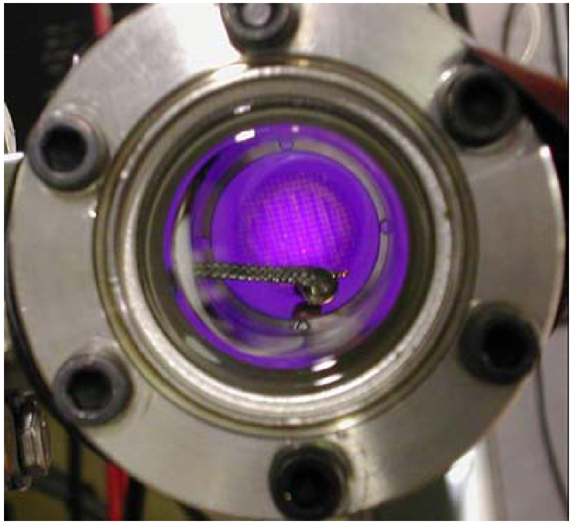
Part I

Introduction to Electron Sources

T. Thuillier

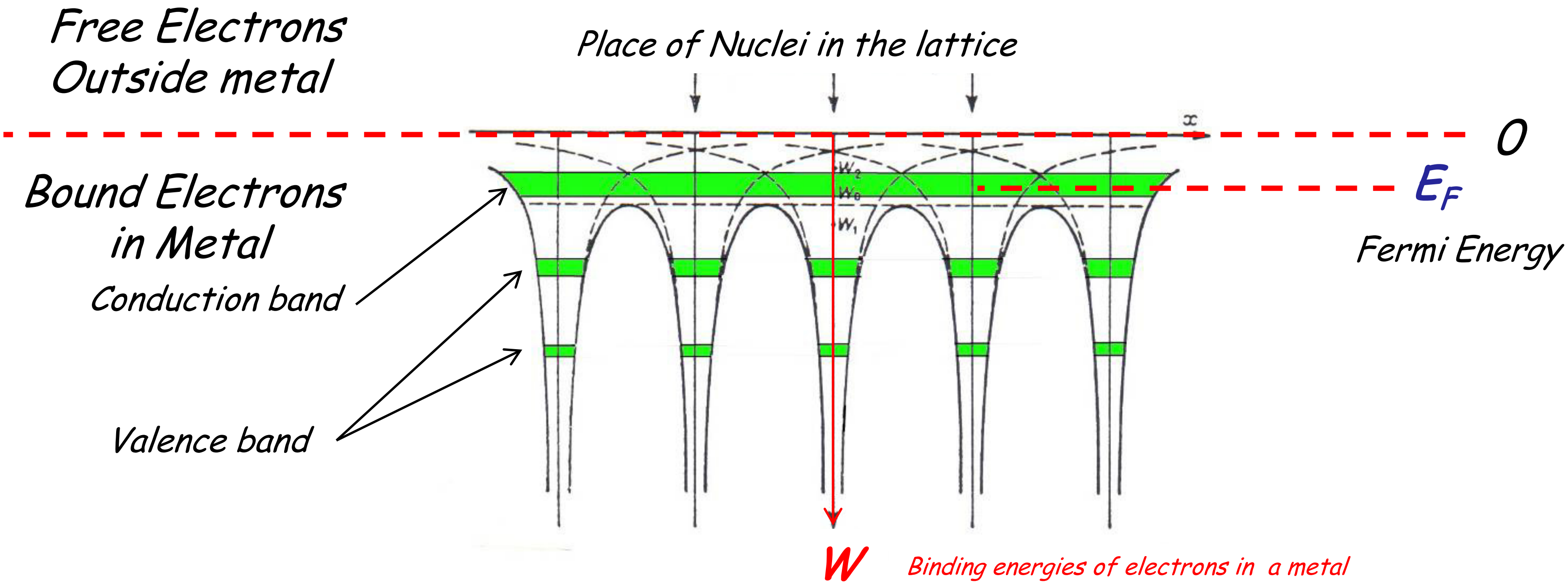
Laboratoire de Physique Subatomique et de Cosmologie ,CNRS -IN2P3-UJF-INPG, 53 rue des martyrs, 38026 GRENOBLE cedex, France

- Thermionic electron sources
- Field Emission electron sources
- Photo Emission electron sources
- Secondary Emission Electron source
- FerroElectric GUN
- RF GUN



Work Function of electrons in metals (reminder)

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



Binding energies of electrons in a metal

Drawing Extracted from : J.Arianer lectures

- In a metal, some electrons are populating the Conduction Band
- The minimum binding energy of electrons in metal corresponds to the Fermi Energy: $W=E_F$

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				

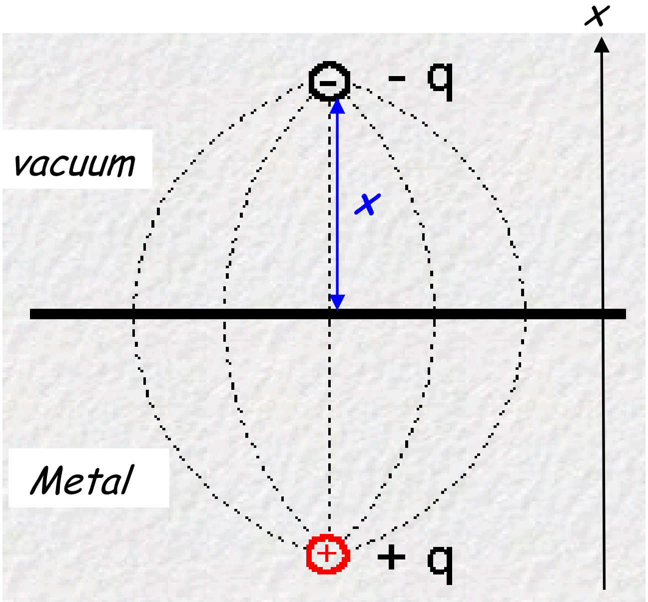
Max Min

The 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)* generated by the charge image (hole) acting on the electron is:

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

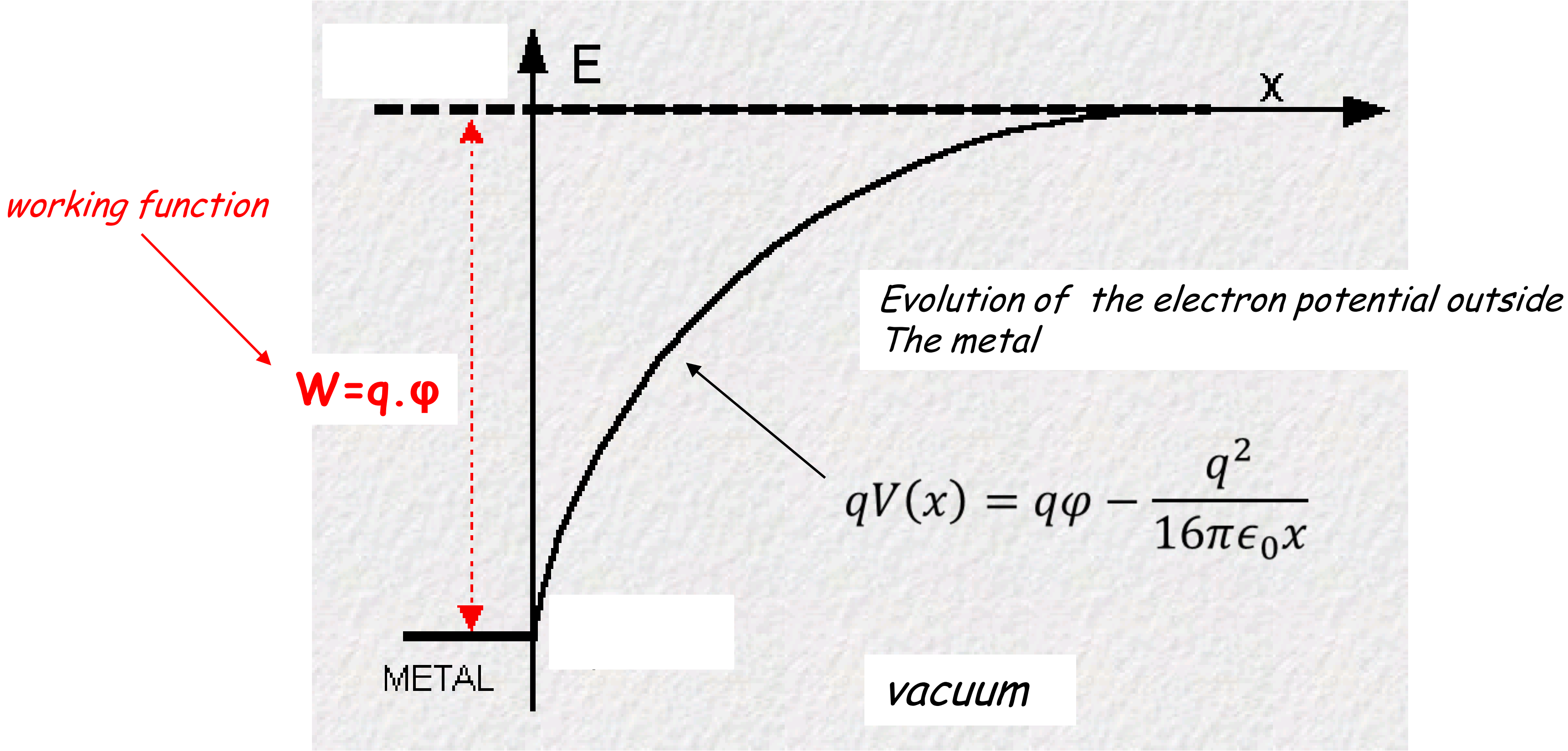


- This electric field tends to attract back the electron toward the metal

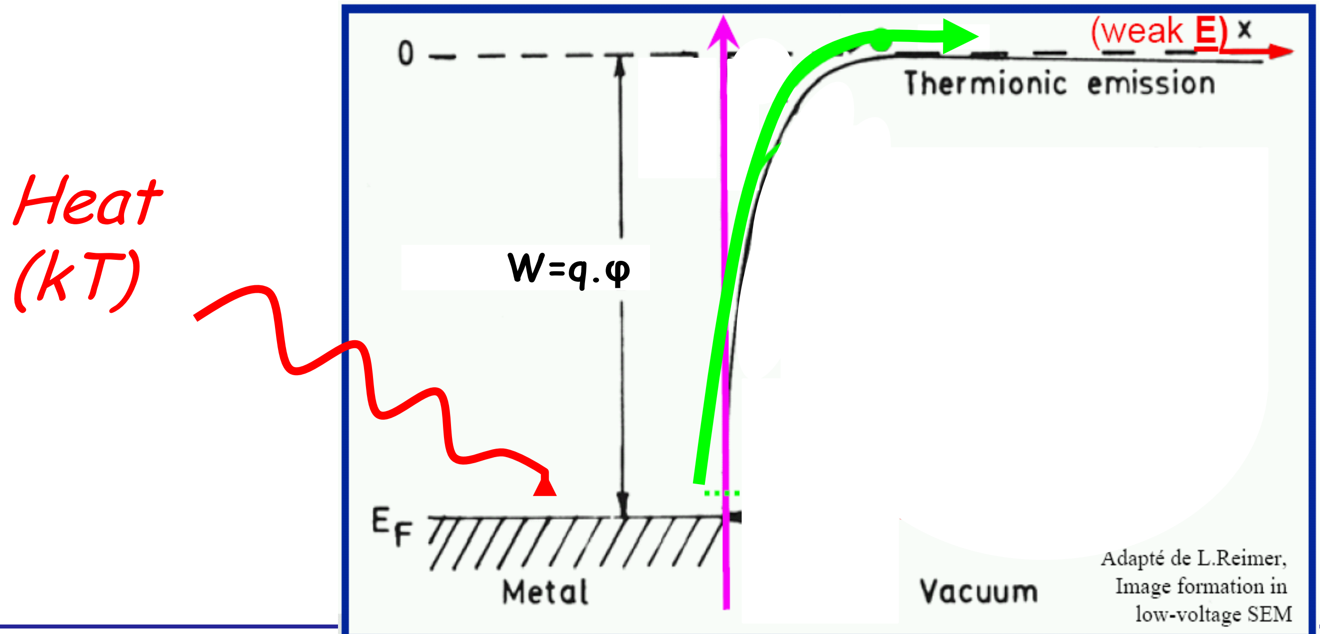
- The Associated potential energy $V_{CI}(x)$ is:

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

- Resulting potential plot near to a metallic surface due to the charge image is $V(x)=W-V_{CI}(x)$
- The electron should be extracted with an energy $E>W=q.\varphi$



- The first way to extract electrons is to heat the metal to high temperature T
  - When the metal is heated, the thermal vibrational energy of electrons can excess the Work Function : **kT > e.φ**
- **The thermionic emission** is the resulting flow of electrons extracted from the heated metal
- Application of a negative voltage (weak E field) helps electron extraction from the metal surface



The Thermionic emission flow is ruled by the Richardson-Dushman equation

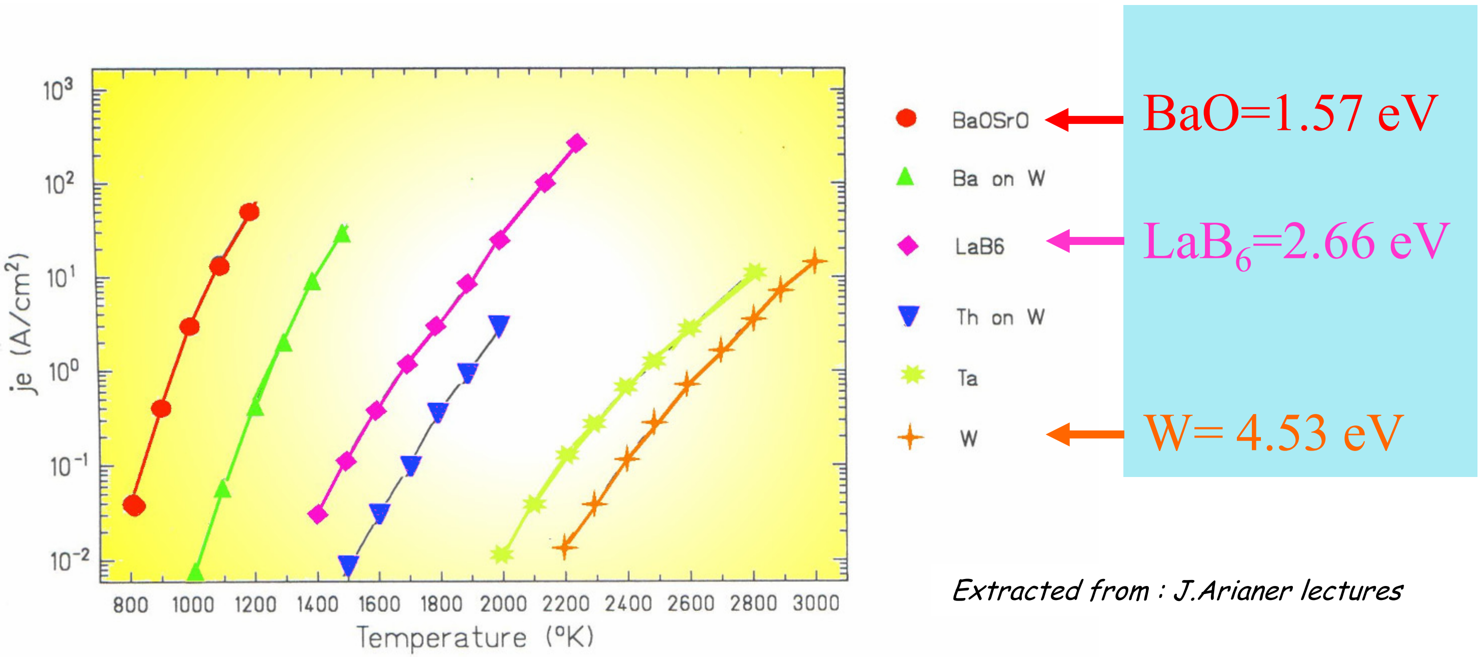
- ***J*** current density (A/cm2)
- ***A*** Richardson constant
- ***W*** =q.φ work function

$$J = AT^2 e^{\frac{-W}{kT}}$$

$$A = \frac{4\pi m k^2 e}{h^3} = 1.20173 \times 10^6 \,\mathrm{A\,m^{-2}}$$

Order of magnitudes :

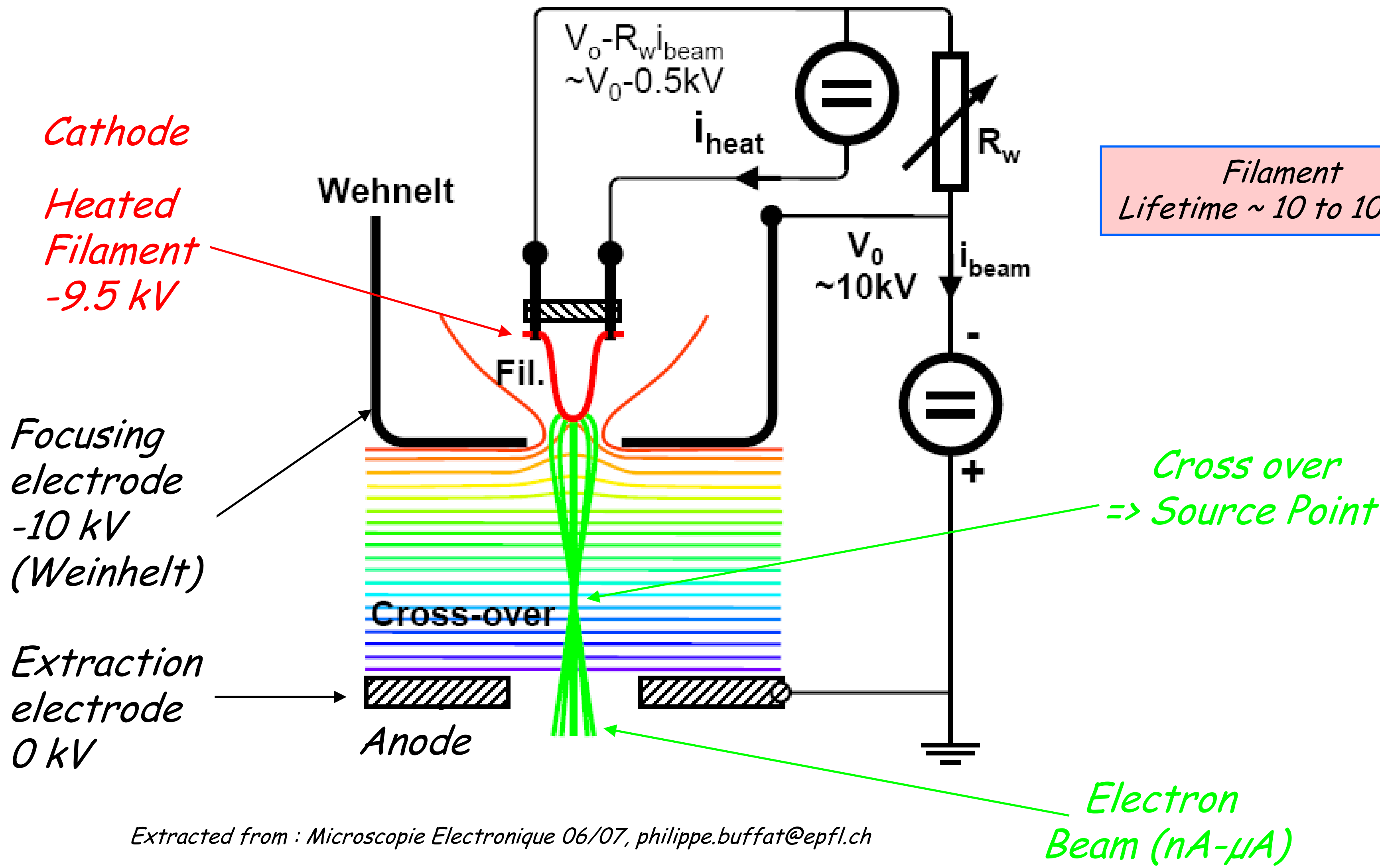
- ***W****olfram* : W_w~4.5 eV ; Tw~2700 K → J~10 A/cm^2
- ***LaB_6*** : W_{LaB6}~2.4 eV ; T_{LaB6}~2100 K → J~10^2 A/cm^2



Extracted from : J.Arianer lectures

Example of a Thermionic Electron Gun

Electronic Microscope source



Filament Lifetime ~ 10 to 1000 h

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

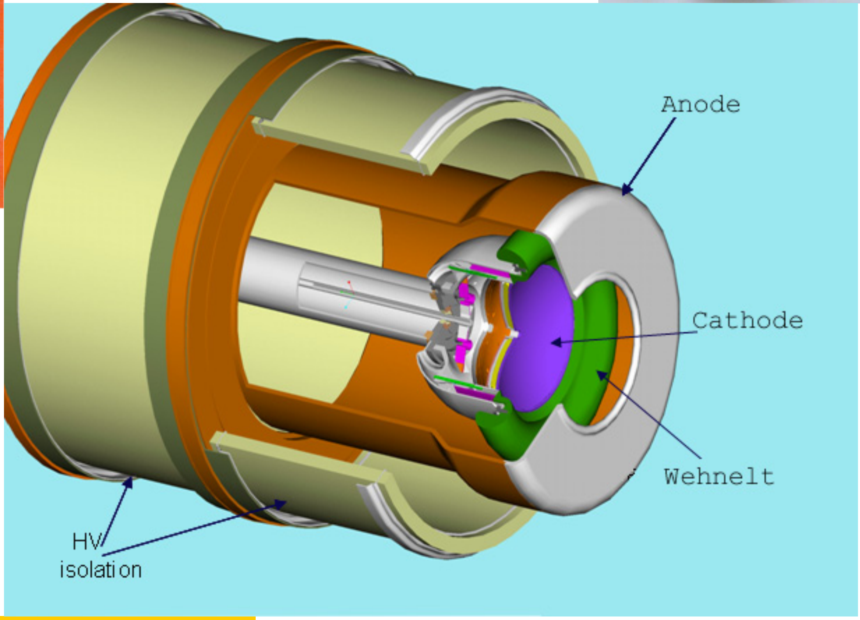
High intensity Thermionic Electron gun

Example of cathodes

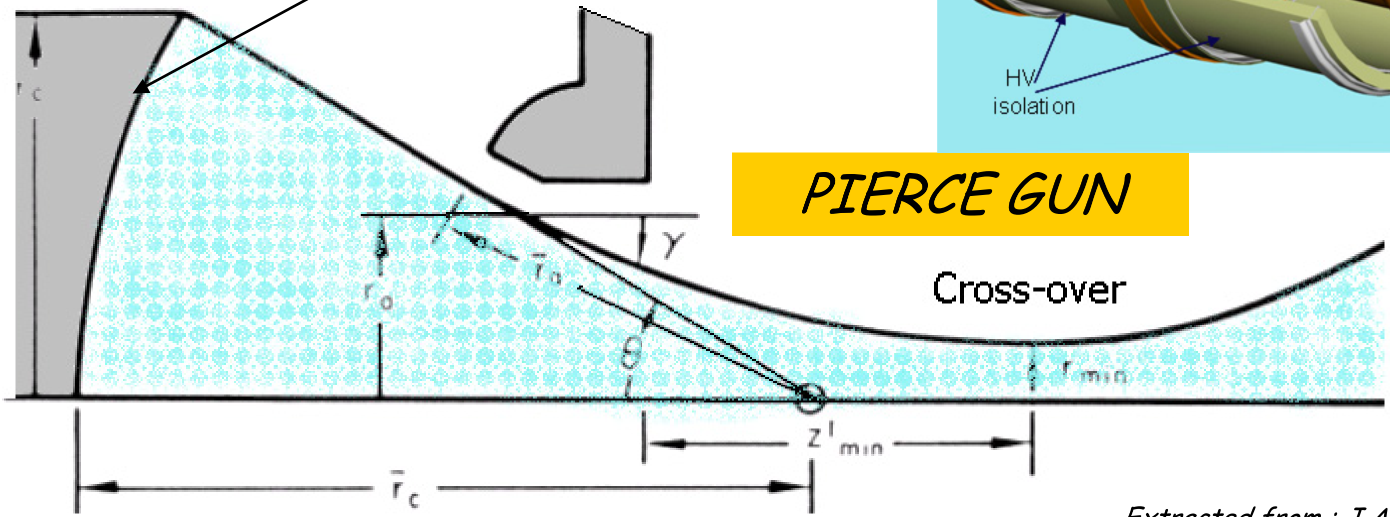
Depending on the design:

Currents from μA to ~100 A

cathodes damaged by sputtering (see later)



Spherical cathod



PIERCE GUN

Extracted from : J.Arianer lectures

- Schottky effect : reduction of the electron work function when an external electric field E is applied
  - Potential energy for *E*: *V(x)=-E.x*
  - New total potential $V_S(x)$:

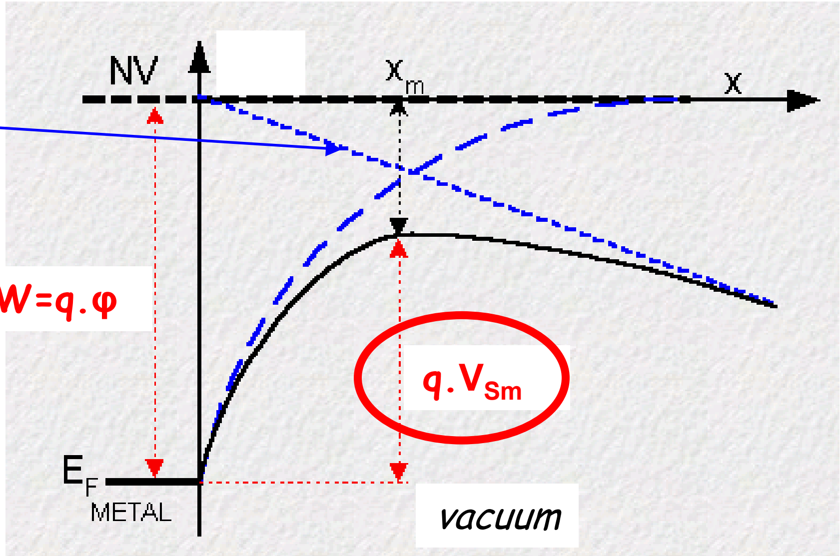
$$qV_S(x) = q\varphi - \frac{q^2}{16\pi\epsilon_0 x} - qE.x$$

  - Location of the optimum in x_m:

$$x_m = \sqrt{\frac{q}{16\pi\epsilon_0 E}}$$

  - And the reduced working function qV_{Sm} is:

$$qV_{Sm} = q\varphi - \delta W \qquad \textit{with} \qquad \delta W = 2qE.x_m = \sqrt{\frac{q^3 E}{4\pi\varepsilon_0}}$$

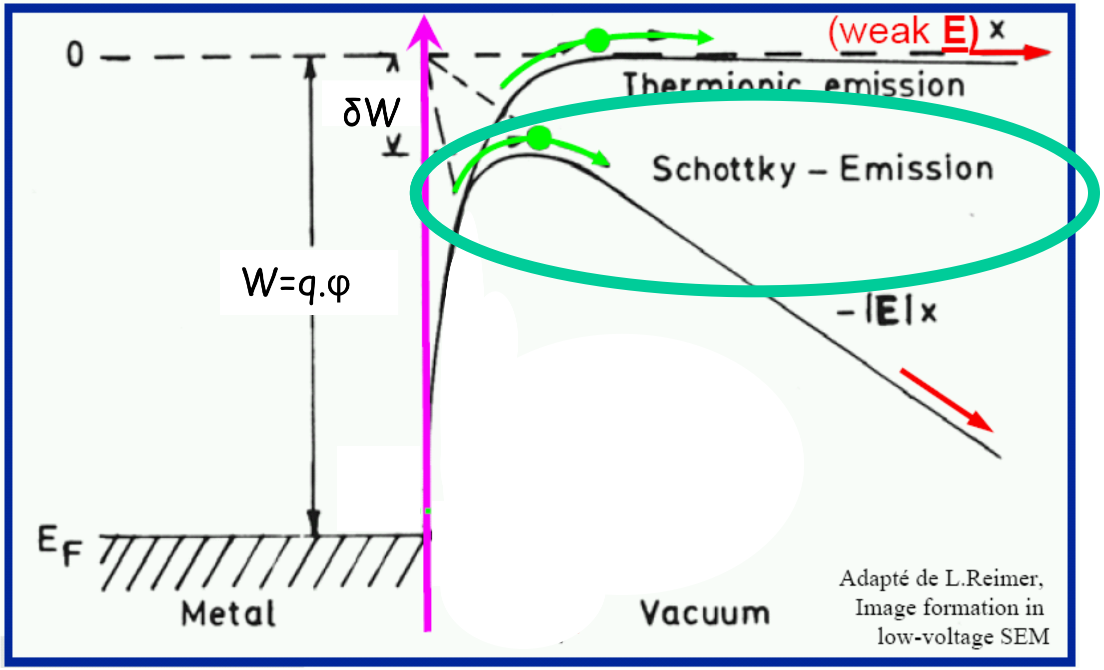


- Schottky effect is usually of second order :
  - E =10 kV/cm => δW=30 meV
  - E =100 kV/cm => δW=100 meV
  - Effect valid up to *E~1 MV/cm* => δW=0,3 eV

- Corrected Richardson-Dushman equation in presence of an externally applied medium electric field (Schottky emission)
- The Thermionic emission is enhanced thanks to the Work function decrease δW

$$J(E,T,W) = AT^2 e^{\frac{-(W-\delta W)}{kT}}$$

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



Field Electron 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
- It is a cold cathod emission => no metal heating is required

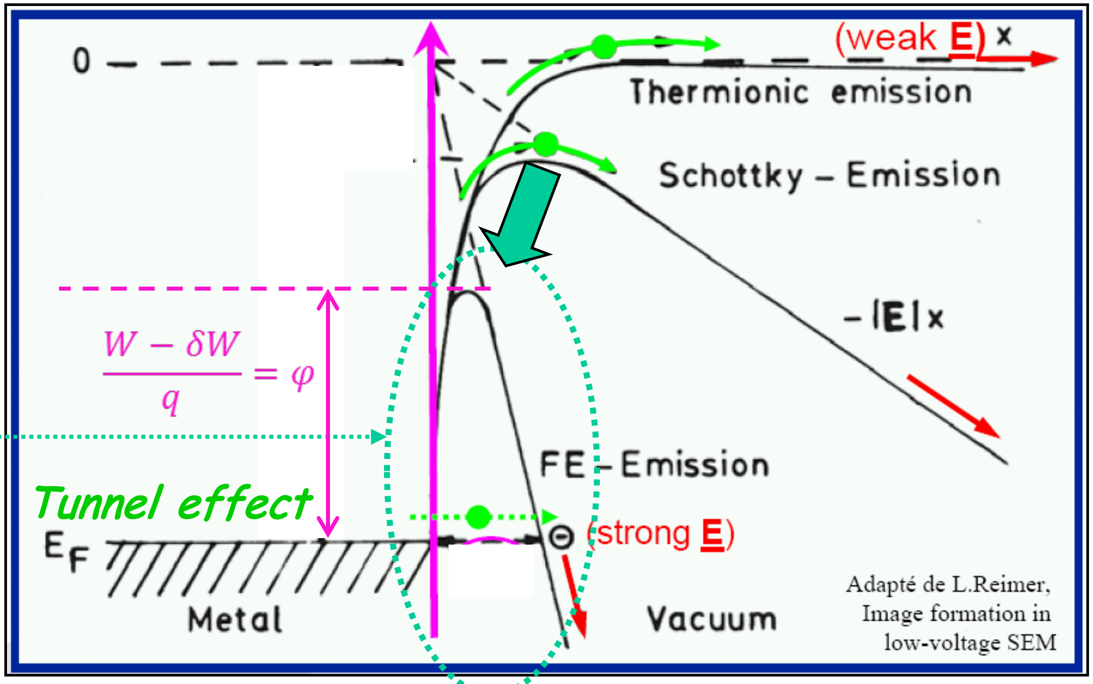
$$J \approx \frac{k_1 E^2}{\varphi} e^{-\left(\frac{k_2 \varphi^{3/2}}{E}\right)}$$

$$k_1 = 1.4\ 10^{-6} (SI)$$

$$k_2 = 6.87\ 10^{7} (SI)$$

- $J \sim 10^6\ A/cm^2$

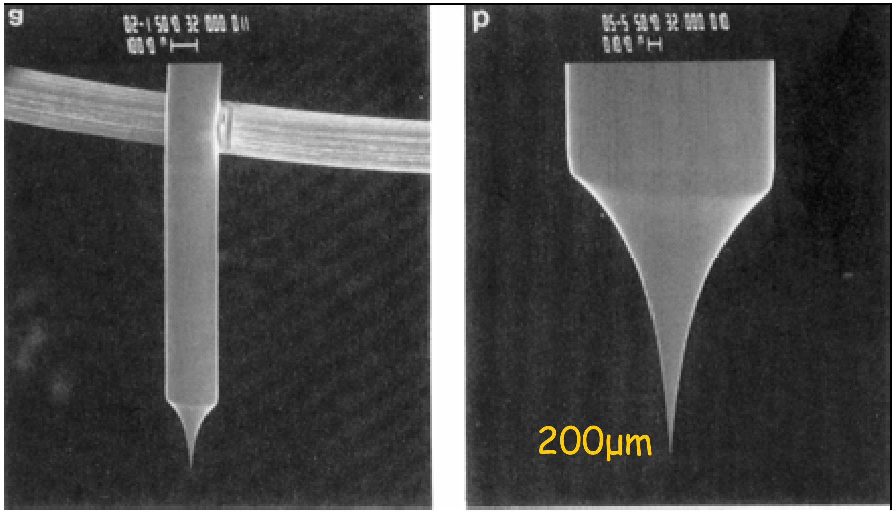
Field Emission (cold cathode)



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

Field Emission Electron Source (electronic microscopy)

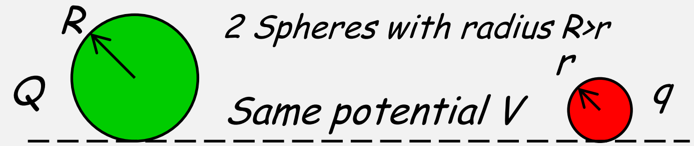
Example of a spike that concentrates the Electric field



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

(from J. Goldstein, Scanning electron microscopy)

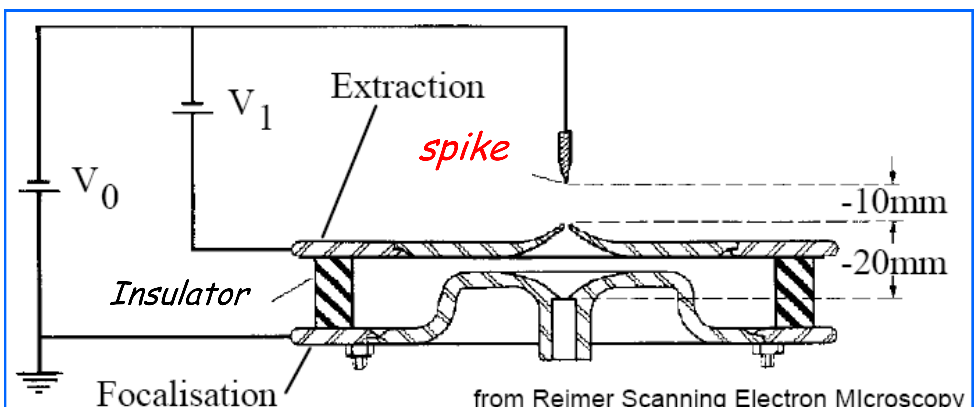
Electrostatic Point effect (Corona)



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

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

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



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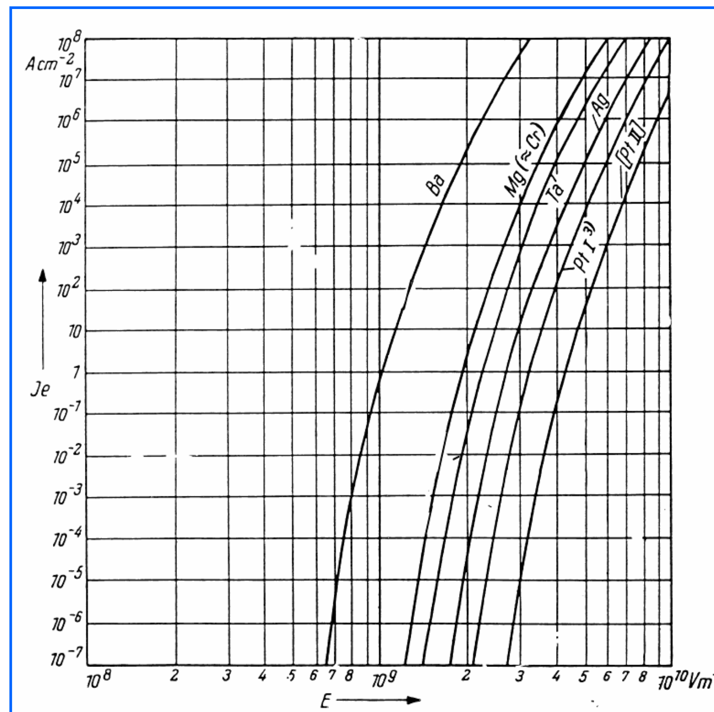
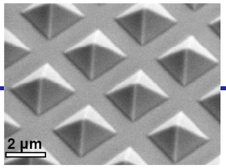
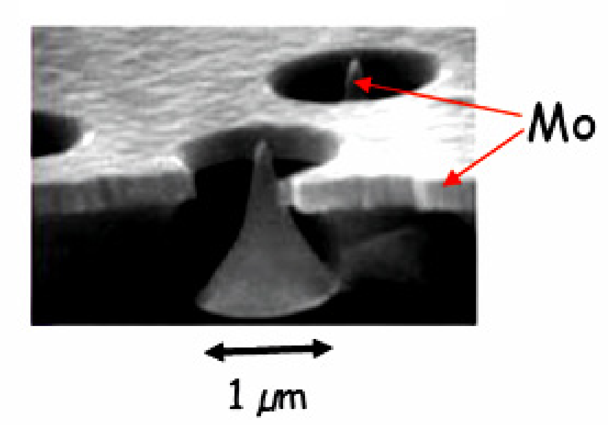
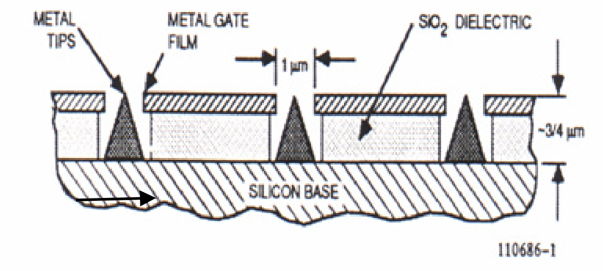


Field Emission Array GUN

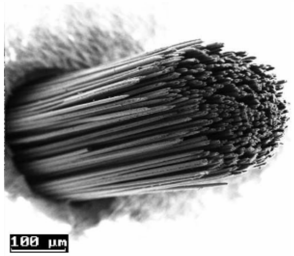


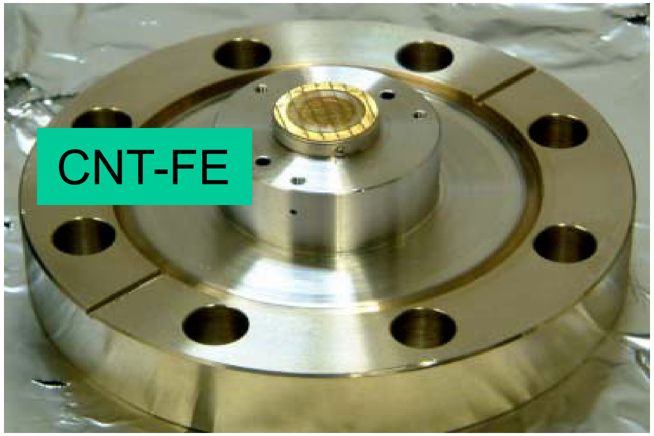
- Built on Si base substrate, using semi-conductor technology
  - Generation of large surface of Field emission array
  - At PSI: 50000 Mo spikes (tips) on a Ø 1 mm disk
  - Requires ultra high vacuum level

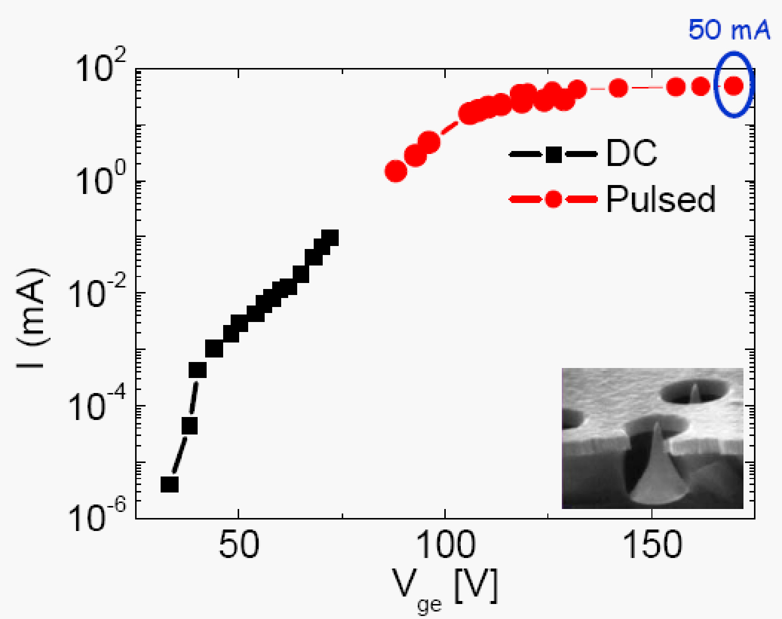




PSI





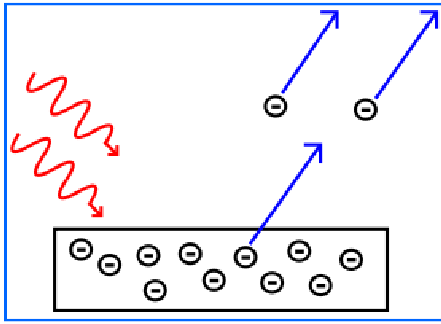


I-V curves in DC and pulsed regime for a Mo-tip FEA

Extracted from : J.Arianer lectures

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).

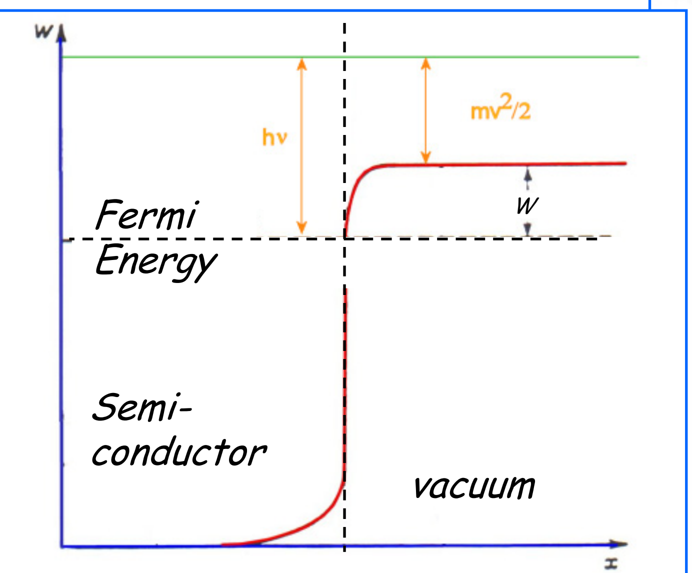


$$h\nu = W + \frac{1}{2}mv^2$$

Photon energy → $h\nu$

W=Work function of photocathode

$\frac{1}{2}mv^2$ ← *Electron kinetic energy*

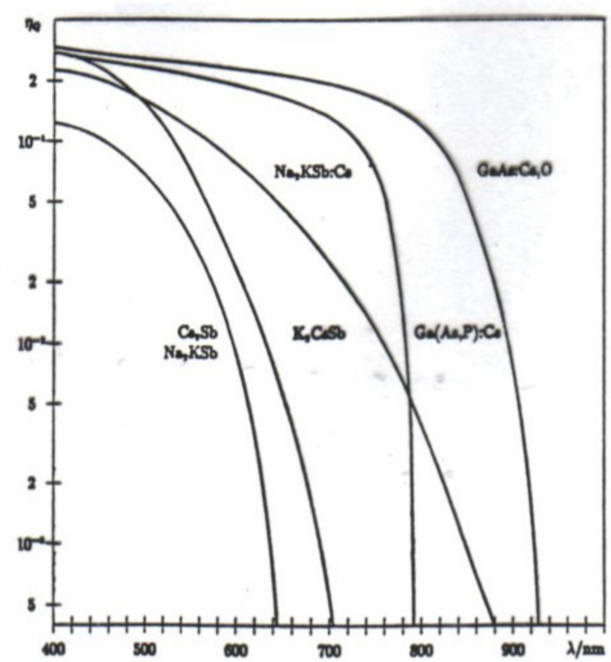


Extracted from : J.Arianer lectures

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

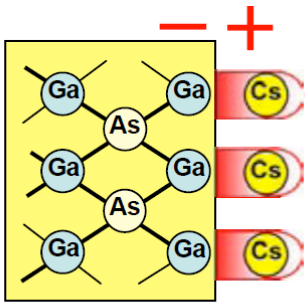
Material	ΔE [eV]	λ_0 [nm]
Cs_3Sb	1.95	640
K_2CsSb	1.8	700
$Na_2KSb:Cs$	1.4	890
GaAs:Cs,O	1.35	930

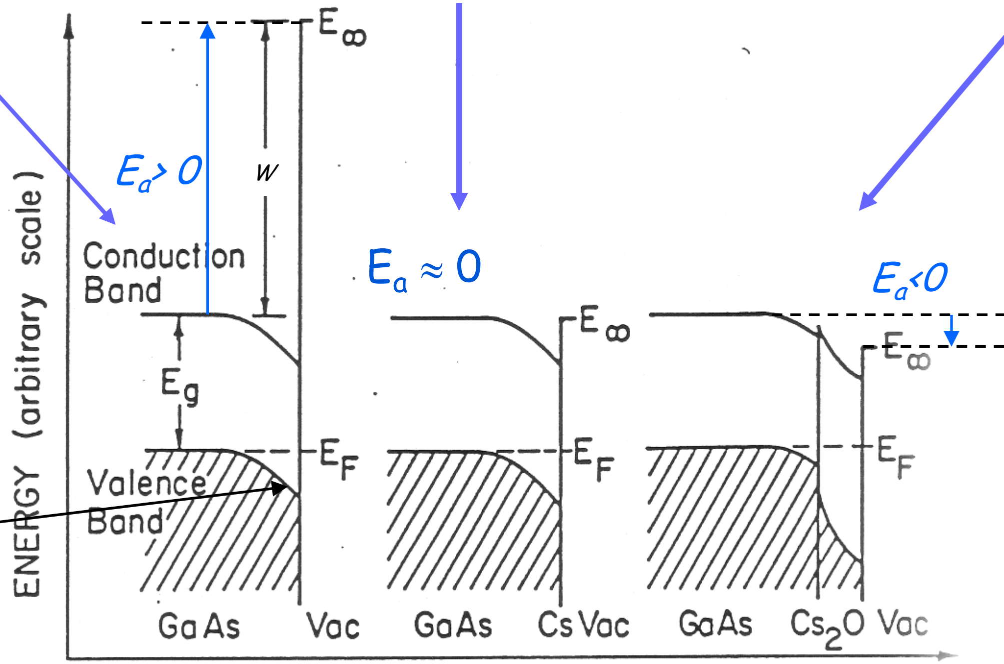
Photocathodes Quantum efficiencies (semi conductors)



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





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

Band bending[**] effect

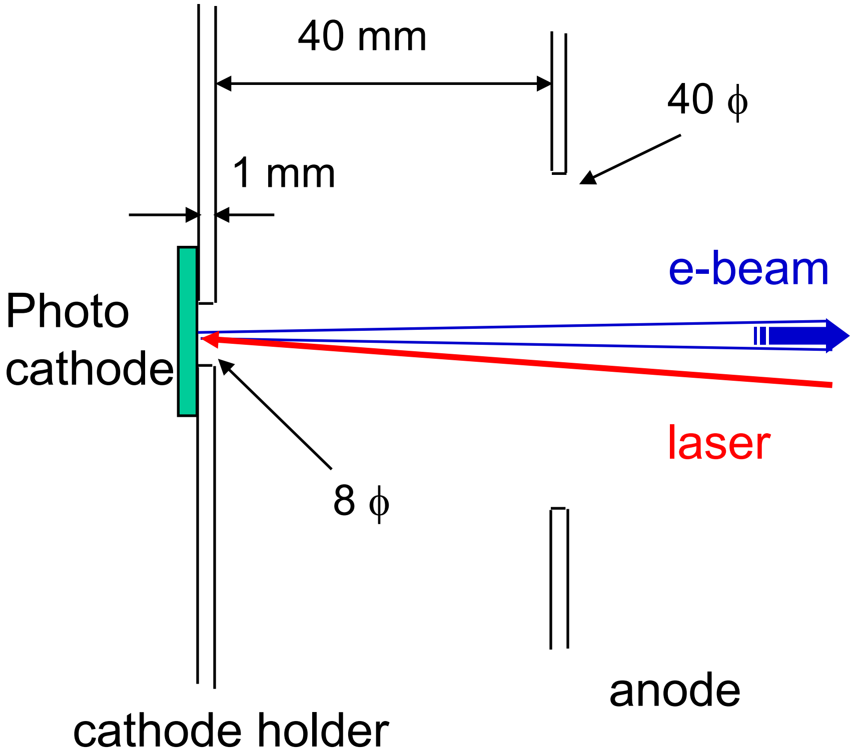
Electron Affinity[*] : $E_a > 0$ $E_a \approx 0$ $E_a < 0$

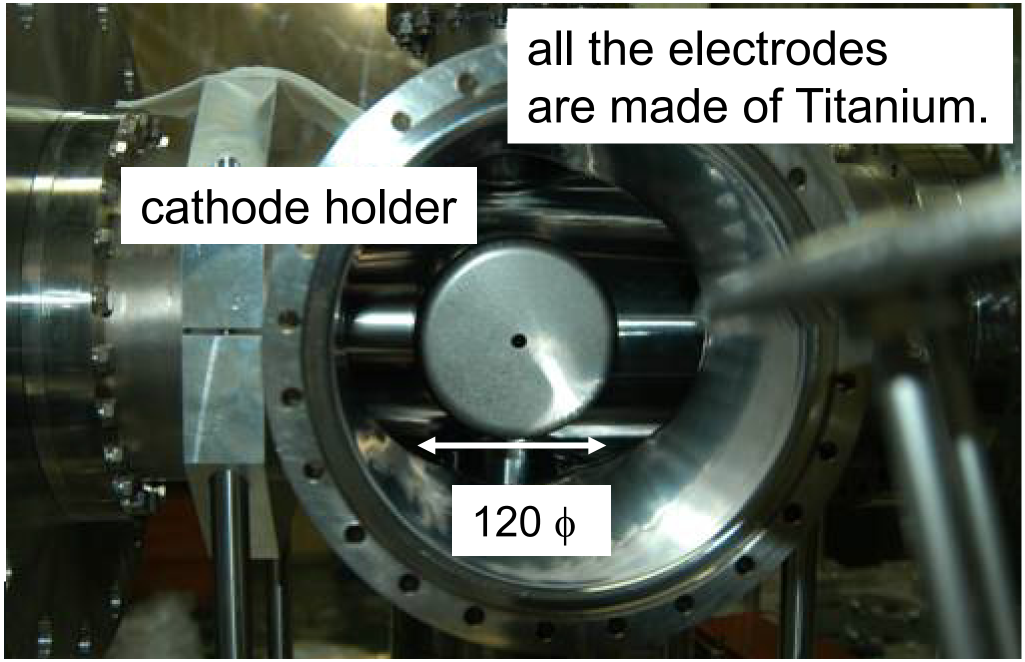
Extracted from slides :
J. Grames, JLab, USA
N. Nishimori, JAEA, Japan

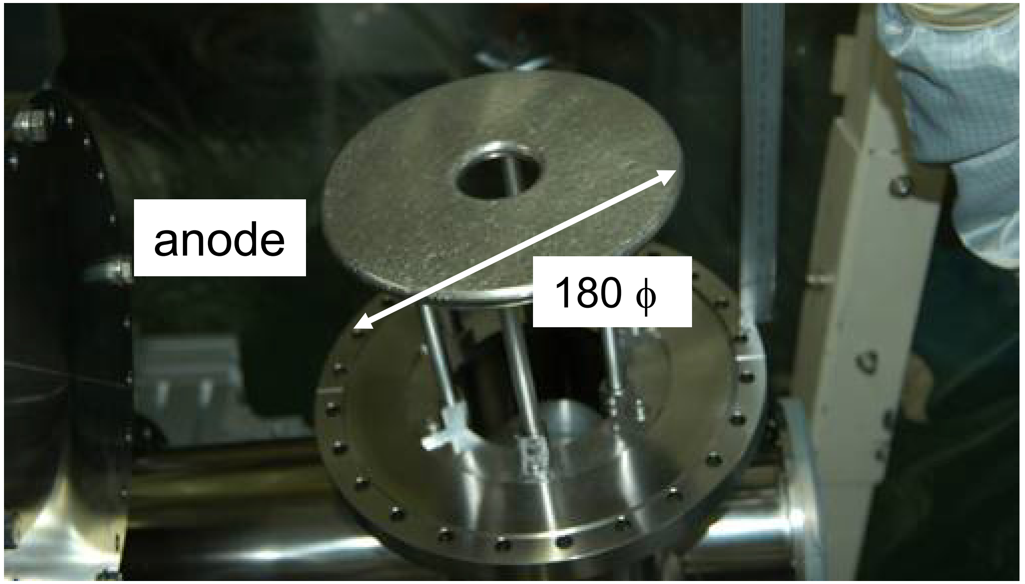
[*]In solids, the Electron Affinity is the energy difference between the vacuum energy and the conduction band minimum.

[**]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.

Example of a Photocathode DC GUN (JAEA-ERL)







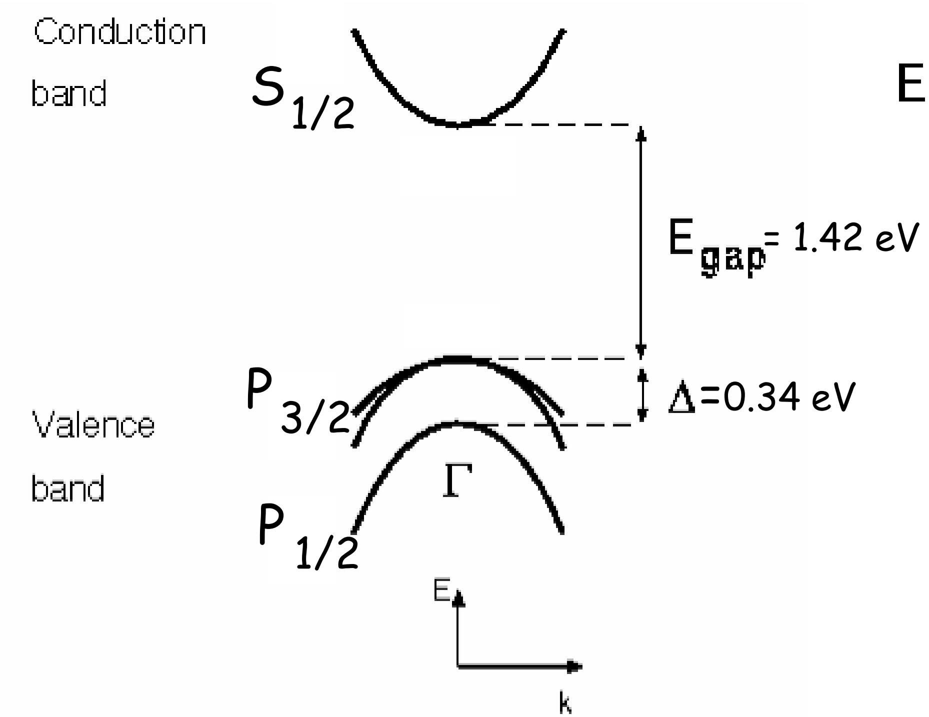
The electric field is 5 MV/m.

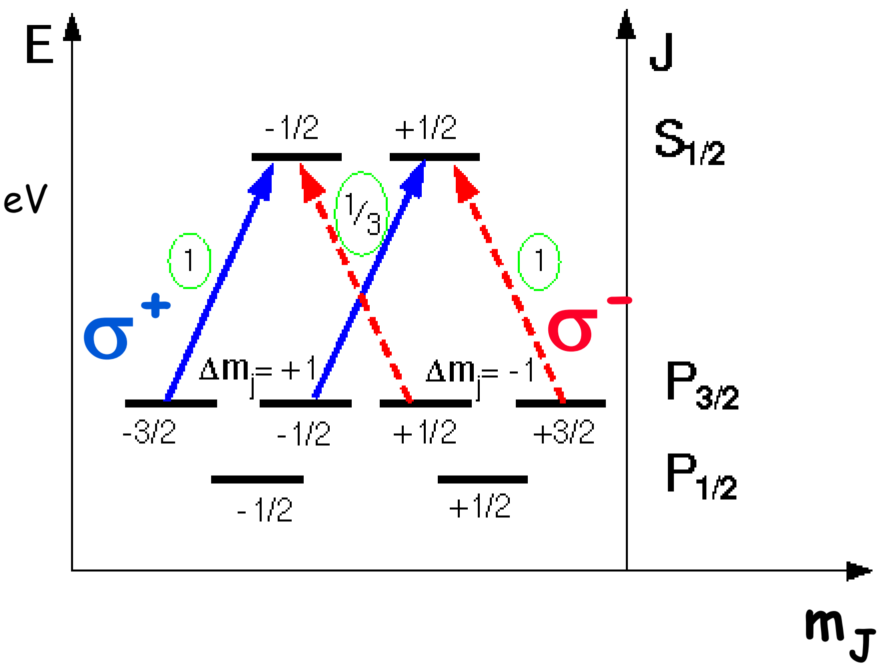
Goal is 50 mA DC beam

Slide is from : N. Nishimori, JAEA, Japan

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

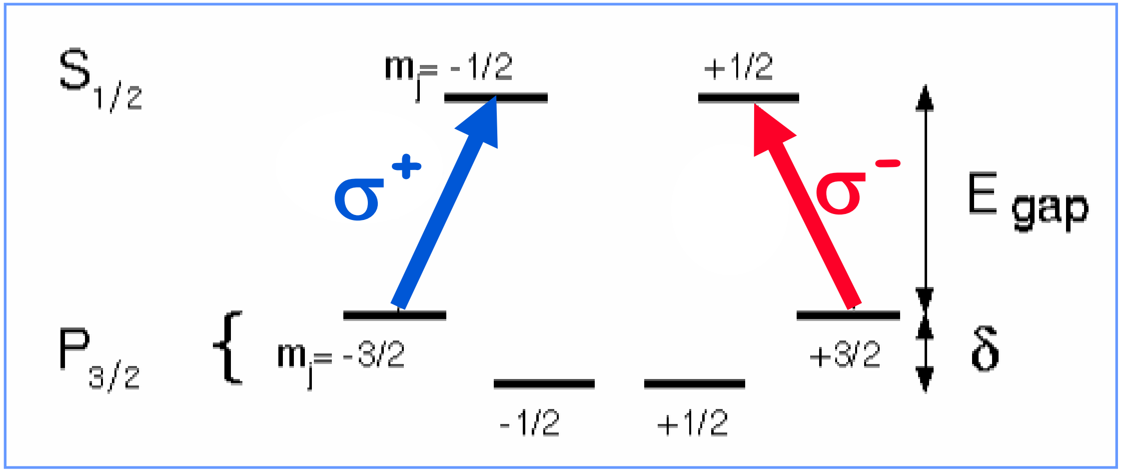
(excess of...) Polarization Ratio of the electron beam

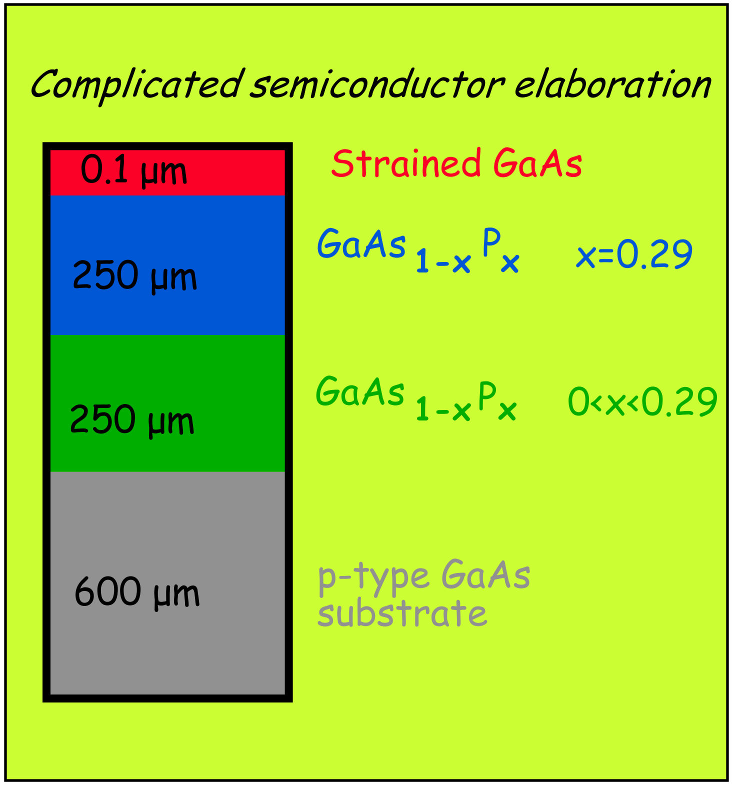
$$P_e = \frac{3-1}{3+1} = +/- \ 50\%$$

Slide is from : J. Grames, JLab, USA

Split degeneracy of $P_{3/2}$

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





theoritical

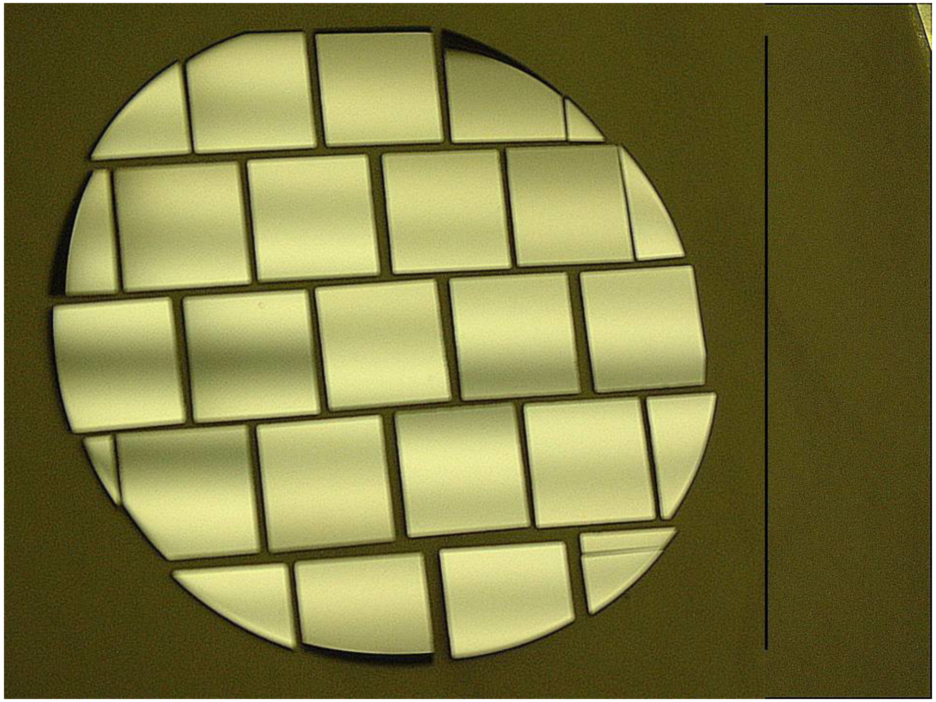
$$P_e = +/-\ 100\%, \text{ with } E_{gap} < E_{\gamma} < E_{gap+\delta}$$

Experimentaly ~85%

Slide is from : J. Grames, JLab, USA

Photocathodes at Jlab, USA

3" wafer cleaved into square photocathodes (15.5 mm) for mounting on a "stalk" using In and Ta cup.

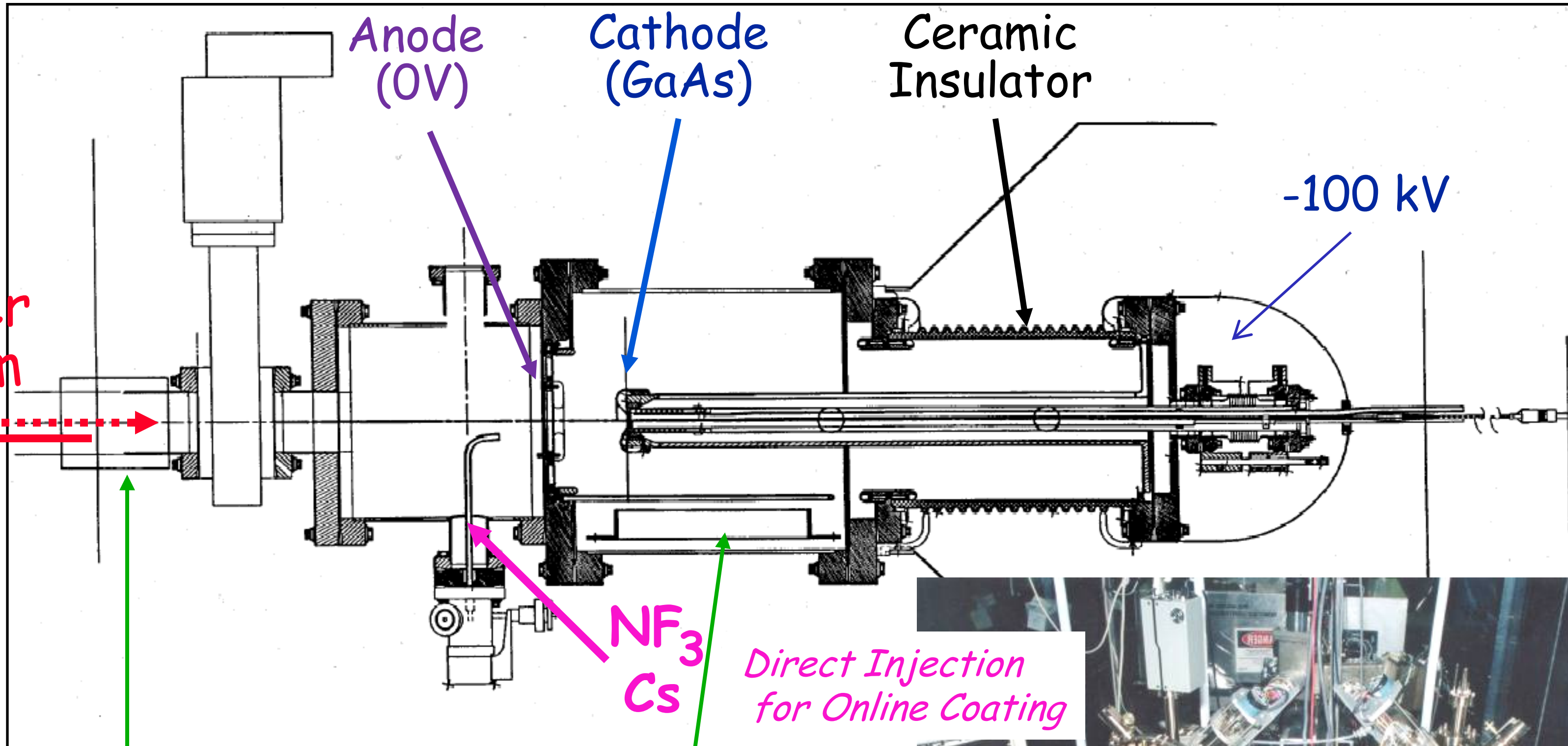


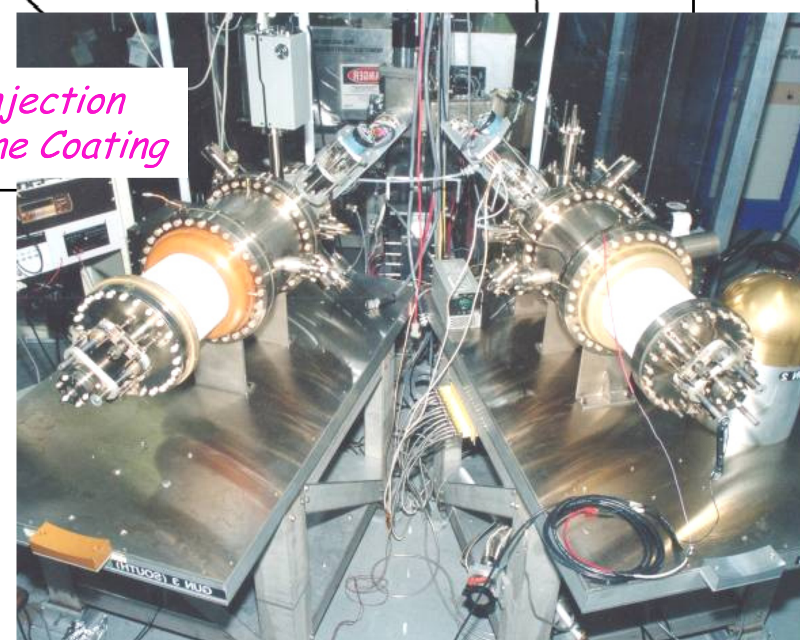
3 " wafer cut into square photocathodes

Stalk for supporting 1 Photocathode

Slide is from : J. Grames, JLab, USA

Present JLab polarized gun design (USA)





NEG coated
beampipe

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

↑

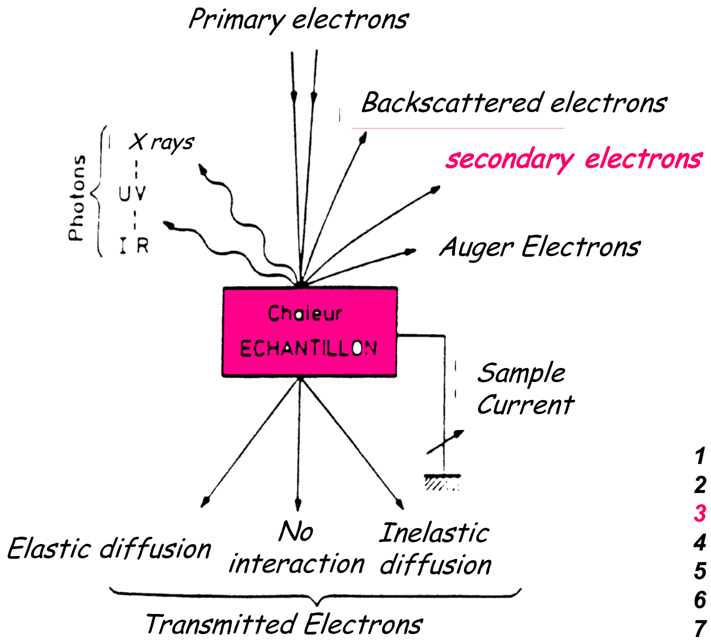
Mandatory to prevent Photocathode early aging

slide adapted from: J. Grames, JLab, USA

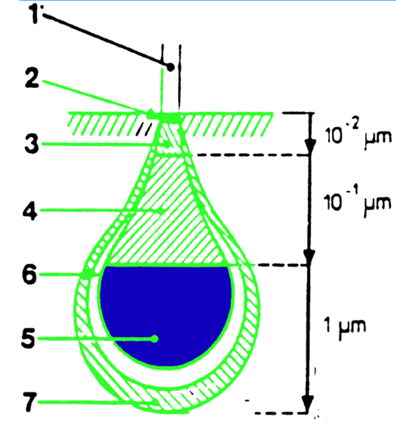
Secondary Electron Emission

Emission of electrons from matter induced by impinging ionizing particles like :

- An incident electron
- An Ion
- A photon



Area of emission of specific Interactions in matter



1	Impinging electron
2	Auger electrons
3	Secondary electrons
4	Backscattered electrons
5	Characteristic X-rays
6	Continuous spectrum of X-rays
7	Fluorecence X rays

For a 40 keV incident electron beam

slide adapted from: J. Arianer

Secondary Electron Emission Yield

Kinetic ejection condition
$E_p > W_{matter}$

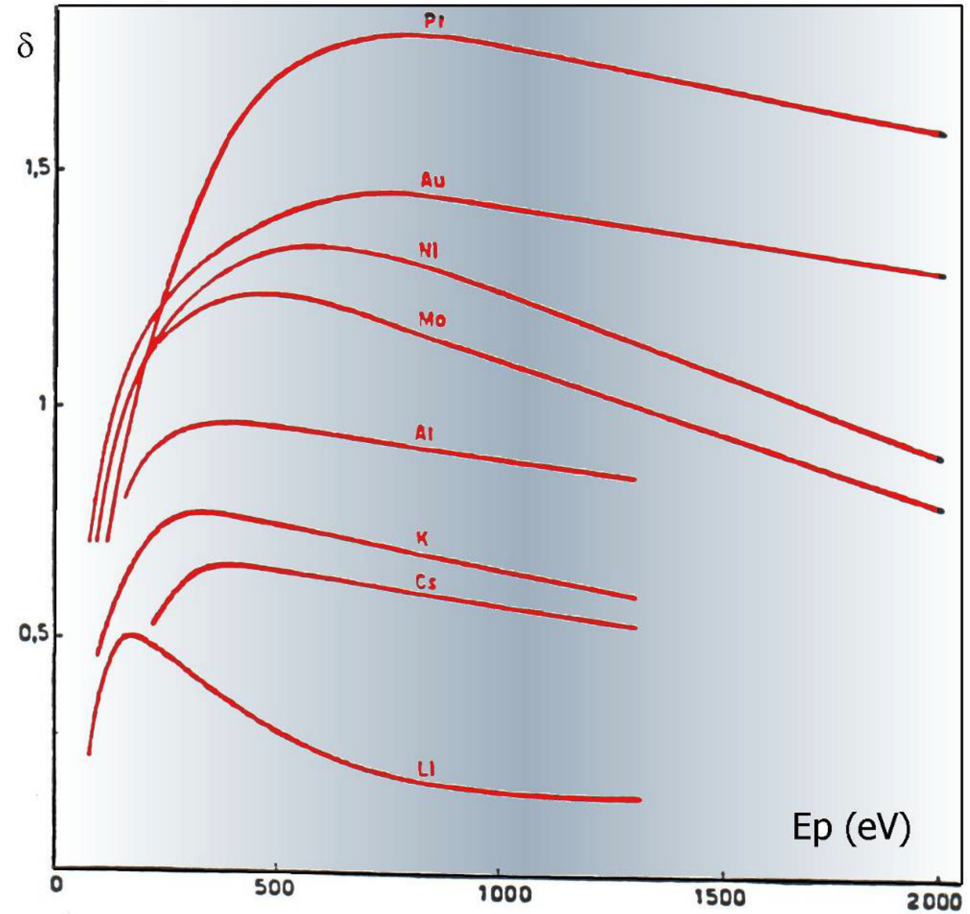
SE Yield: $\delta = \frac{N_{e_s}}{N_{e_p}}$ $\frac{\textit{secondary}}{\textit{primary}}$

$\delta = f(E_P, \text{matter})$

$0 \div$ some 10^3

likely

$0 \div$ some 10

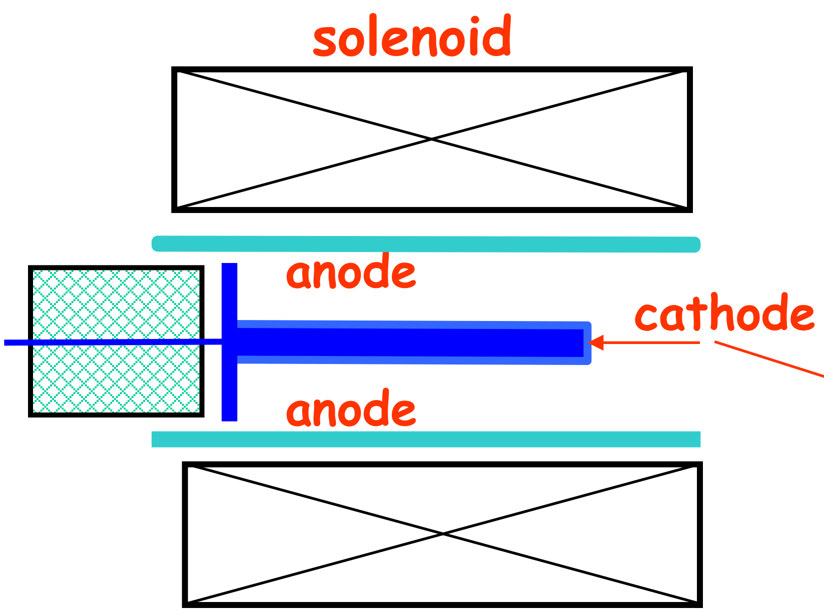


=> Secondary Electron Emission can be used as an electron current amplifier

slide adapted from: J. Arianer

SEMIG : Secondary Emission Magnetron Injection Gun

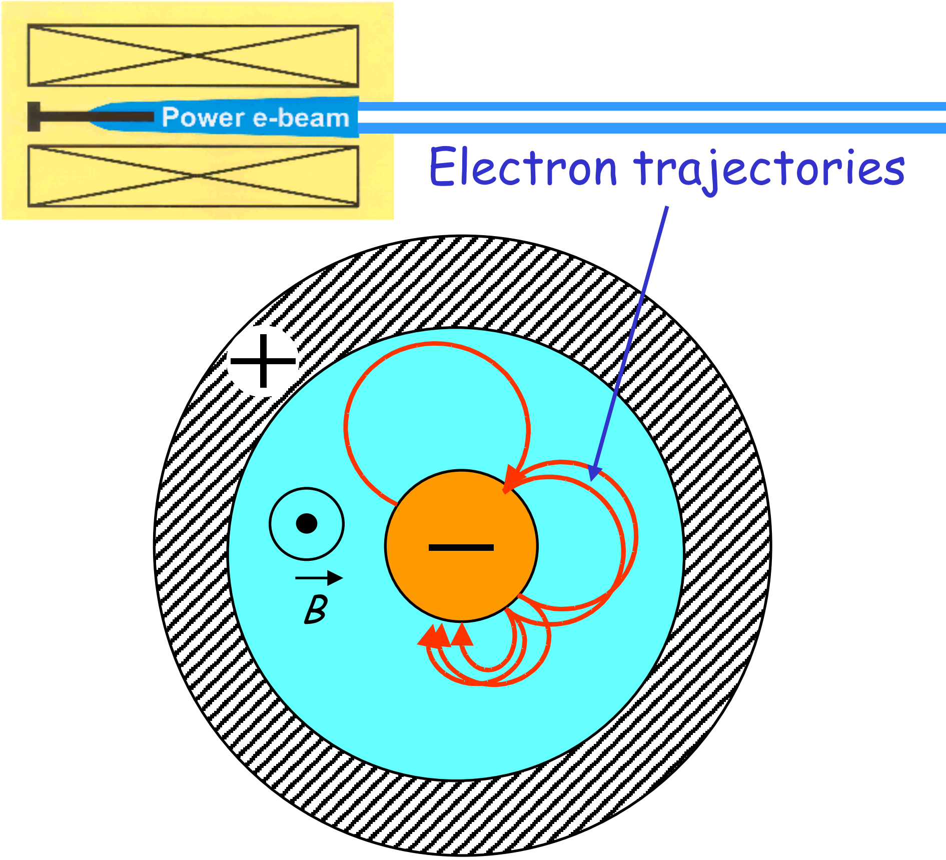
Next 5 slides see: S.A.Cherenshchikov, A.N.Dovbnya, A.N.Opanasenko,National Science Center, Institute of Physics & Technology, Kharkiv, 310108 Ukraine.

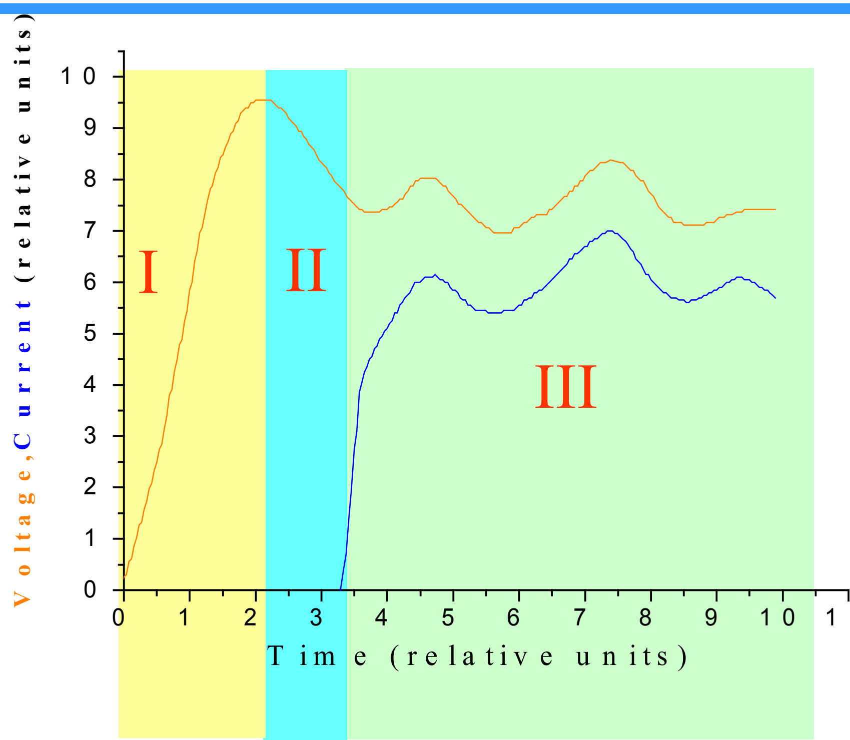


The schematic image of the gun

The set of cathodes

SEMIG : Beam Ignition





Secondary emission multiplication

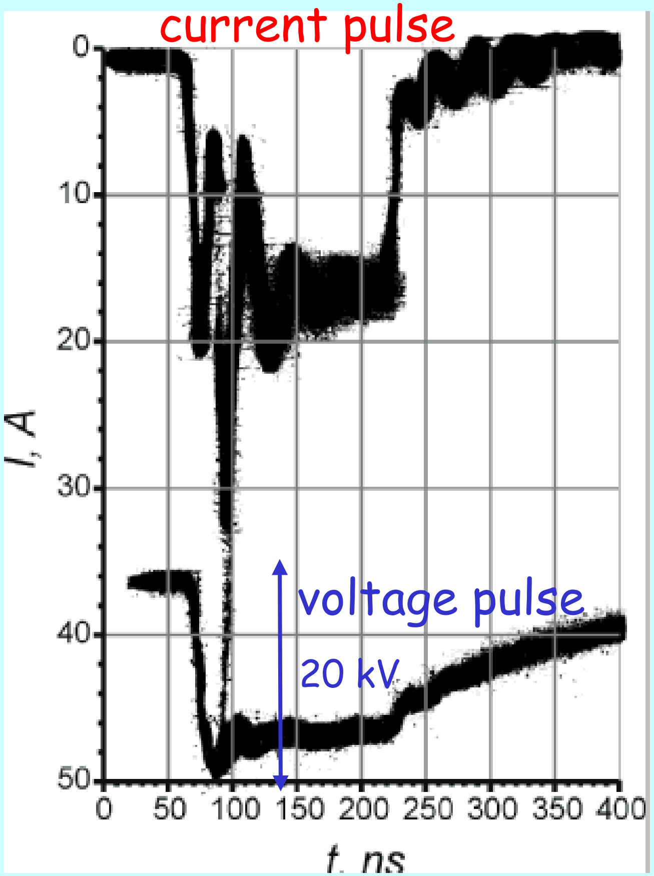
Gun voltage and beam current dependence on time

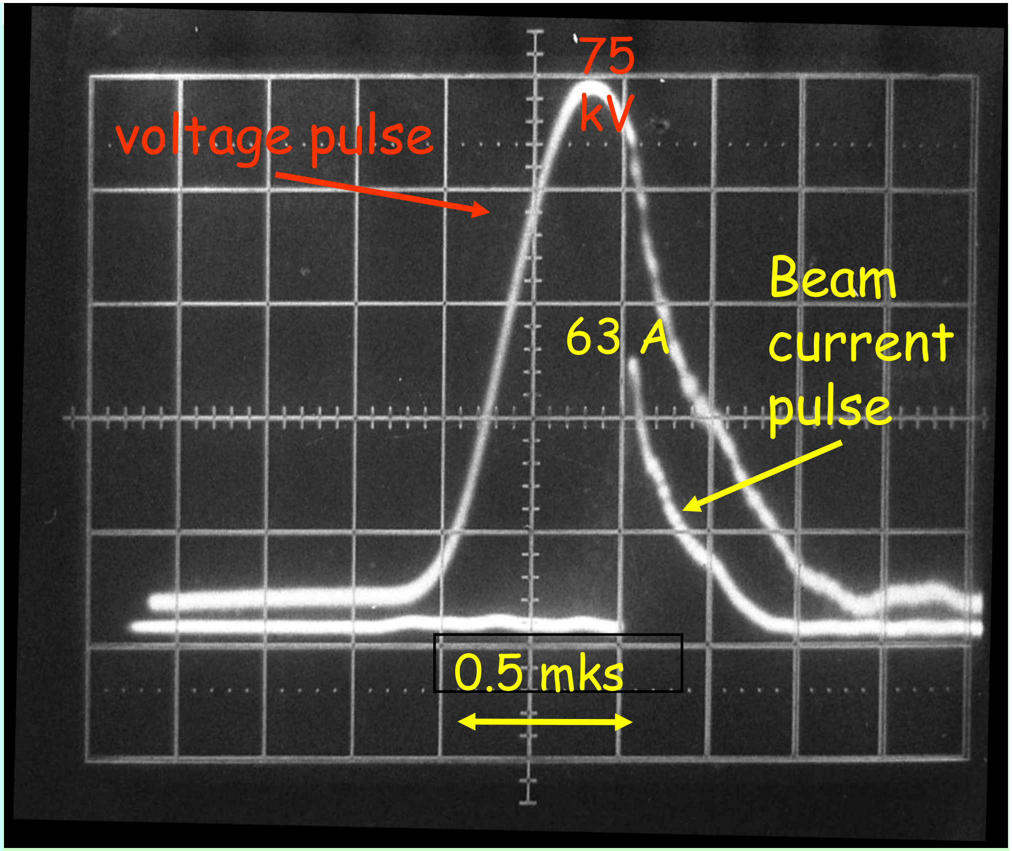
I. Voltage application (V=f(time))

II. Secondary emission multiplication

III. Self-support secondary emission

SEMIG : electron pulses



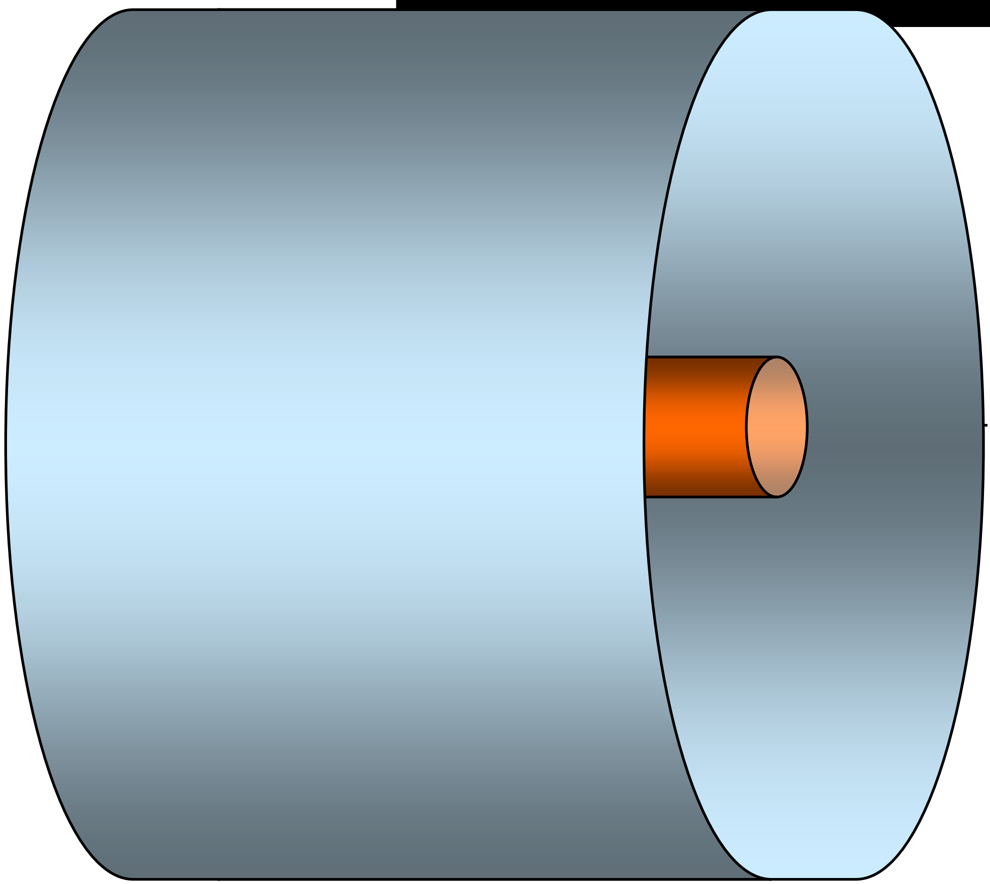


SEMIG ignition	Magnetic field 0.202 T
Cathode diameter	14 mm
Anode diameter	30 mm
Repetition frequency	3Hz

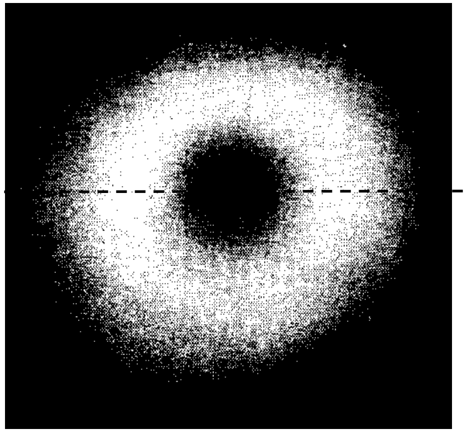
Cold-cathode magnetron ignition

SEMIG : beam size

Beam Cross-Section in X-rays

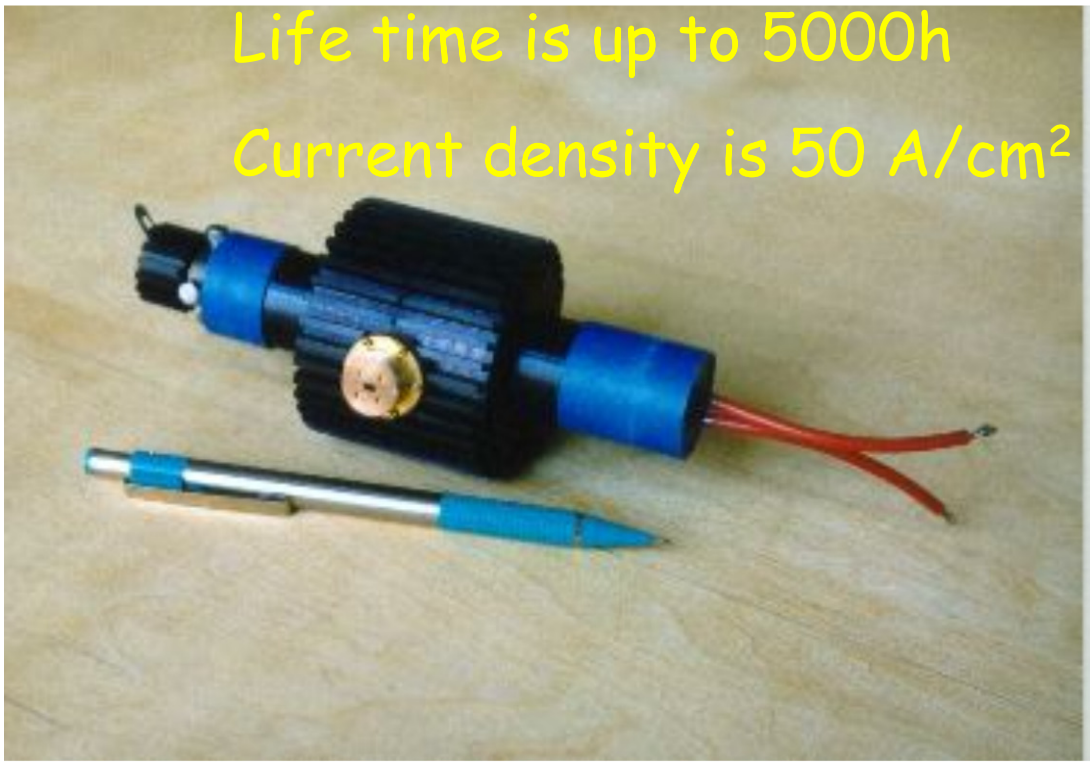


Gun end in scale



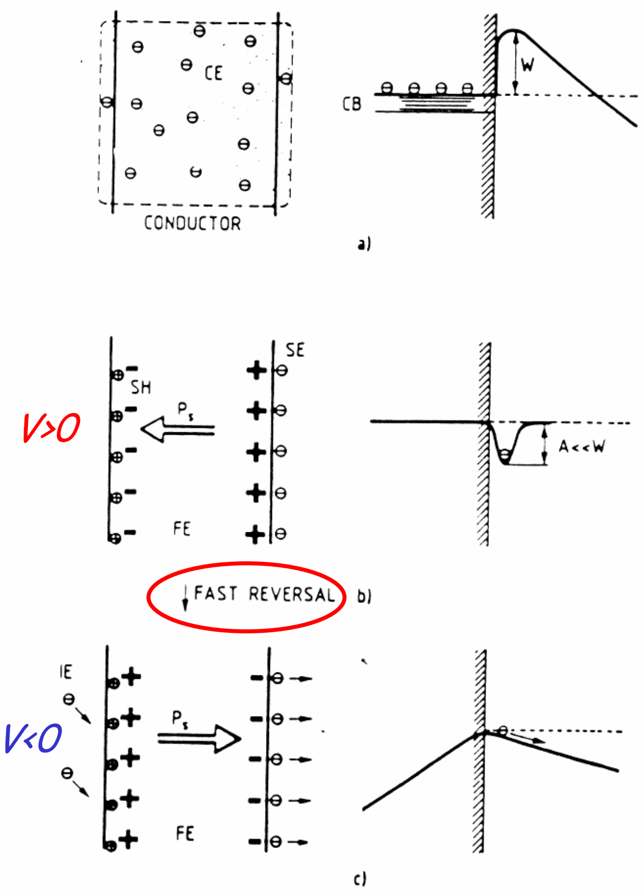
beam size D=1 cm
current I=10 A,
energy 40 keV.

SEMIG : dimension



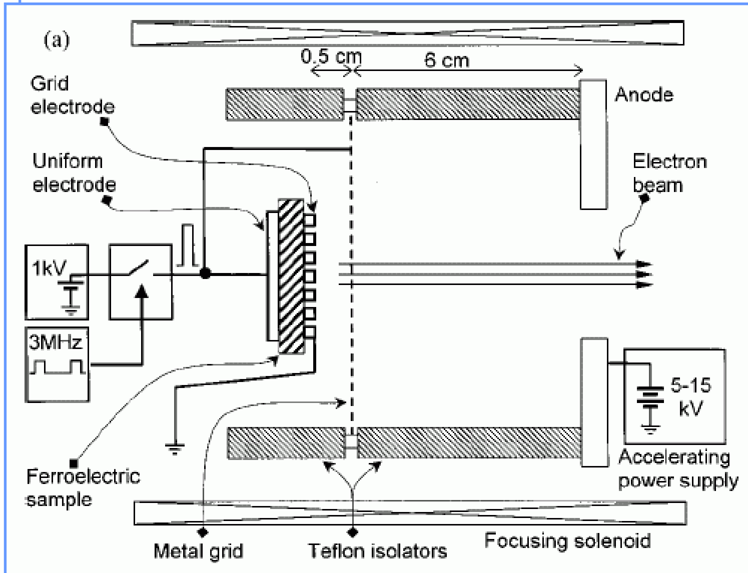
A secondary emission 3-mm magnetron with a platinum cathode

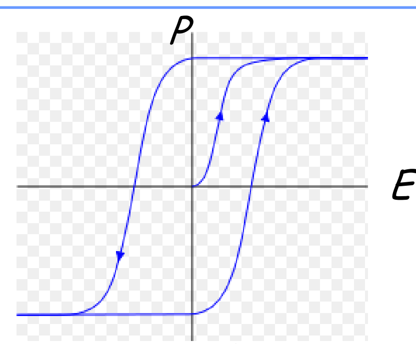
Ferroelectric Emission



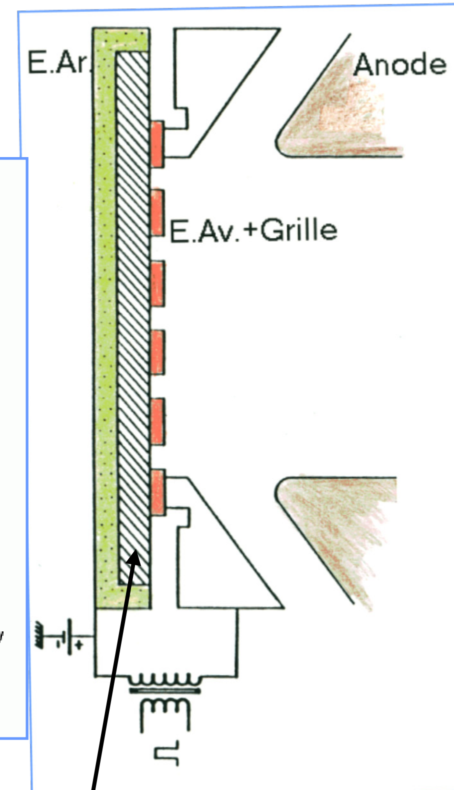
Principle of FE space-charge emission after a polarization change. a) Emission of conduction electrons from a metal (W = work function, CB = conduction band). b) Neutralization of FE by screening electrons (SE) and holes (SH). c) Emission from FE after P_s reversal and neutralization by injected electrons (IE).

R&D in labs
no contamination
low cost, low vacuum
simpleTechnology
$J>100 A.cm^{-2}$





Hysteresis loop of ferroelectric material

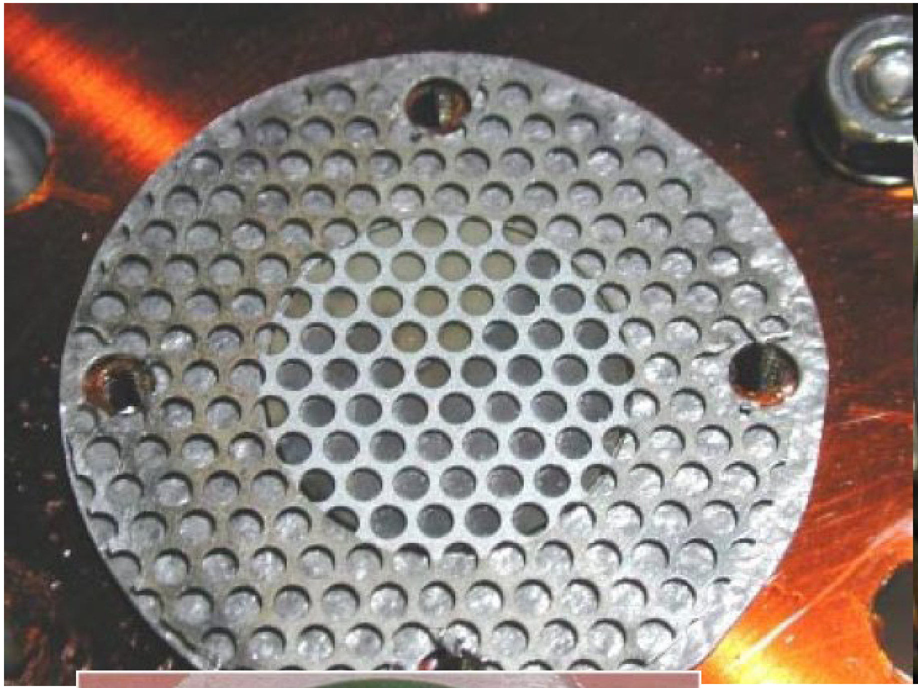


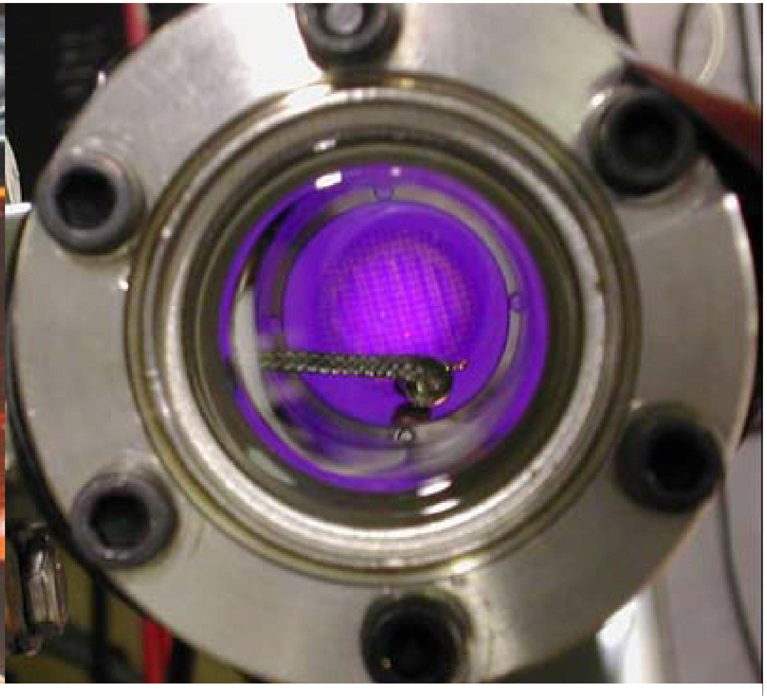
Pb,La,Zr,Ti (PZLT)

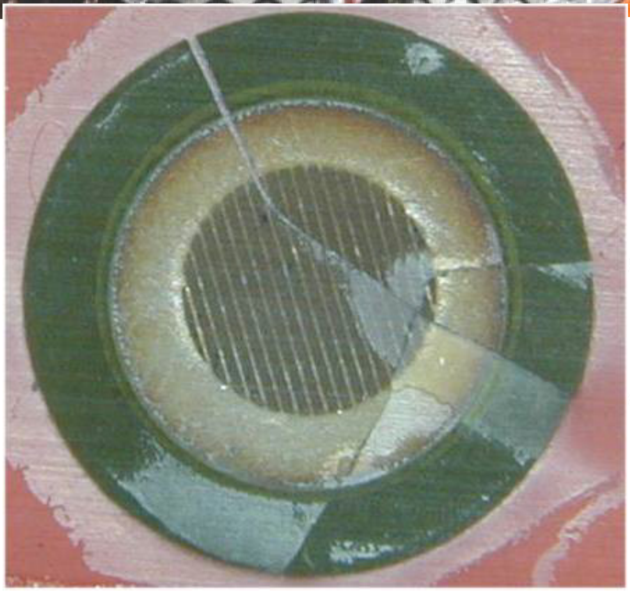
Ceramic coated on both face
With thin metal layer

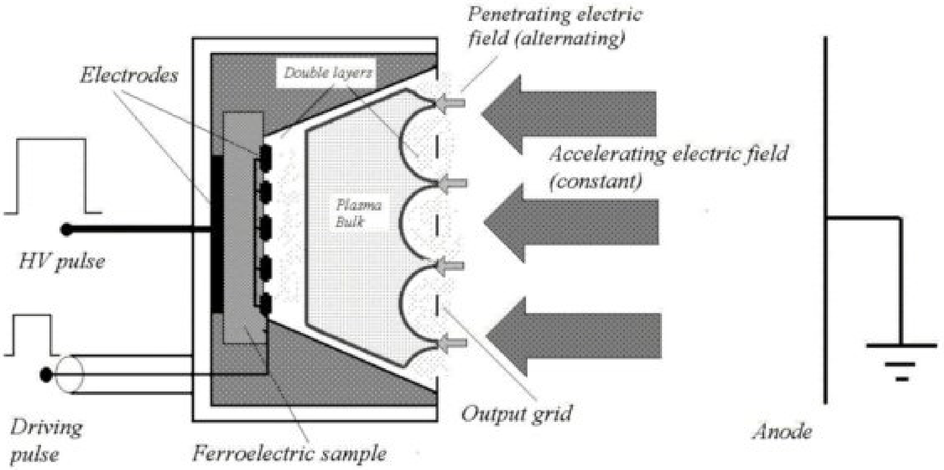
Behaviour and theory still under study !

FerroElectric Emission GUN





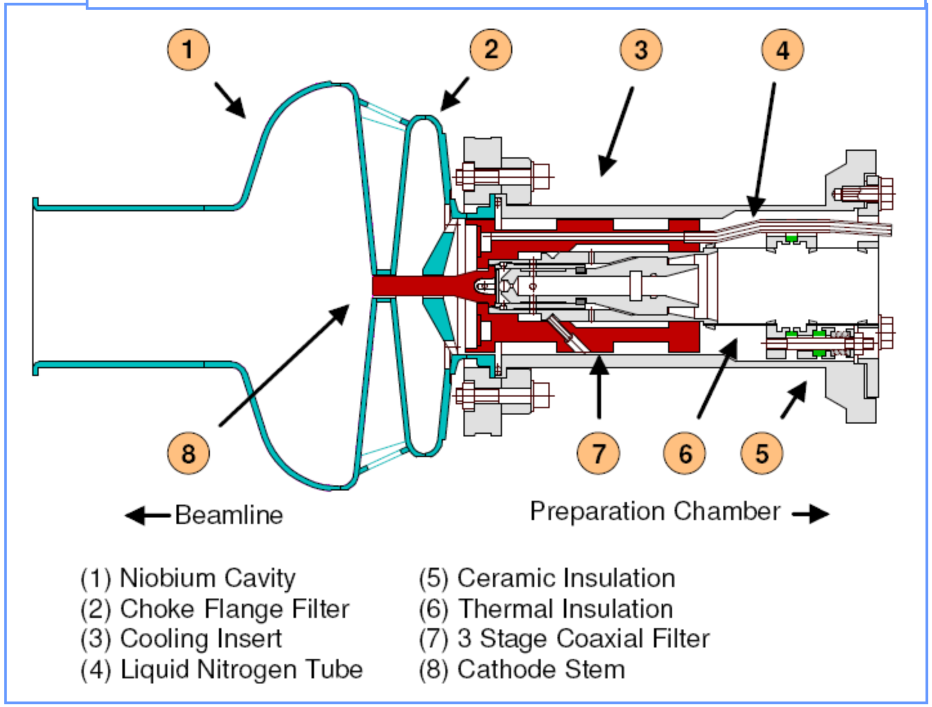




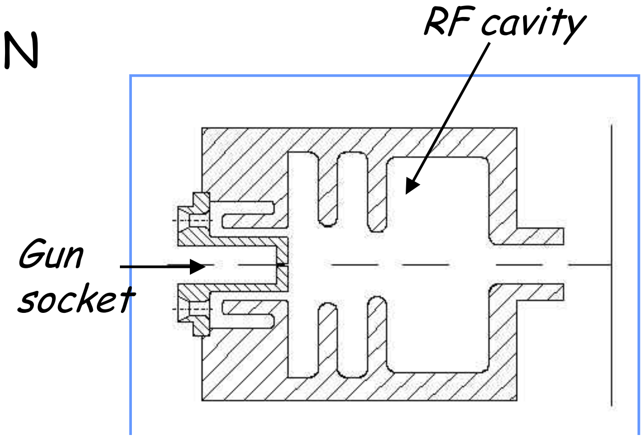
The electron Gun is directly coupled to a RF Cavity

- compact solution to accelerate directly above MeV Energies
- higher currents are reachabme
- Can be used with many kind of electron GUN

Rossendorf ½ cell Supercon. RF gun prototype



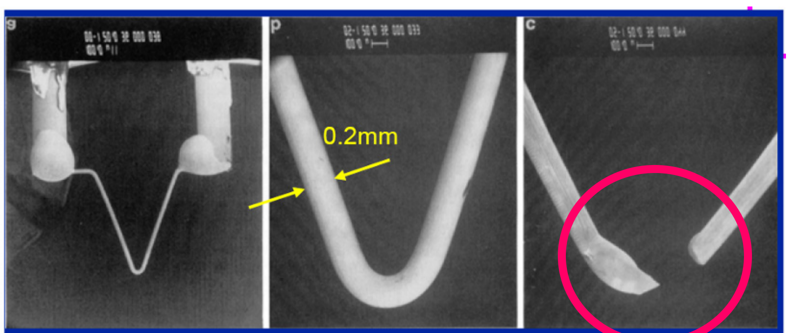
D.Janssen et al., NIM A507(2003)314.

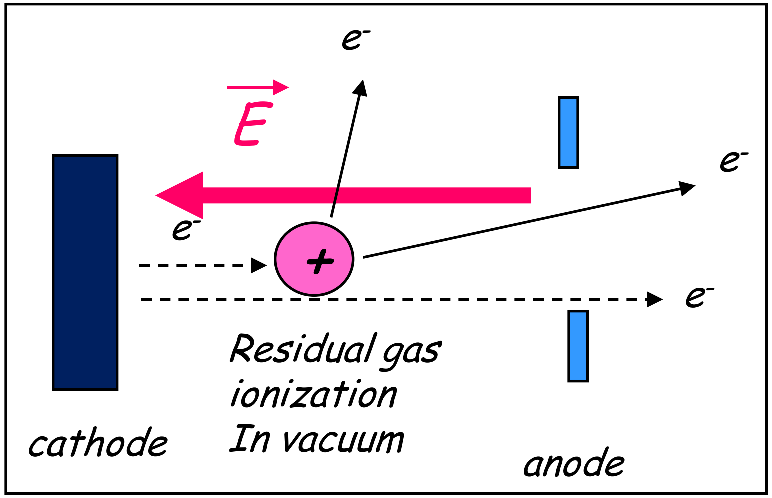


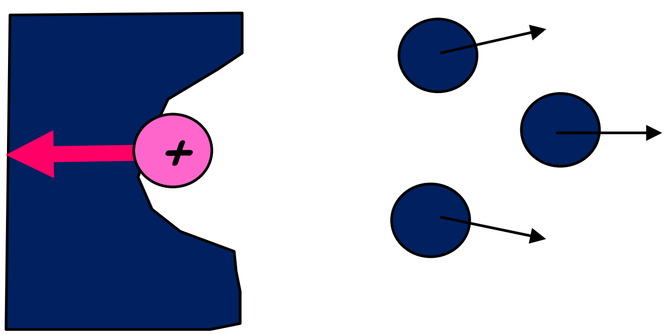
A 3 GHz thermionic RF gun has been designed. It will produce a 2.3 MeV electron beam with bunch charge up to 0.2 nC (600 mA) at 10 pmm mRad normalised emittance.

Aging of cathodes by Sputtering Effect

- The electron beam ionizes partially the residual gas under vacuum
- The negative biased voltage of the gun cathode accelerates ions toward its surface
- The ion bombardement sputters atoms from the lattice and dig holes
- Sputtering is also preseted in Ion Source course







Cathode bombardment :
Atoms are expelled out the lattice