity[*] *:* $E_a > 0$ $E_a \approx 0$ $E_a < 0$

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

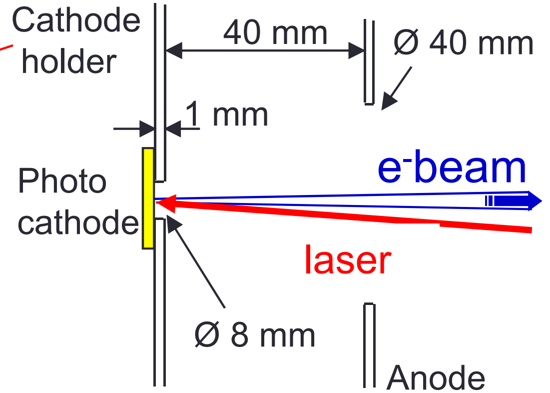
- [*]In solids, the Electron Affinity is the energy difference between the vacuum energy and the conduction band minimum.
- [**]Band bending refers to the local change in energy of electrons at a semiconductor junction due to space charge effects. The degree of band bending between two layers depends on the relative Fermi levels and carrier concentrations of the materials forming the junction.

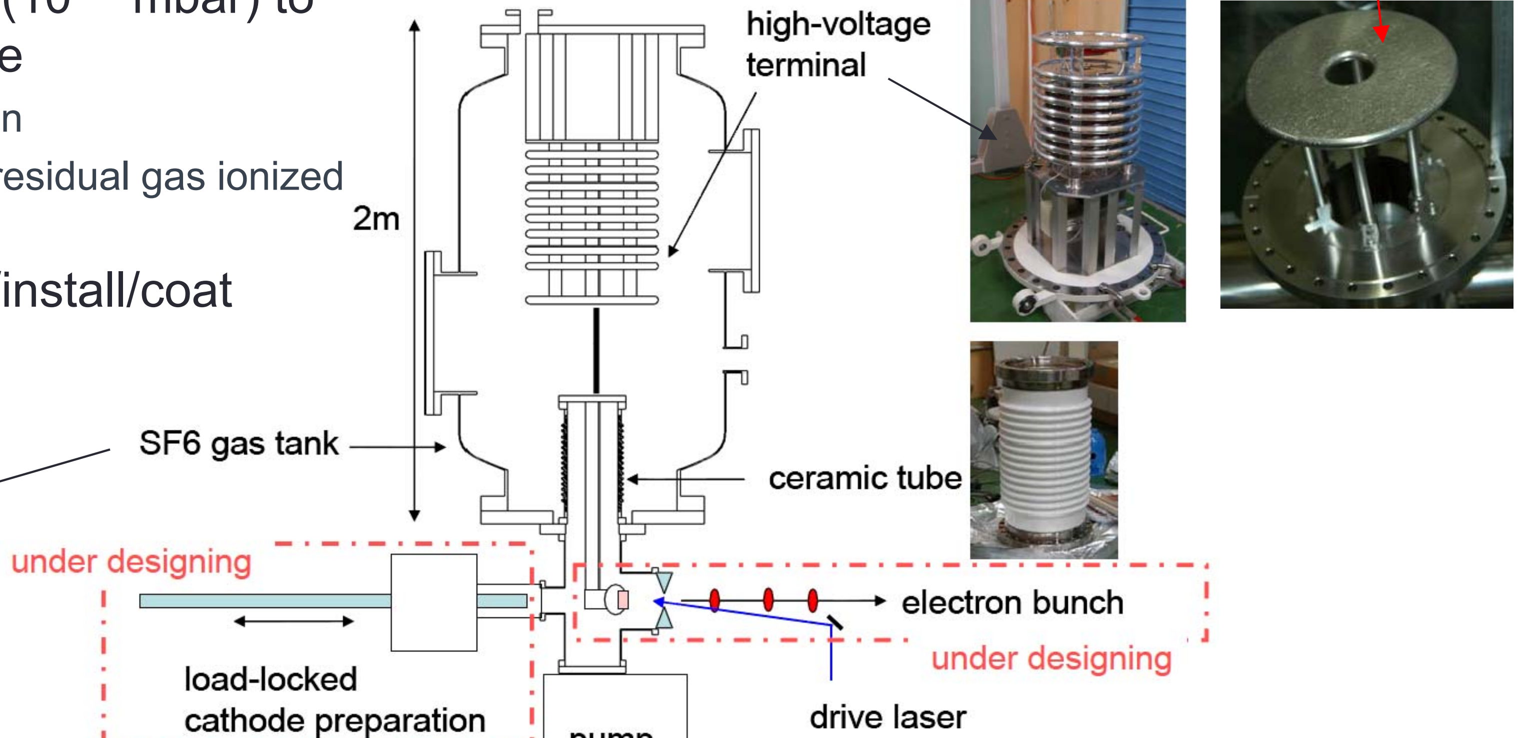
Example of a Photocathode DC SOURCE (JAEA-ERL)

- A NEA-GaAs photocathode is hit by a laser beam
- Photoelectrons are accelerated by a 5 MV/m electric field
  - 250 kV High voltage / average 50 mA beam intensity
- Ultra low secondary vacuum (10^{-12} mbar) to increase photocathode lifetime
  - To prevent cathode contamination
  - To minimize sputtering from the residual gas ionized by the electron beam
- Load-Lock system to remove/install/coat photocathode on site



all the electrodes are made of Titanium

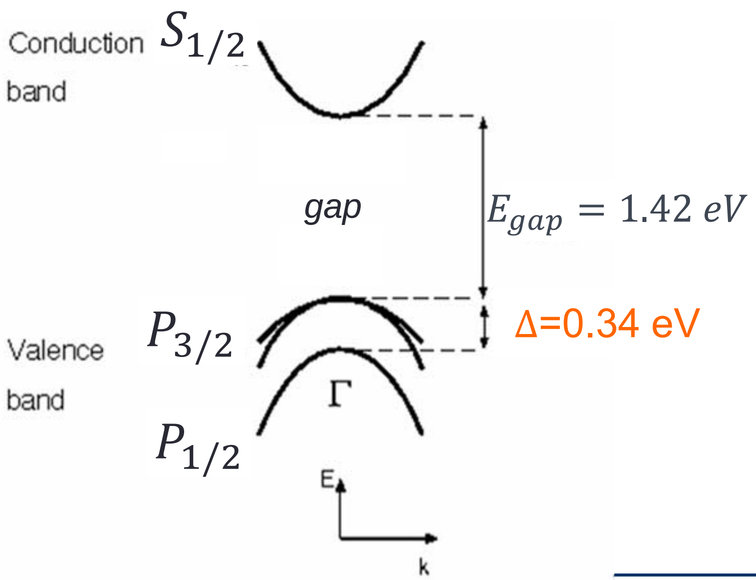




Slides extracted from www.jacow.org TUPPH007,Proceedings of FEL 2006, BESSY, Berlin, Germany

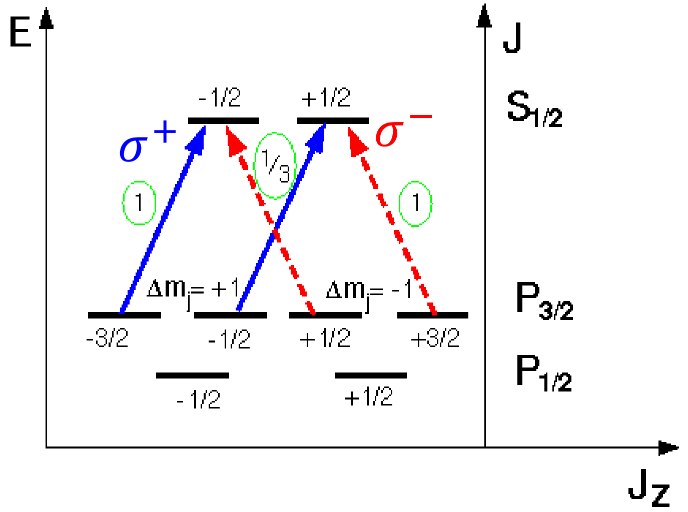
Polarized Photoemission electron source at Jlab (1/2)

- When the laser beam is circularly polarized, the electron beam is partially polarized
  - Optical pumping between $P_{3/2}$ and $S_{1/2}$ states
  - The photon energy E_γ is chosen such that $E_{gap} < E_\gamma < E_{gap} + \Delta$
  - Laser circularly polarized σ^+ or σ^-
  - The probability to populate $-\frac{1}{2}$ and $+\frac{1}{2}$ states on $S_{1/2}$ being different, a 50% excess of polarization is obtained



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

$$P_e = P\left(+\frac{1}{2}\right) - P\left(-\frac{1}{2}\right)$$



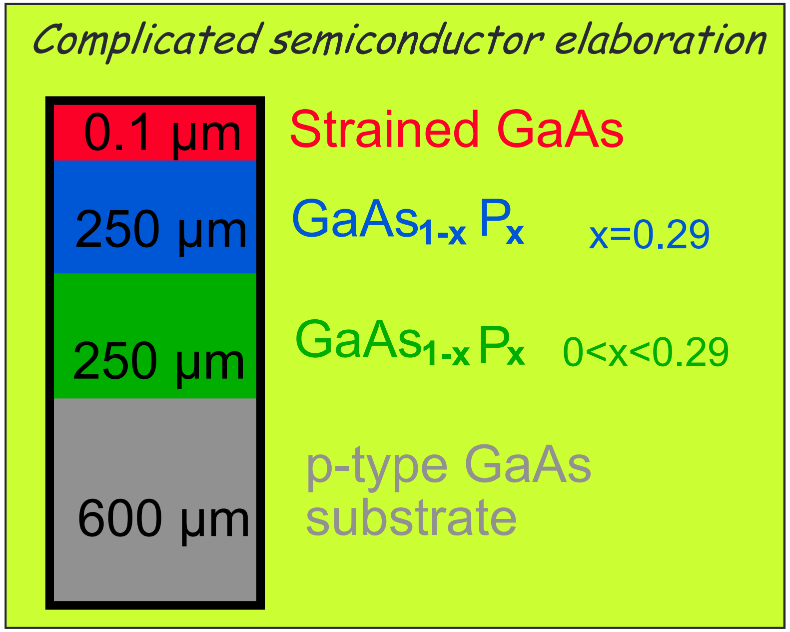
Slide adapted from : J. Grames, JLab, USA

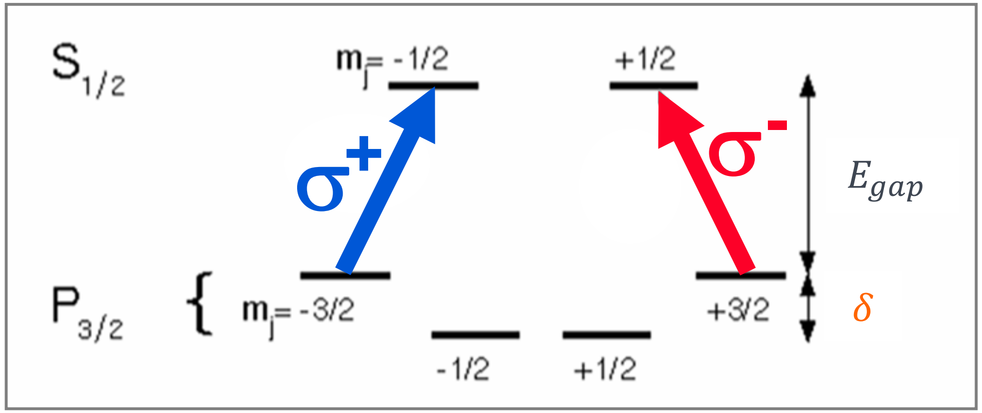
Polarized Photoemission electron source at Jlab (1/2)

- A refinement of the polarization is obtained by adding extra layers on the photocathode :
  - Split degeneracy of $P_{3/2}$
  - Direct optical pumping between $P_{3/2}$ and $S_{1/2}$
  - When $E_{gap} < E_{\gamma} < E_{gap} + \delta$:

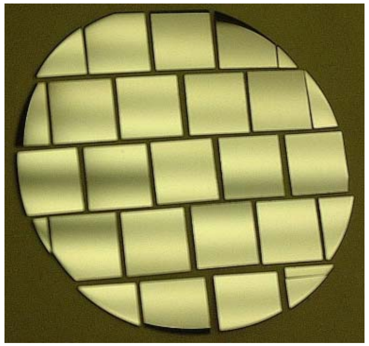
$$\boldsymbol{P_e = \pm 100\%}$$

  - Experimentally $\boldsymbol{P_e \sim \pm 85\%}$





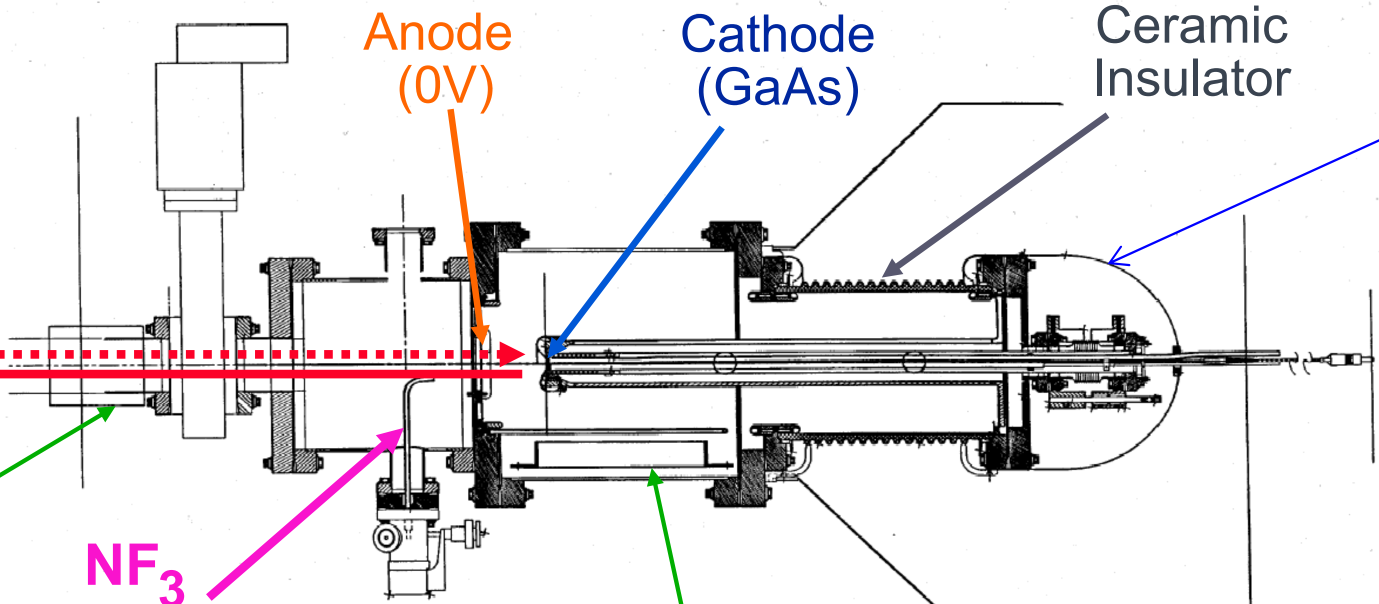
Slide adapted from J. Grames, JLab, USA



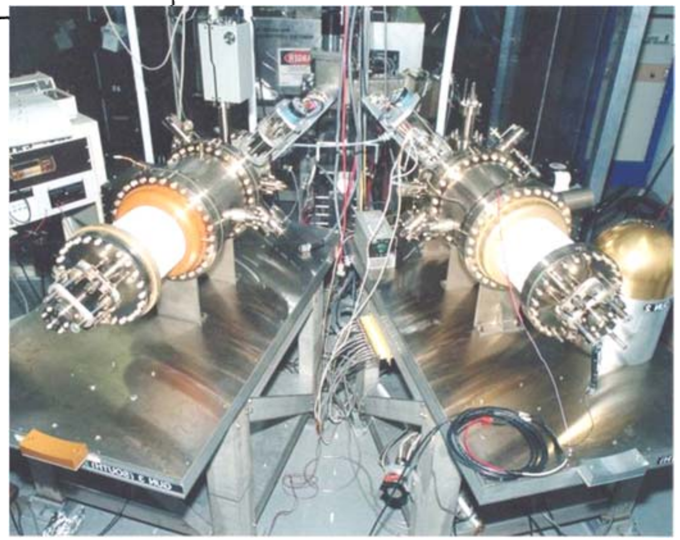
3 " wafer cut into square photocathodes

Stalk for supporting 1 Photocathode

Jlab polarized Photoemission gun



Non evaporable getter pumps (NEG)
4,000 liter/s pump speed ⇒ ~410^{-12} mbar
↑
Mandatory to prevent Photocathode early aging



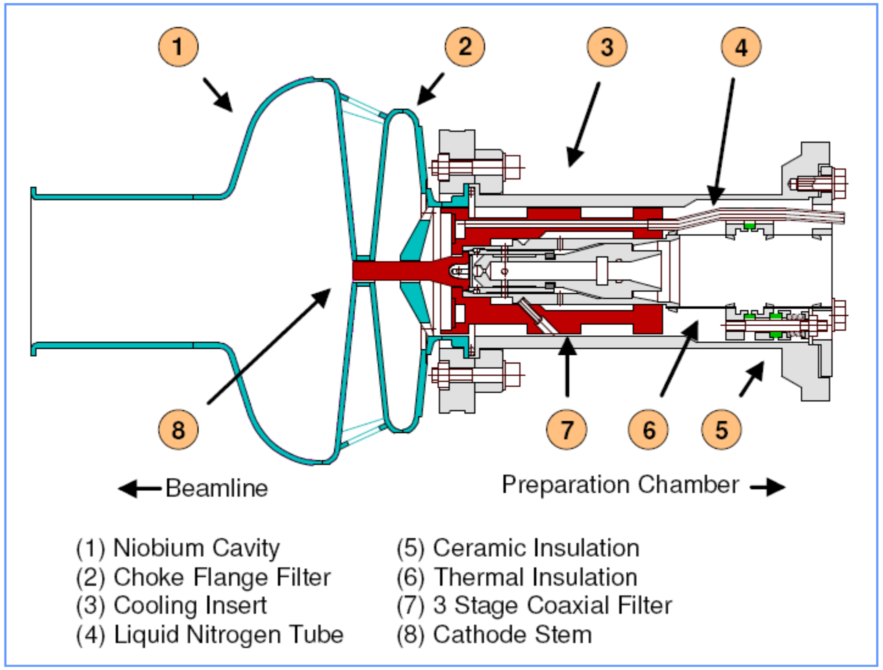
slide adapted from: J. Grames, JLab, USA

Radio Frequency Guns

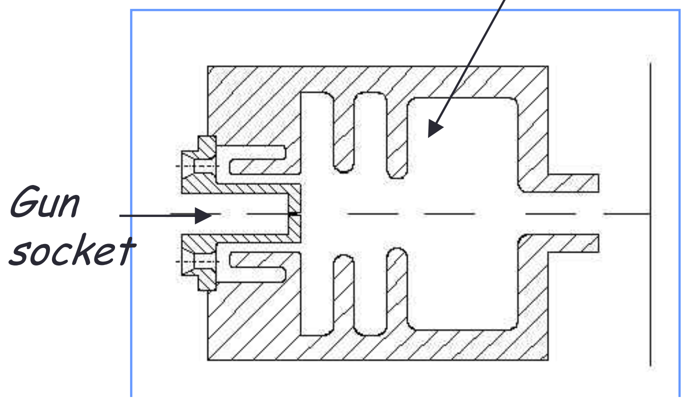
The RF gun is the name given when the electron ion source is directly coupled to a RF Cavity

- compact solution to accelerate directly above MeV Energies
- Work function reduced by the Shottky effect
- higher currents are reachable
  - space charge limitation at a much higher beam intensity
- Can be used with many kind of electron source

Rossendorf ½ cell Supercon. RF gun prototype



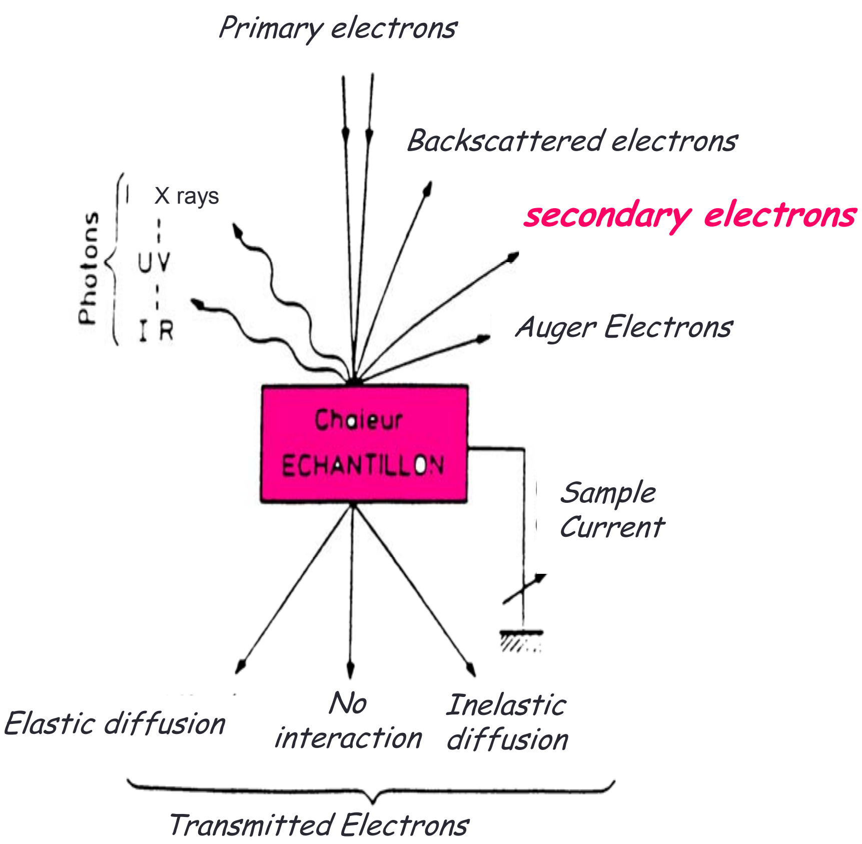
D.Janssen et al., NIM A507(2003)314.



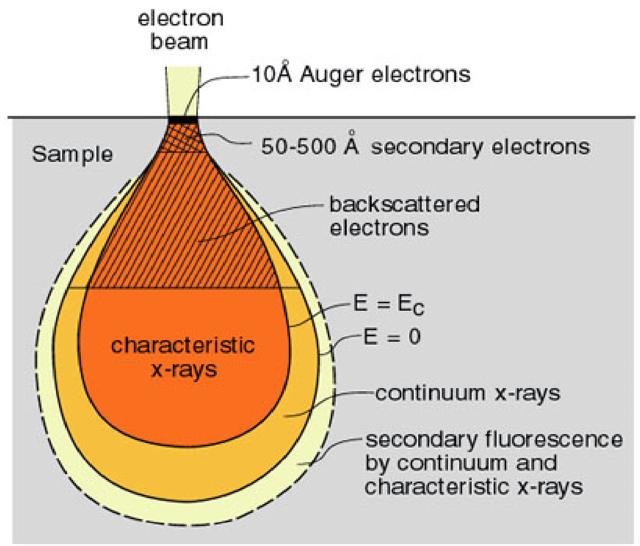
A 3 GHz thermionic RF gun has been designed. It will produce a 2.3 MeV electron beam with bunch charge up to 0.2 nC (600 mA) at 10 pmm mRad normalised emittance.

Secondary electron emission

- Any particle (ion, electron, photon) impinging on a material with an energy higher than the electron work function *W* of this material can eject **secondary electrons** (among many other things…)
  - Electron penetration depth: $x(\mu m) = \frac{0.1E^{1,5}}{\rho}$, ρ material density in *g/cm³* , E *kinetic energy in KeV*



Interaction volume of different effects



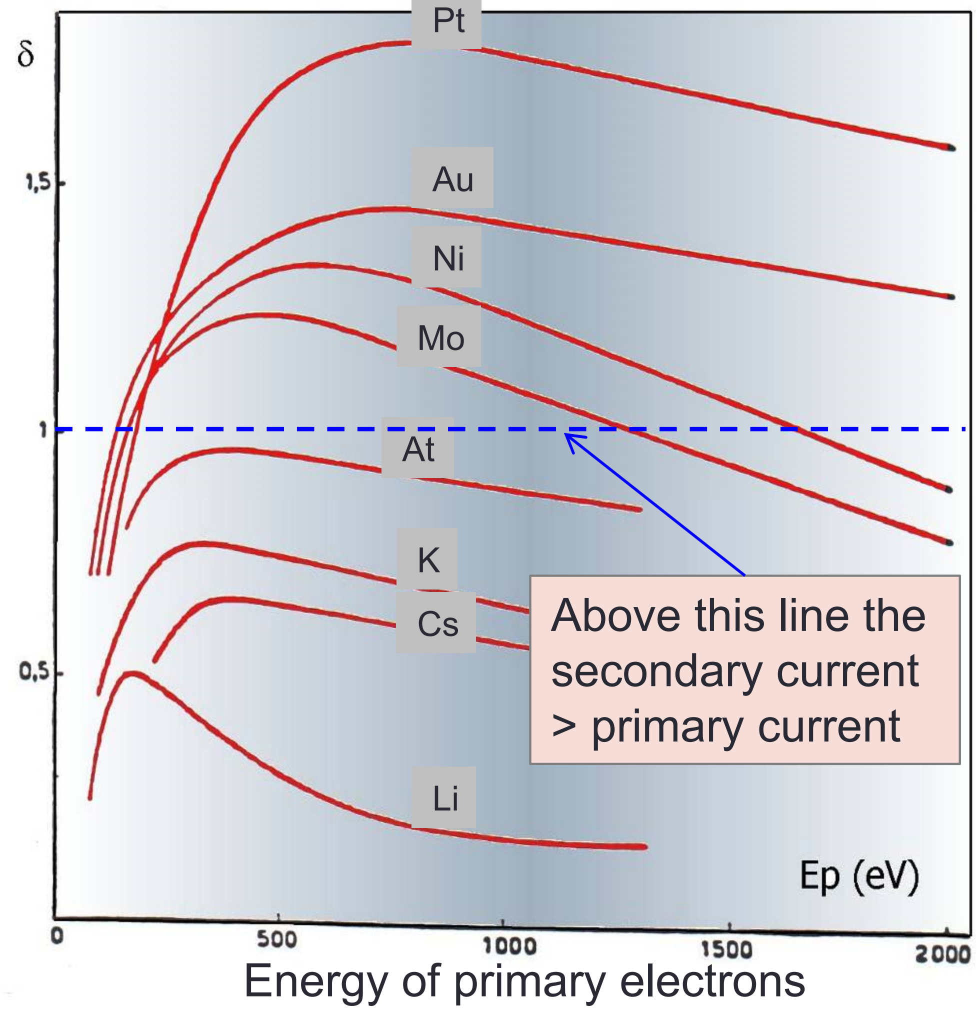
http://www4.nau.edu/microanalysis/microprobe-sem/signals.html

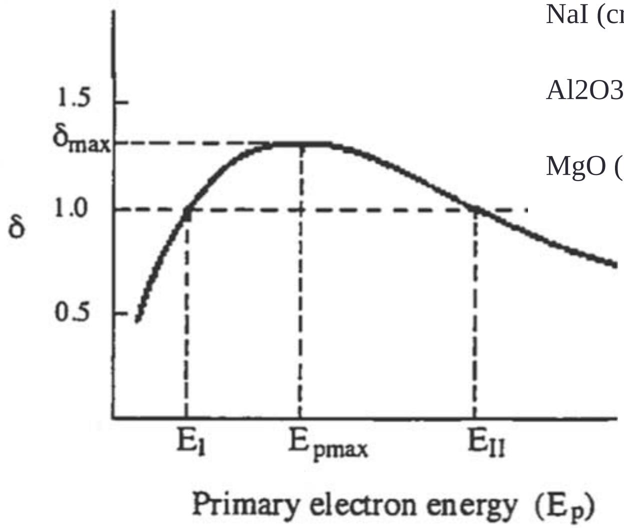
Slide adapted from J. arianer, H. Koivisto

Secondary electron Yield

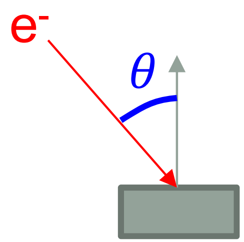
SE Yield: $\delta = \dfrac{N_{e_s}}{N_{e_p}}$ $\dfrac{\text{Secondary electrons}}{\text{Primary electrons}}$

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		



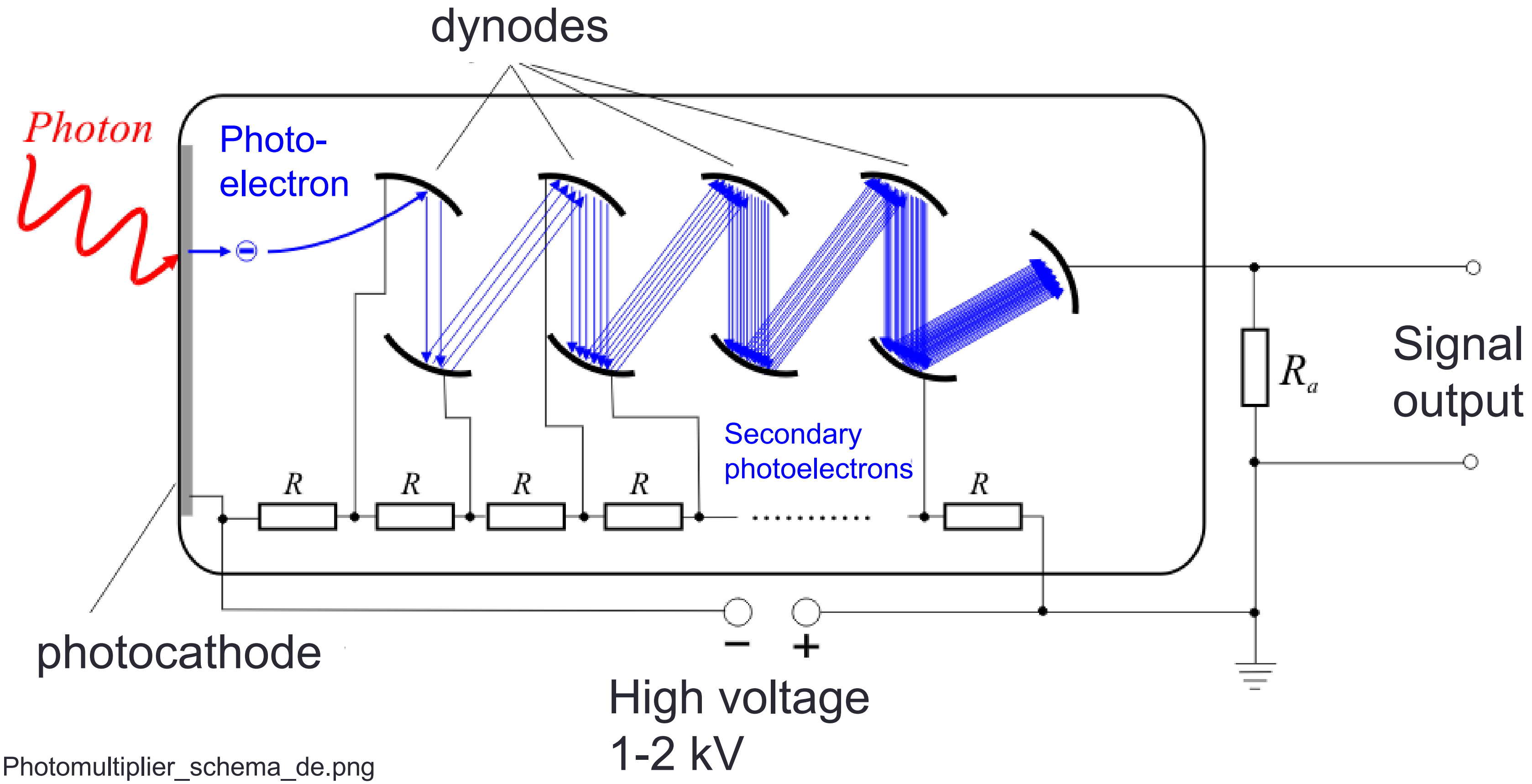


- SE Yield depends on:
  - Material
  - Contamination
  - Energy
  - Incident angle : $\delta(\theta) \sim \dfrac{\delta_0}{\cos\theta}$
  - SE emission can be used to amplify an electron signal!



The photomultiplier

- It's not exactly an electron source, but a concept of interest in this lecture….
  - Can detect a single photon
  - 1 photon →1 photo-electron→ n secondary elecotron/dynode/electron
  - The electron signal is amplified (and accelerated) through a set of dynodes



http://commons.wikimedia.org/wiki/File:Photomultiplier_schema_de.png

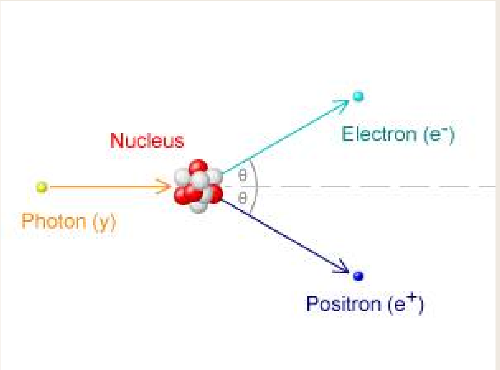
Electron source beam emittance

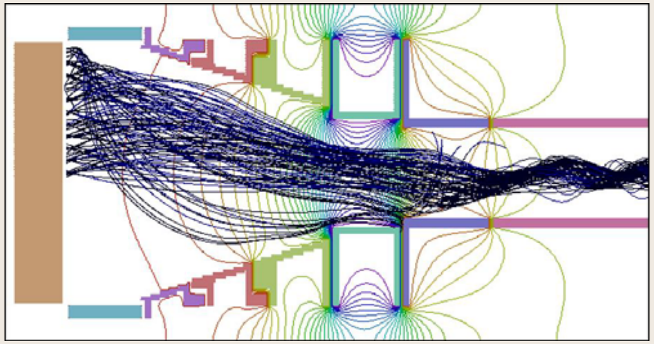
- General formula for a 1 σ RMS normalized transverse emittance: $\epsilon_N = \gamma\beta\sigma_x\sigma_{x'}$
  - $\sigma_x = \sqrt{\langle x^2 \rangle}$ RMS beam size, calculated on the cathode surface
  - $\sigma_{x'} = \frac{\sqrt{\langle {p_x}^2 \rangle}}{p}$
- Thermionic gun
  - $\boldsymbol{\epsilon_N = \sigma_x \sqrt{\frac{kT}{m_e c^2}}}$
    - $\sigma_{x'} = \frac{\sqrt{\langle {p_x}^2 \rangle}}{\gamma\beta m_e c} = \frac{\sqrt{\langle {v_x}^2 \rangle}}{\gamma\beta c} = \frac{1}{\gamma\beta c}\sqrt{\frac{kT}{m_e}}$, assuming a Maxwell Boltzmann distribution
- Field emission
  - $\boldsymbol{\epsilon_N = \sigma_x \sqrt{\frac{E_F}{m_e c^2}} \left[\frac{4E_F}{\hbar F}\sqrt{2m_e w}.t(y) - 1\right]^{-1/2}}$
    - $F = e \times [Electric\ field\ intensity]$
    - $w\ work\ function\ of\ cathode$
    - $E_F\ Fermi\ energy$
    - $t(y) \cong 1 + \frac{1}{9}y^2(1 - \ln(y))$, with $y = \sqrt{\alpha\hbar c F}/w$, $\alpha = e^2/\hbar c 4\pi\epsilon_0$
- Photo emission (pulsed beam)
  - $\boldsymbol{\epsilon_N = \sigma_x \sqrt{\frac{\hbar\omega - w - \sqrt{\alpha\hbar c F}}{3 m_e c^2}}}$

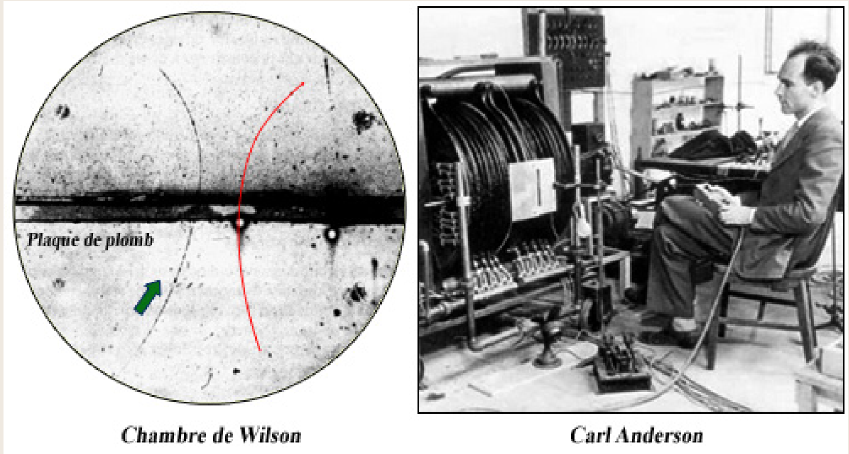
Electron source type	ϵ_N/σ_x [micron/mm]
Thermionic	~0.3
Field Emission	~0.5-1
Photo Emission	~0.5-2

N.B. : micron is a commonly used unit in the electron beam community:
- $1\ \pi.mm.mrad$ emittance corresponds to
- $3.14 \times 10^{-6}\ m.rad \Leftrightarrow 3.14\ \mu m$

See K.L. Jensen et al., Jour. Appl. Phys. 107, 014903 (2010)







C.D. Anderson, Physical Review 43, 491 (1933)

POSITRON SOURCE

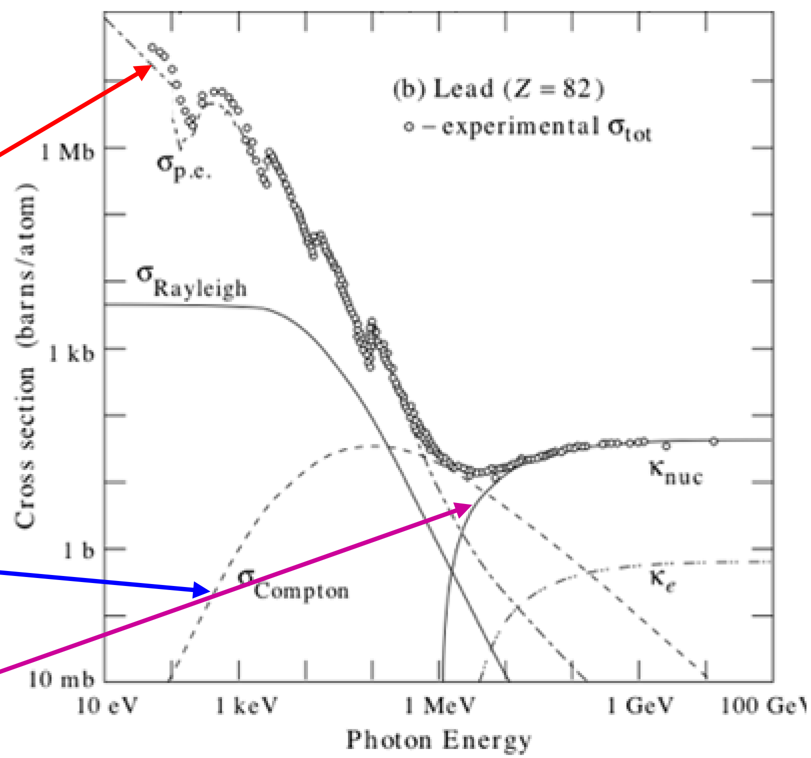
An introduction

Positron Source

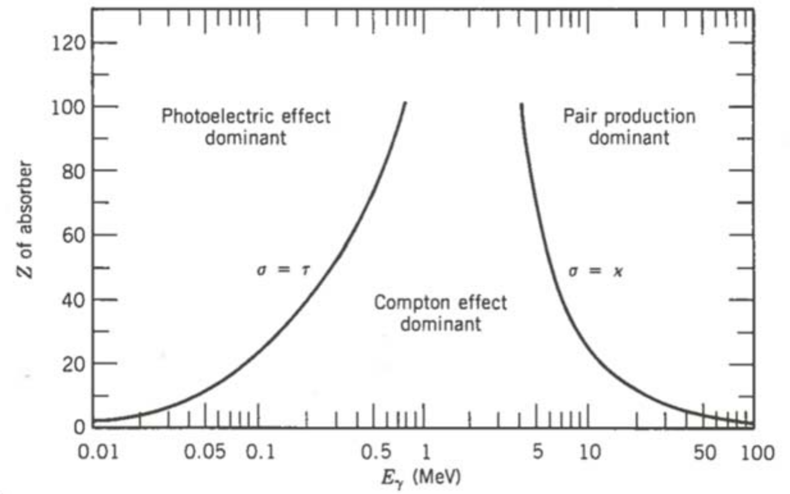
- The positron is the antiparticle of the electron, it has a positive charge
- Mechanism to make a positron:
  - β^-decay :
    - ${}^{A}_{Z}N \rightarrow {}^{A}_{Z}N' + e^+ + \nu_e$
    - Many nuclear reactions occur through the β^-decay channel
  - Pair production:
    - $\gamma + X \rightarrow X + e^+ + e^-$, where X is either a nucleus or an electron
    - The gamma photon must have an energy $E > 2m_e c^2 \sim 1\ MeV$
    - The pair production process is dominant at high energy
- Interaction of positron with matter
  - The positron interact with an electron to form a quasi-stable positronium which eventually anihilates into two photons: $e^+ + e^- \rightarrow \gamma + \gamma$
- Interest of the positron:
  - Condensed matter study: positrons can penetrate deeply into matter and can help making non-destructive 3D analysis of materials
  - Accelerator : positron is foreseen to be used in a leptonic collider able to accelerate both $e^+$and e^- in the same vacuum pipe → **CLIC**

Photon Interaction with matter

- The main photon interaction with ordinary matter depends on its energy:
  - Low energy: the photoelectric effect is dominant (*E<1 keV*). Interaction of the photon with the bound electrons.
  - Medium energy: the Compton effect is dominant (*1 keV<E<1 MeV*). Diffusion of the photon on a knocked-out electron
  - High Energy: the **pair production** is the dominant effect (*E>1 MeV*)
    - $\gamma + X \rightarrow X + e^{+} + e^{-}$
    - X is either a nucleus or an electron
    - Threshold energy $E > 2m_e c^2 \sim 1\ MeV$
- The cross section of these processes increases with the atomic number Z

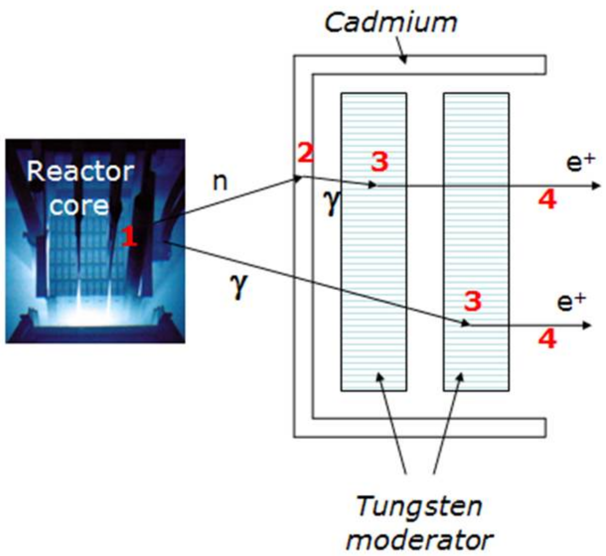


K.S. Krane, Introductory Nuclear Physics

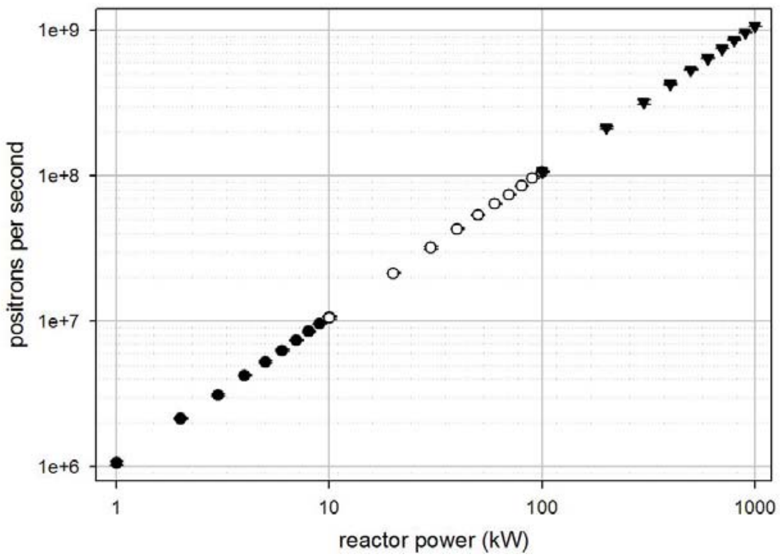


Positron beam at NC State University (1/2)

- A 1 MW nuclear reactor (PULSTAR) generates neutrons and gammas
  - Neutrons are converted into γ in a cadmium shroud
  - γ are converted in $e^+ + e^-$ pair in Tungsten metal strips
  - The tungsten strips also play the role of moderator to slow down e^+ to a few eV

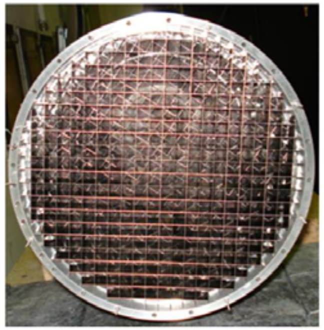


1. Neutrons (n) and gammas (γ) are emitted from fission reactions in the reactor core.
2. Neutrons react in the cadmium shroud producing additional gamma rays.
3. Gamma rays interact by pair production in the tungsten moderator to form positrons.
4. Positrons thermalize and are emitted from the tungsten surface with energies of a few electron volts (eV).



Positron beam intensity available for experiments

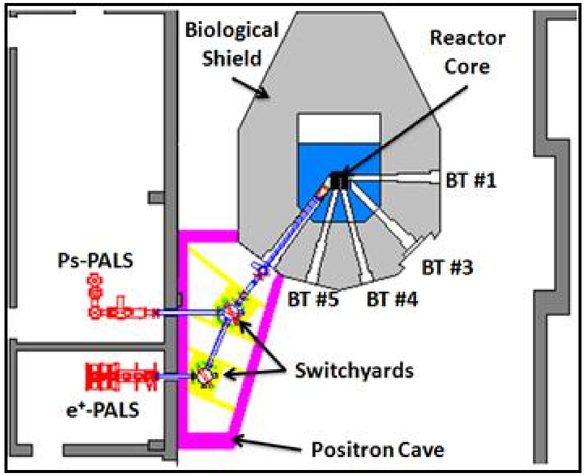
Tungsten Moderator Assembly
- 2 Moderator Banks
- Made from Tungsten metal strips
- Each bank 8" OD, 1 in thick
- Cleaned and annealed at 2200K for 4 hours
- Evacuated to 5E-8 millibar



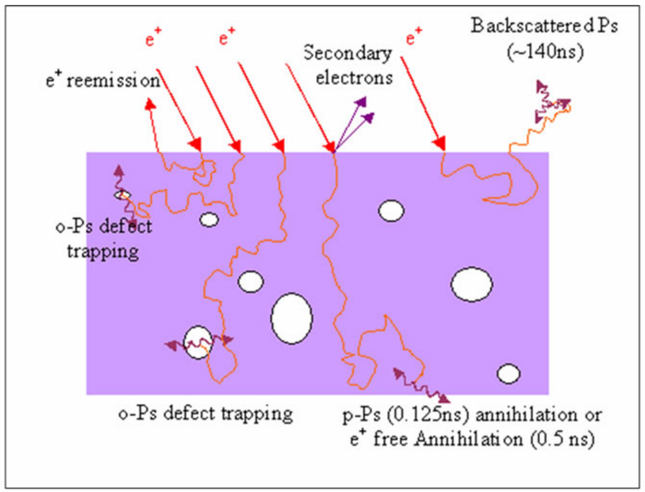
Content extracted from http://www.ne.ncsu.edu/nrp/ips.html

Positron beam at NC State University (2/2)

- e^+ are focused by Electrostatic lenses at the exit of the converter
- e^+ beam is transported in a magnetic LEBT toward experimental caves
- Application of positron beam: non destructive technique to detect defects and free volume in a wide variety of material
  - Pore sizes ranging from several angstroms to ~30 nm can be determined
  - Positron often form meta-stable positronium ($e^+ - e^-$bound state)
  - Positron and positronium naturally seek out the defects and void due to coulomb and dielectric interaction

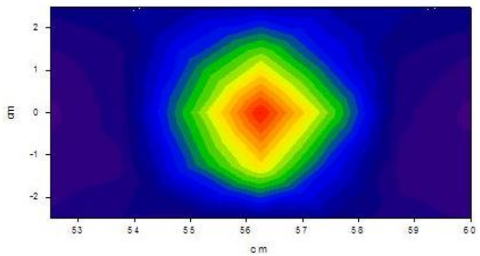


Beam line overview with the reactor

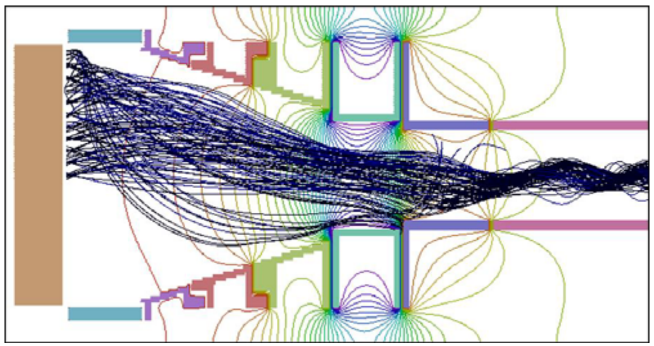


Positron and Positronium Interactions with Condensed Matter

Figure courtesy of NanoPos group, Dept. of Physics, Univ. of Michigan



Beam profile



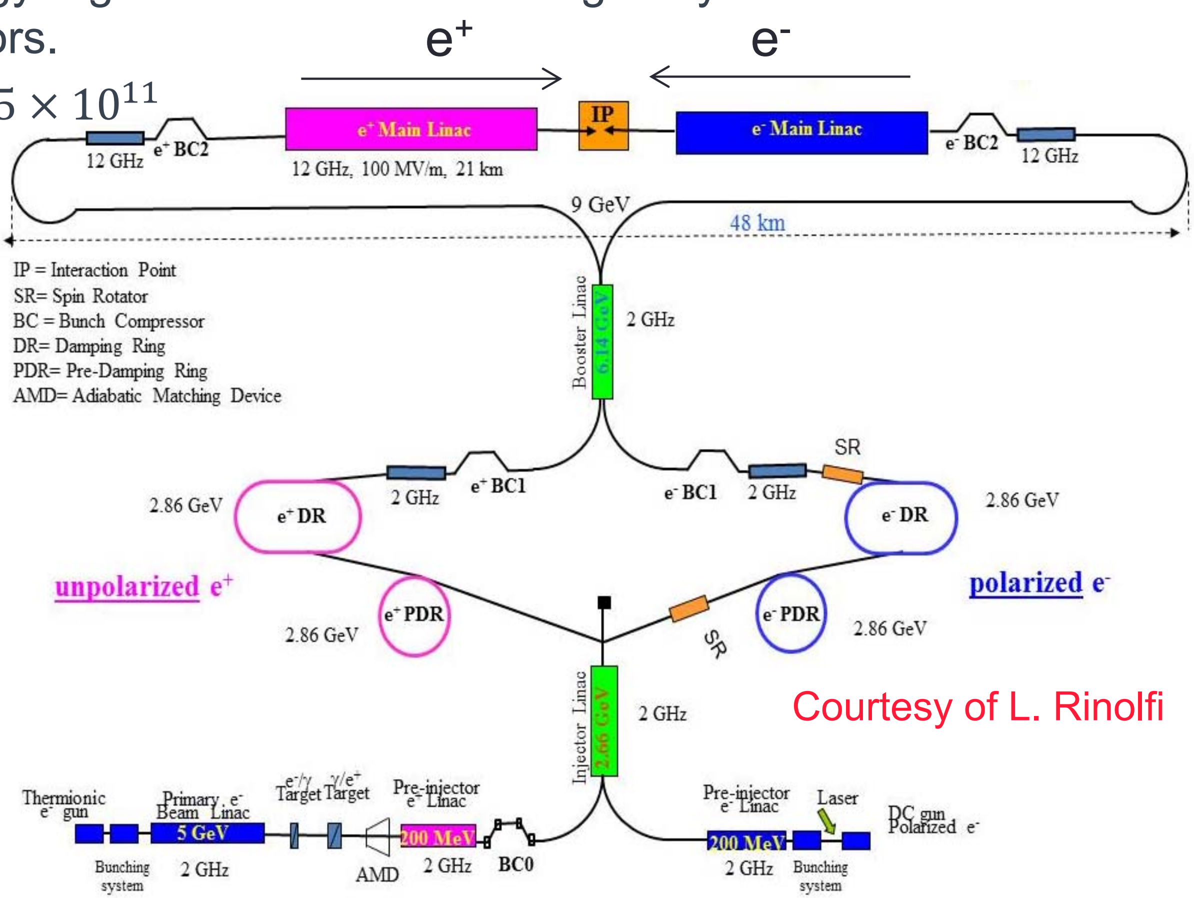
Electrostatic Focusing Lens

Positron beam for the CLIC facility

- 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) $\approx\ 11.5 \times 10^{11}$
  - Flux: $1.1\ \times 10^{14} e^+/s$ (challenging!)

- How to produce such a Flux?

3 schemes…/…

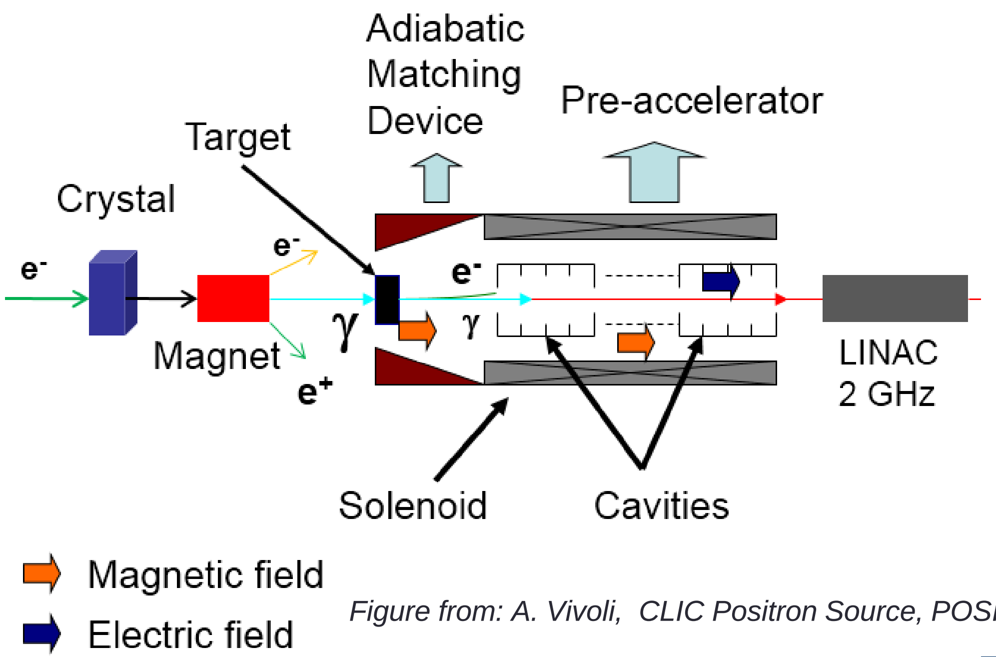


Courtesy of L. Rinolfi

CLIC baseline scenario

Possible schemes to produce positrons for CLIC (1/3)

- Scheme A, (up to date) Conventional way:
  - a 5 GeV primary e^- pulsed beam is first converted into γ in a tungsten crystal oriented on its <111> axis.
    - γ escape the target helped with the **channeling effect**
    - e^+e^-, also created in this section, are next swept away by a magnetic dipole
  - The γ are next converted into e^+e^- pairs in a thick amorphous tungsten target
  - An Adiabatic Matching Device (tapered axial magnetic field) focuses the e^+ beam
  - A pre-injector LINAC capture the e^+ bunches and accelerate them up to 200 MeV



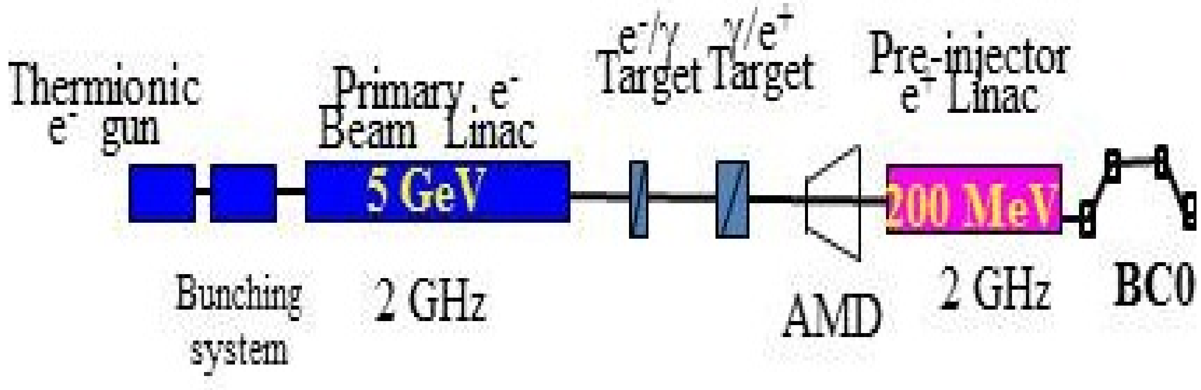
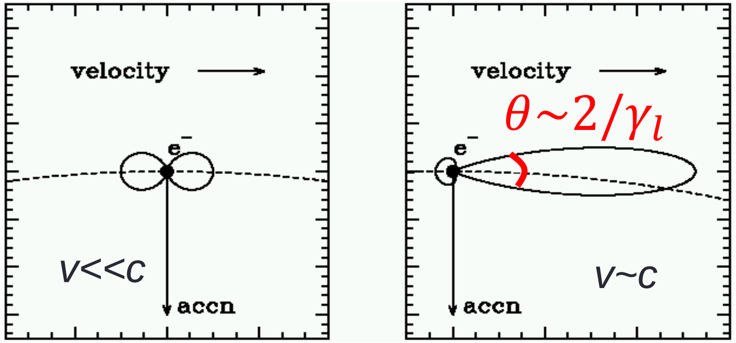


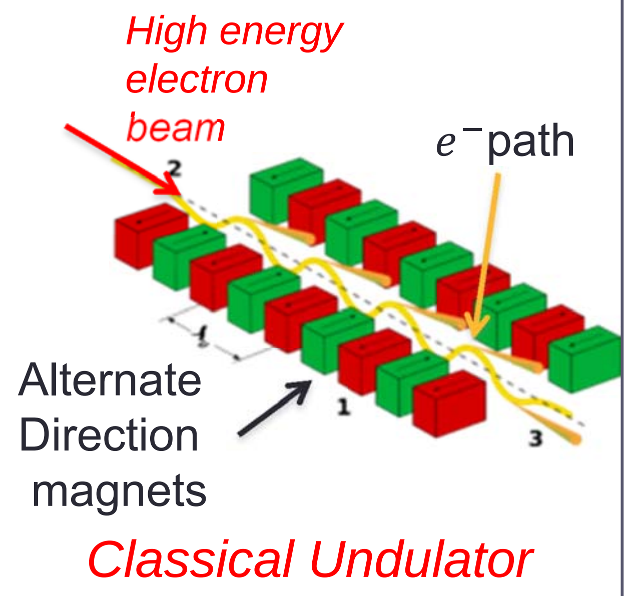
Figure from: A. Vivoli, CLIC Positron Source, POSIPOL 2009, LYON

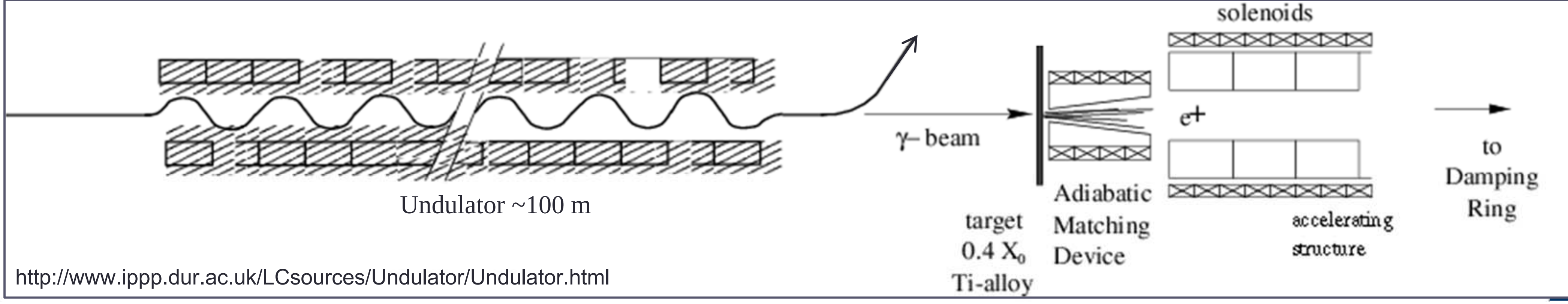
Possible schemes to produce positrons for CLIC (2/3)

- Scheme B: Undulator based γ-radiation:
  - γ photons can be produced by synchrotron radiation from a high energy e^- beam
  - Any charged particle radiates photons when it accelerates
  - An electron placed in a magnetic field radiates synchrotron light
  - The higher the Lorentz factor γ_l, the higher the photon collimation
  - The longer the undulator, the higher the γ photon intensity
- <u>This process suppresses the use of the scheme A crystal target</u>



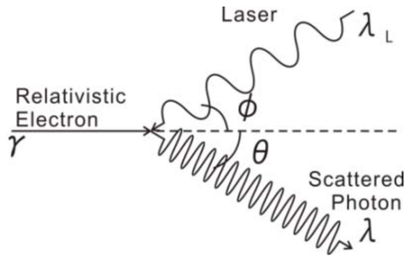
Synchrotron radiation from an electron turning in a magnetic field
(http://www.astro.utu.fi/)





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

Possible schemes to produce positrons for CLIC (3/3)



- Scheme C: Compton back-scattering
  - A 1 GeV electron beam interacts with a circularly polarized laser beam
  - Circularly polarized γ photons are emitted via Compton backscattering
  - The polarized γ photons generate polarized e^+ via pair production in target
- Advantages:
  - Suppresses the crystal target
  - Higher collider reaction cross section with polarized e^+ and polarized e^- beams
- Inconvenient:
  - Requires electron and laser bunch intensities which are not available today

The CLIC 3 scheme will require strong and active R&D!

Reuse high power laser pulse by optical cavity.