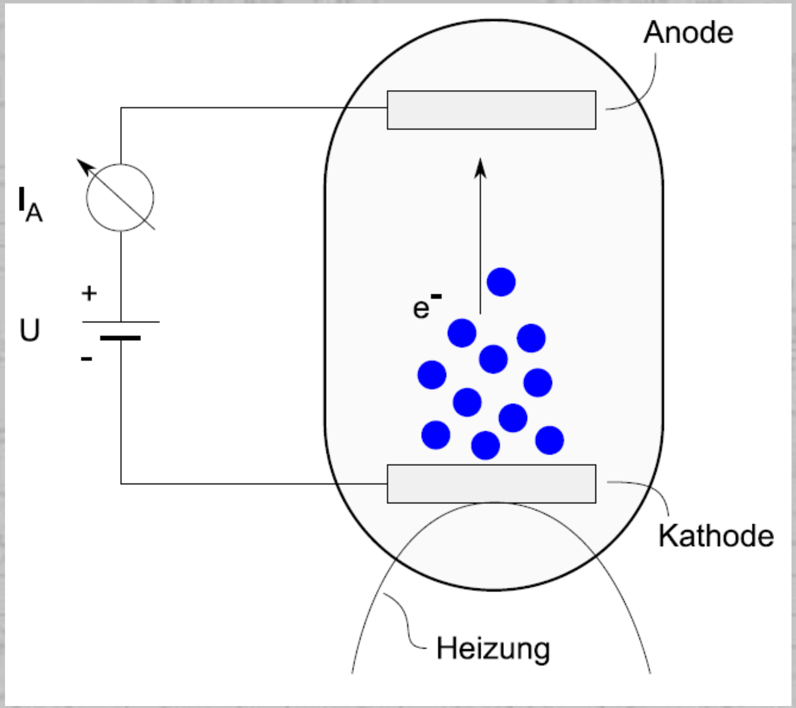
Vorlesung

Hochleistungsmikrowellentechnik

Prof. Dr.-Ing. John Jelonnek

Institut für Hochleistungsimpuls- und Mikrowellentechnik (IHM)

Kapitel 2, Abschnitt 1



Chapter 2.1

CATHODES - (EMITTER-) TECHNOLOGIES AND OPERATING MODES

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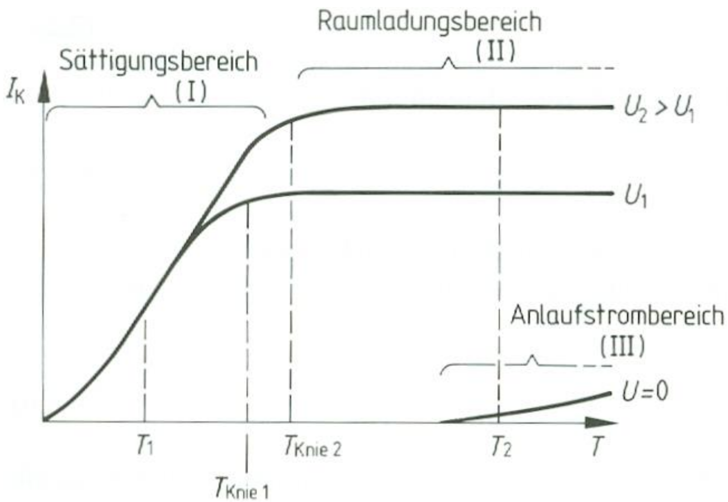
Literatur Chapter 2.1

Shulim E. Tsimring, **Electron Beam and Microwave Vacuum Electronics**,
John Wiley & Sons, New Jersey 2007

Gilmour, A. S., Jr., **Microwave Tubes**,
Artech House, Norwood, MA, 1986

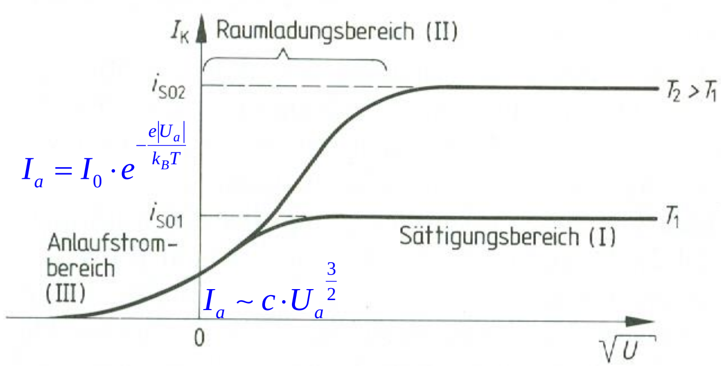
M.V. Kartikeyan **Gyrotrons: High-Power Microwave and Millimeter Wave Technology**
Springer Verlag, Heidelberg 2004

Reminder: The characteristic of an emission diode



Emission current vs. temperature.

For low temperatures the emitter is arranged in the temperature limited area. At the knee-temperature the electron emission is space charge limited and is therefore independent of the temperature.



Cathode emission vs. anode voltage.

For high voltages the current is limited by the saturation current, which is calculated by the Richard-Dushman-Schottky equation.

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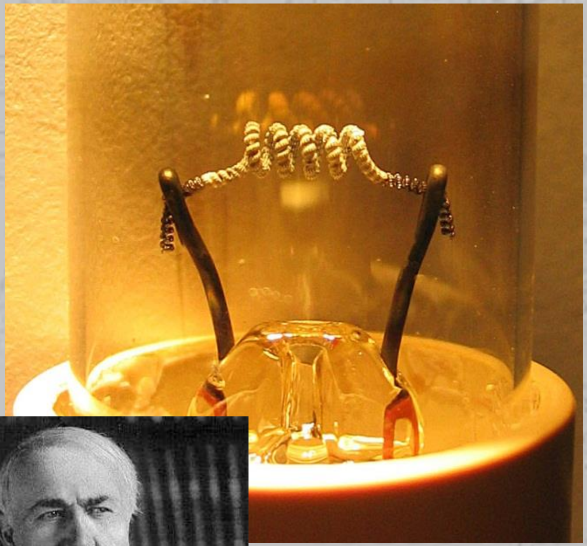
History of electron emission

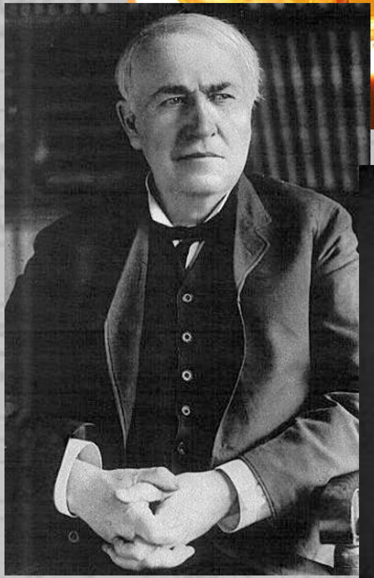
Thermionic emission of electrons from a heated tungsten cathode

1883 from ***Thomas Alva Edison*** observed

1901 From ***Sir Owen Williams Richardson*** mathematically formulated

1928 Physic Nobel prize: *"...for his work on the thermionic phenomenon and especially for the discovery of the law named after him"*





Thomas Alva Edison (1915)
www.wikipedia.org

Owen Williams Richardson
www.wikipedia.org

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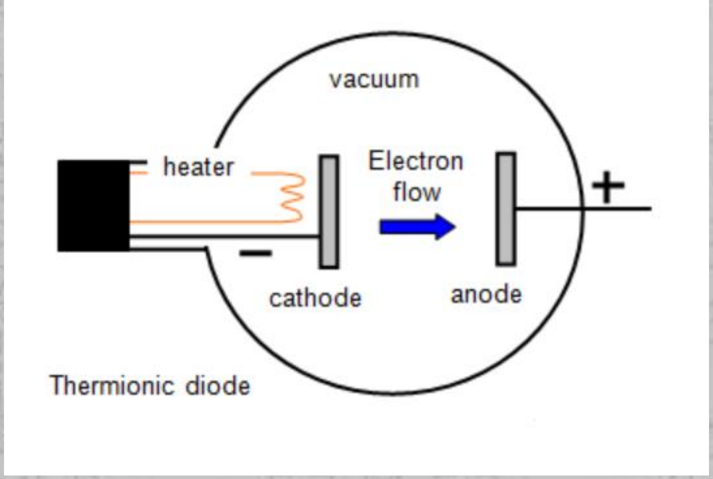
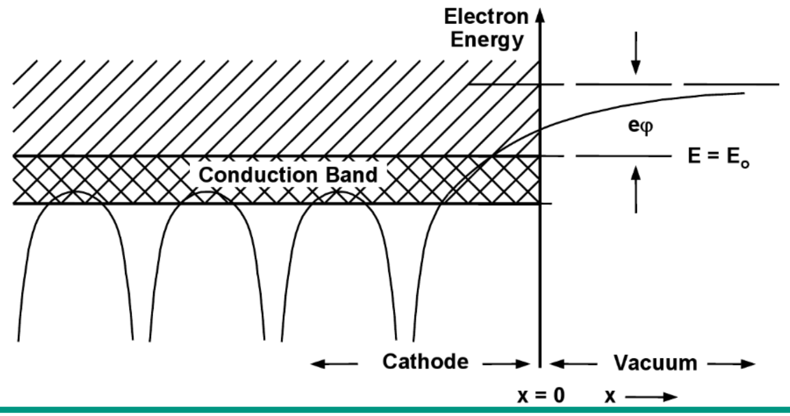
Thermionic Cathodes

- The cathode is the source of electrons for the electron beam in every microwave tube.
- The current density of the electron emission from the cathode ranges from milliamps to tens of amperes per square centimeter of cathode area
- Two cathode emission mechanisms are used in conventional tubes:
  - Thermionic emission (linear beam tubes, e.g. gyrotron)
  - Secondary emission (crossed-field tubes, e.g. magnetron)



Thermionic Emission



- At a temperature of 0 K, no electrons have energy greater than E_0, which is the top of the conduction band (Fermi level).
- The energy difference between the top of the conduction band in the cathode and the vacuum level adjacent to the cathode is the work function ($e\varphi$).
- At temperatures above zero, some electrons have energy greater than E_0.
- Emission of electrons can occur if their energy is $E_0 + e\varphi$ or greater.
- Electrons in the emitter move in a random direction. Those moving toward the surface have the highest probability of being emitted.

Material	Work function [eV]
Pt	5,32 … 5,66
Ni	5,0
Au	4,8 … 5,4
W	4,54 … 4,6
Zn	4,34
Ti	4,33[3]
Cu	4,3 … 4,5
Ta	4,19
Mo	4,16 … 4,2
Ag	4,05 … 4,6
Al	4,0 … 4,20
Na	2,28
K	2,25
Li	2,2
LaB_6	2,14
Rb	2,13
Ba	1,8 … 2,52
Cs	1,7 … 2,14
BaO + SrO	1,0

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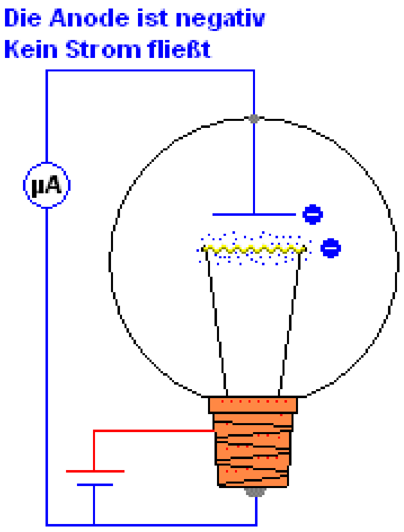
Thermionic Emission

At **temperature limited** mode (all emitted electrons are emitted from the emitter surface) the saturation current density j_s is determined by the Richardson-Dushman Equation.



$$J(A/m^2) = A_R T^2 e^{-\frac{e\Phi}{kT}}$$

Metal	Φ (eV)
Cs	2.1
Ba	2.7
Mo	4.5
W	4.6
Carbon	5.0

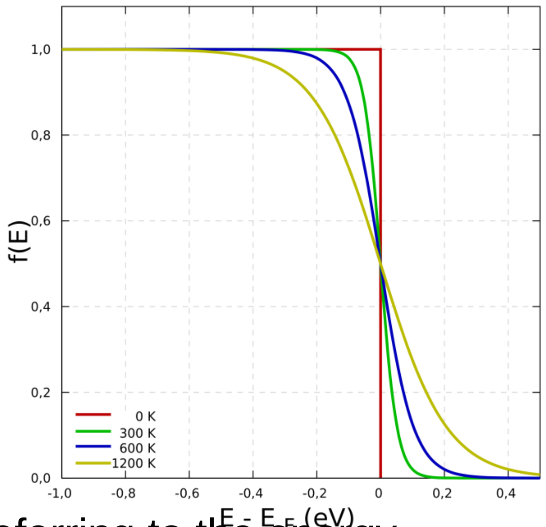
A_R – emission constant $120\ \mathrm{A/(cm^2K^2)}$
T – temperature
k – Boltzmann constant: $1.38 \cdot 10^{-23}\ \mathrm{JK^{-1}}$
Φ – work function

The Fermi-Distribution Function

For electrons in a cathode material applies the **Fermi-Distribution function**

$$f(E,T)=\frac{1}{e^{\frac{E-E_F}{k_B T}}+1}$$

k_B : Boltzmann-constant
T : absolute temperature



For high temperature T applies the approximation

$$f_B(E,T)\approx e^{-\frac{E}{k_B T}}$$

The **Fermi energy** is a concept in quantum mechanics usually referring to the energy difference between the highest and lowest occupied single-particle states in a quantum system of non-interacting fermions at absolute zero temperature. In a Fermi gas the lowest occupied state is taken to have zero kinetic energy, whereas in a metal the lowest occupied state is typically taken to mean the bottom of the conduction band.

- All energy levels between the lowest and the Fermi-energy are fully filled with particles.
- Feeding the system with energy, the Fermi-energy is the energy which is in a thermodynamic balance with a occupation probability of ½.

The state space and the energy of electrons

In the momentum space, the **De-Broglie-Relation** applies for the fermi-ions

$$p = \hbar \cdot \vec{k} = \frac{h}{\lambda} \ \text{mit}\ \vec{k} = \left|\vec{k}\right| = \frac{2\pi}{\lambda}$$

p : Impulse
λ : Wave length
$\vec{k}$: Wave vector

with $\hbar = \frac{h}{2\pi}$ the Planck'sche quantum of action.

The energy of electrons with the mass m_e and the wave vector $\vec{k}$ relates to

$$E = \frac{1}{2} \cdot m_e \cdot v^2 = \frac{1}{2} \cdot \frac{\vec{p}^{\,2}}{m_e} = \frac{1}{2} \cdot \frac{\hbar \cdot \vec{k}^{\,2}}{m_e}$$

The Richardson-Dushman Equation

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The emission of the electrons from the cathode (emitter)

We imagine the cathode in x-direction. The x-component j_x of the current density $\vec{j}$ is in favor.

$$j_x = \frac{e^-}{V} \cdot \sum_{\vec{k}} v_x\left(\vec{k}\right)$$

At the transition to the integral the term $2\pi/\lambda$ is transferred to the statal differential dk. Electrons whose energy E exceed at least the Fermi-energy by the amount of the work function are emitted.

$$j_x = \frac{e^-}{\left(2\pi\right)^3} \cdot \int_{E \geq E_F + W_A} v_x\left(\vec{k}\right) d^3k$$

Furthermore applies

$$p_x = m_e \cdot v_x = m_e \cdot \hbar k_x$$

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The Richardson-Dushman Equation

- The work function of electrons, which amount at least $W_F + W_{A,}$ is consistent to values of k_x^2. These values extend between $(E_F + W_A) \cdot \frac{2 \cdot m_e}{\hbar^2}$ and endless.
- In addition, the electrons will be appropriate the approximation of the Boltzmann distribution *f*(*E*,*T*) considered . The Fermi-distribution can be approximated at room temperature. The used energy is the excess which the energy in the state space above the Fermi-energy have.

$$\frac{1}{2} \cdot \frac{\hbar^2 \cdot k^2}{m_e} - E_F$$

- Finally, it has been taken into account that in the same spatial increment d^3k^2 electrons are located. Two electrons have with opposite spin always the same energy.
- Altogether results in:

$$j_x = \frac{e^-}{(2 \cdot \pi)^3} \cdot \frac{\hbar}{m_e} \cdot 2 \cdot \int_{-\infty}^{\infty} \mathrm{d}k_y \cdot \int_{-\infty}^{\infty} \mathrm{d}k_z \cdot \int_{\sqrt{(E_\mathrm{F}+W_\mathrm{A}) \cdot \frac{2 \cdot m_e}{\hbar^2}}}^{\infty} \mathrm{d}k_x \cdot k_x \cdot f_B\left(\frac{1}{2} \cdot \frac{\hbar^2 \cdot \vec{k}^2}{m_e} - E_\mathrm{F}, T\right)$$

The Richardson-Dushman Equation

- The term of the Boltzmann equation can be taken apart, so that it is possible to integrate each variable

$$f_B\left(\frac{1}{2}\cdot\frac{\hbar^2\cdot\vec{k}^2}{m_e}-E_\mathrm{F},T\right)=\mathrm{e}^{-\frac{\frac{1}{2}\cdot\frac{\hbar^2\cdot\vec{k}^2}{m_e}-E_\mathrm{F}}{k_\mathrm{B}\cdot T}}=\mathrm{e}^{-\frac{\frac{1}{2}\cdot\frac{\hbar^2}{m_e}\cdot\left(k_x^2+k_y^2+k_z^2\right)-E_\mathrm{F}}{k_\mathrm{B}\cdot T}}=\mathrm{e}^{-\frac{1}{2}\cdot\frac{\hbar^2}{m_e\cdot k_\mathrm{B}\cdot T}\cdot k_x^2}\cdots\mathrm{e}^{\frac{E_\mathrm{F}}{k_\mathrm{B}\cdot T}}$$

- The y- and z-integral consists of $u_i:=\frac{\hbar}{\sqrt{m_e\cdot k_\mathrm{B}\cdot T}}\cdot k_i\left(\Rightarrow \mathrm{d}k_i=\frac{\sqrt{m_e\cdot k_\mathrm{B}\cdot T}}{\hbar}\cdot\mathrm{d}u_i\right)$

$$\int_{-\infty}^{\infty}\mathrm{d}k_i\cdot\mathrm{e}^{-\frac{1}{2}\cdot\frac{\hbar^2}{m_e\cdot k_\mathrm{B}\cdot T}\cdot k_i^2}=\frac{\sqrt{m_e\cdot k_\mathrm{B}\cdot T}}{\hbar}\cdot\underbrace{\int_{-\infty}^{\infty}\mathrm{d}u_i\cdot\mathrm{e}^{-\frac{u_i^2}{2}}}_{=\sqrt{2\cdot\pi}}$$

- The x-integral consists of $\mathrm{d}k_x\cdot k_x=\frac{1}{2}\cdot\mathrm{d}k_x^2$

$$\int_{\sqrt{(E_\mathrm{F}+W_\mathrm{A})\cdot\frac{2\cdot m_e}{\hbar^2}}}^{\infty}\mathrm{d}k_x\cdot k_x\cdot f_B\left(\frac{1}{2}\cdot\frac{\hbar^2\cdot k_x^2}{m_e}-E_\mathrm{F},T\right)=\frac{1}{2}\int_{(E_\mathrm{F}+W_\mathrm{A})\cdot\frac{2\cdot m_e}{\hbar^2}}^{\infty}\mathrm{d}k_x^2\cdot\mathrm{e}^{-\frac{\frac{1}{2}\cdot\frac{\hbar^2\cdot k_x^2}{m_e}-E_\mathrm{F}}{k_\mathrm{B}\cdot T}}$$

$$=\frac{m_e\cdot k_\mathrm{B}\cdot T}{\hbar^2}\cdot\mathrm{e}^{-\frac{W_\mathrm{A}}{k_\mathrm{B}\cdot T}}$$

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The Richardson-Dushman Equation

It results the Richardson Equation

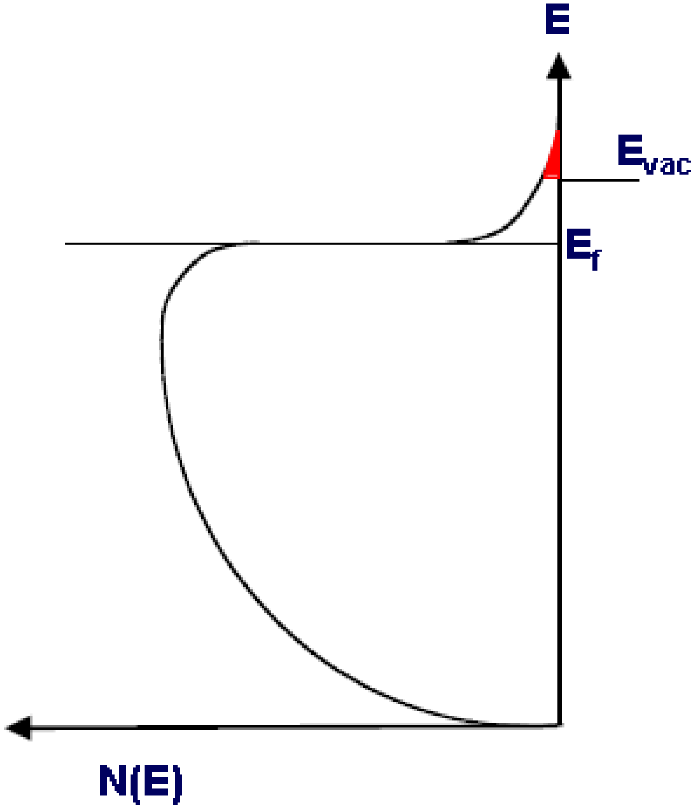
$$j_x = \underbrace{\frac{e^- \cdot m_e}{2 \cdot \pi^2 \cdot \hbar^3} \cdot k_\mathrm{B}^2}_{=:A_\mathrm{R}} \cdot T^2 \cdot \mathrm{e}^{-\frac{W_\mathrm{A}}{k_\mathrm{B} \cdot T}}$$

A_R is the Richardson constant

$$A_R \approx 1,202 \cdot 10^6 \frac{\mathrm{A}}{\mathrm{m}^2 \cdot \mathrm{K}^2}$$

Example

Typical electron distribution in metal



$$\Phi = E_{vac} - E_f$$

Richardson equation

$$J = AT^2 e^{-\Phi/\kappa T}$$

$$A = 120\ A/cm^2 K$$

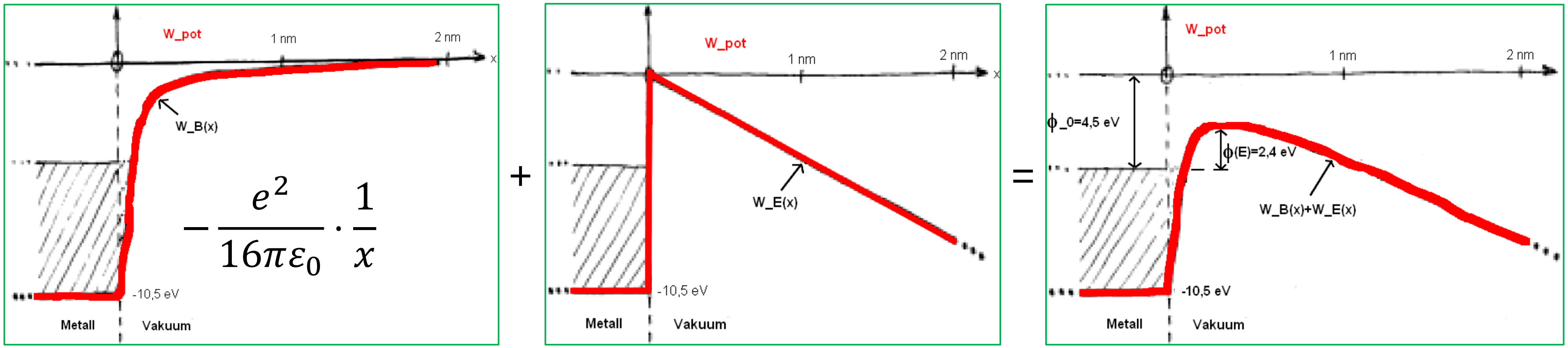
Φ (eV)	T (K)	J (A/cm^2)
4.6	2600	1
4.6	2500	0. 4
3.6	2500	41

Φ **about 4.6 eV for W** (Wolfram)

→ The amount of the work function is essential for the electron emission!

The Schottky-Effect

The **Schottky-Effect** causes a reduction of the work function for electrons at the metal surface, due to an high electric field strength.



An electron in a distance x to a metal surface generates a image charge in the metal. The force is

$$F(x) = \frac{-e^2}{4\pi\varepsilon_0 (2x)^2}$$

The potential energy in order to move from infinity to the position x can be calculated by

$$\Delta E = W - eE_x x - \frac{e^2}{16\pi\varepsilon_0}\cdot\frac{1}{x}$$

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The Schottky-Effect

A constant electric field, applied from the outside, produces the potential $-eE_x x$.

W is the total energy which have to be applied that the electrons can leave the metal. It exists at position

$$x = \sqrt{\frac{e}{16\pi\varepsilon_0} \cdot \frac{1}{E_x}}$$

The differentiation yields the place with the maximum barrier

$$\frac{\partial}{\partial x}\Delta E = 0 \;\Rightarrow\; x = \sqrt{\frac{e}{16\pi\varepsilon_0} \cdot \frac{1}{E_x}} \;\Rightarrow\; \begin{aligned} \Delta E_{\max} &= W - eE_x x_{\max} + \frac{e^2}{16\pi\varepsilon_0 x_{\max}} \\ &= W - \sqrt{\frac{e^3 E_x}{4\pi\varepsilon_0}} \end{aligned}$$

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The Schottky-Effect and the field emission

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The modified work function is defined by

$$W_A' = \Delta E_{\max} - E_F$$
$$= W_A - \sqrt{\frac{e^3 E_x}{4\pi\varepsilon_0}}$$

That results in the modified Richardson-equation

$$j_x = A_R \cdot T^2 \cdot e^{-\frac{1}{k_B T}\left(W_A - \sqrt{\frac{e^3}{4\pi\varepsilon_0}}\sqrt{E_x}\right)}$$

It is possible that the field strength increase so strong that the work function is vanished.
→ Field emission

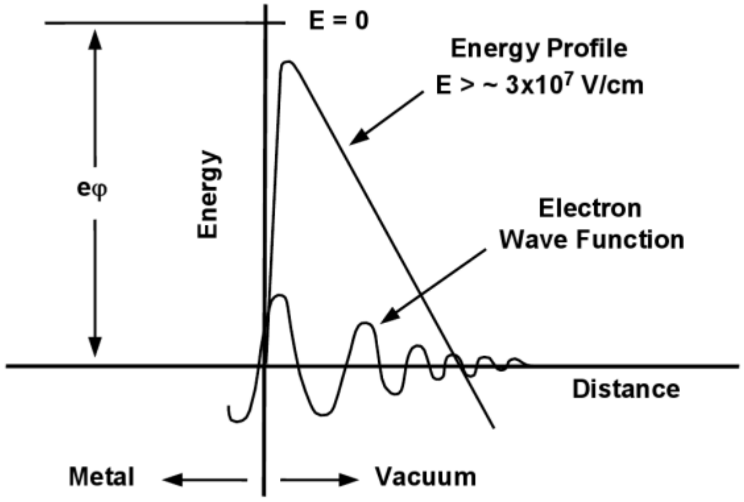
$$W_A - \sqrt{\frac{e^3}{4\pi\varepsilon_0}}\sqrt{E_x} = 0$$

Example: W_A = 4 eV ➡ $E_x = \frac{4\pi\varepsilon_0 W_A^2}{e^3} \approx 11\ \frac{\mathrm{GV}}{\mathrm{m}}$

Der quantenmechanische Tunneleffekt reduziert allerdings diesen Wert

Field Emission

The electron emission increases very rapidly, if the electric field strength is about $10^9 – 10^{10}$ V/m. The width of the potential barrier at the surface of the cathode is very narrow. Because of the wave nature of the electrons, there is some probability that an electron can exist on the vacuum side of the barrier even though it does not have sufficient kinetic energy to overcome the barrier. This is known as the **tunneling effect**. The resulting electron is called **field emission.**



Construction of a Field Emission Cathode

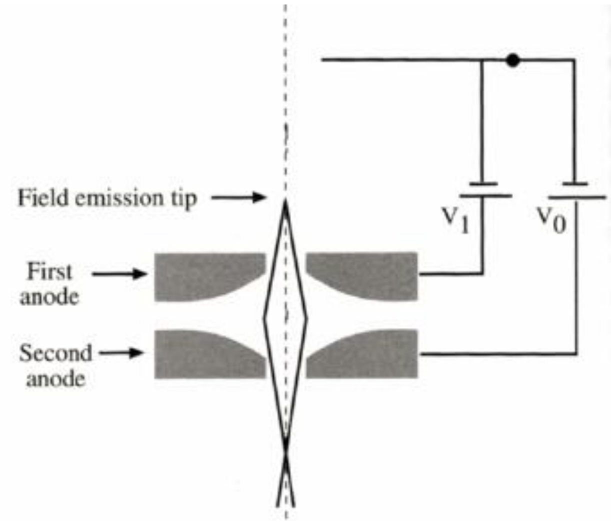
First anode (V_1) is extraction voltage

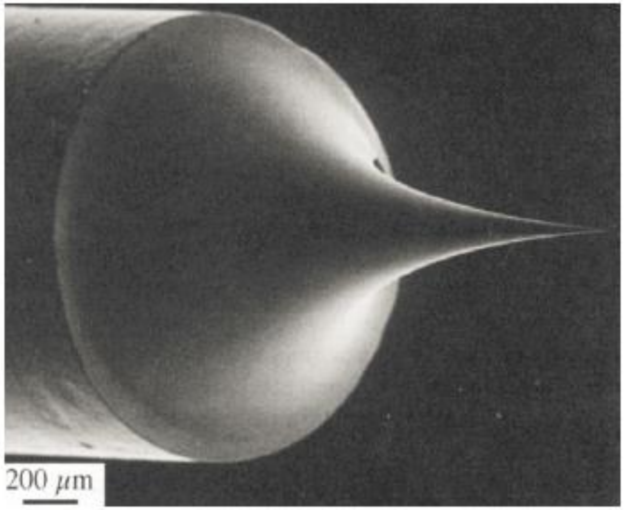
Second anode (V_2) acts as an electrostatic lens

As an opertator, you slowly increase V_1

- That's pretty much it.
- Automated in latest machines

Different extraction voltages for different operation modes





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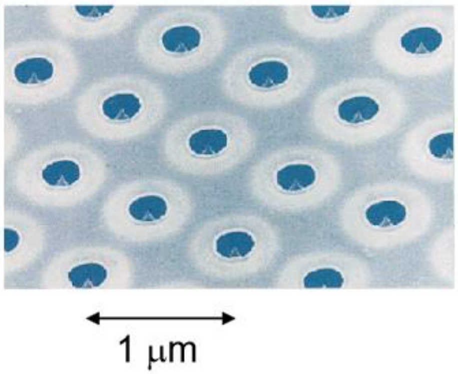
Application Field Emission

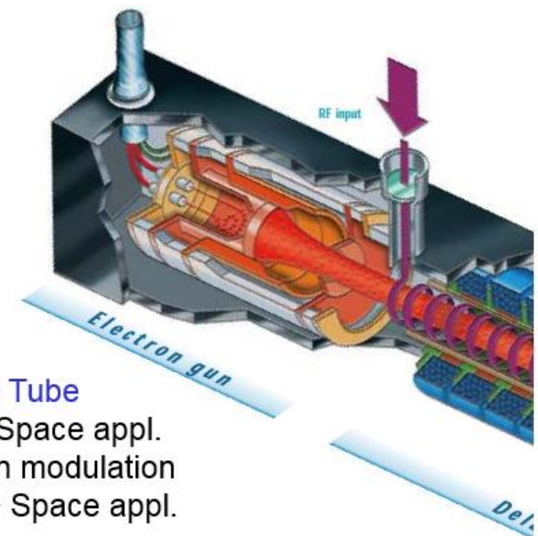
Materials Science & Technology

Field Emission Display
- Image quality of CRT
- Low power
- 5-10 mm thick



Parallel e-Beam Lithography
Data Storage
- Massively parallel (>1'000 beams)
- High resolution (< 50 nm features)

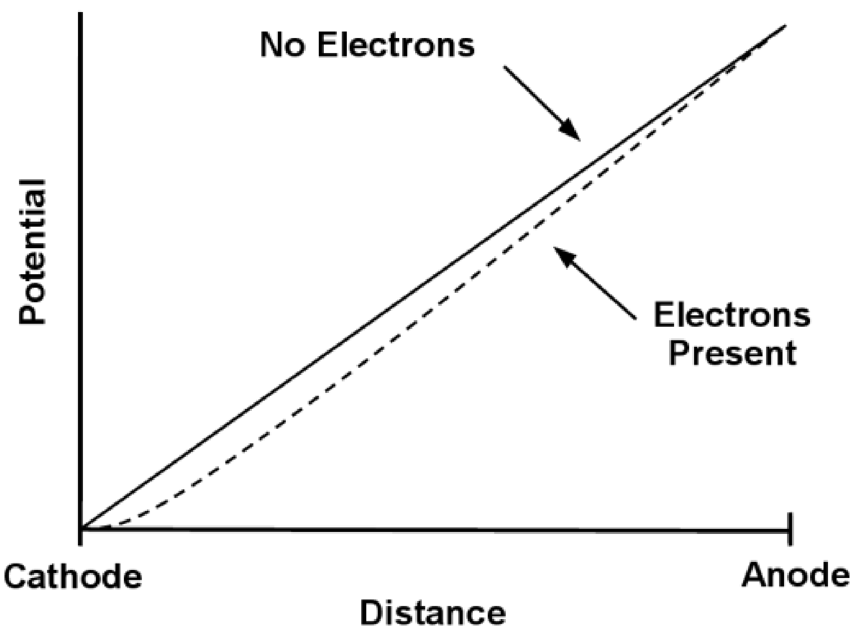
X-Ray tubes
- Micro X-Ray generators
- Low power -> portable
- Microfocus



Travelling Wave Tube
- Low power -> Space appl.
- Direct emission modulation
- Light weight -> Space appl.

Space Charge Limitation

The effect of the negative charge of an electron is to reduce the potential that is present in the absence of the electron. Near the emitting cathode where many electrons are present, the reduction in potential are considerable. With no electrons the potential increases linearly from the cathode to the anode. With electrons, the potential profile is depressed (dashed line).



The space charge limited mode

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- Normally, the maximum cathode emission is not temperature - but also space charge limited.
- The electrostatic potential due to electron charge, protect the cathode. The resultant consequence is a space charge limited electron beam.
- The space charge limited emission is specified by the *Child-Langmuir-Law.*

$$I_a = c \cdot (U_a + U_0)^{\frac{3}{2}} \quad \text{with} \quad c = \frac{4}{9}\varepsilon_0 \sqrt{2\frac{e}{m_e}} \cdot \frac{A}{d^2}$$

U_a: Anode voltage

eU_0: Work function

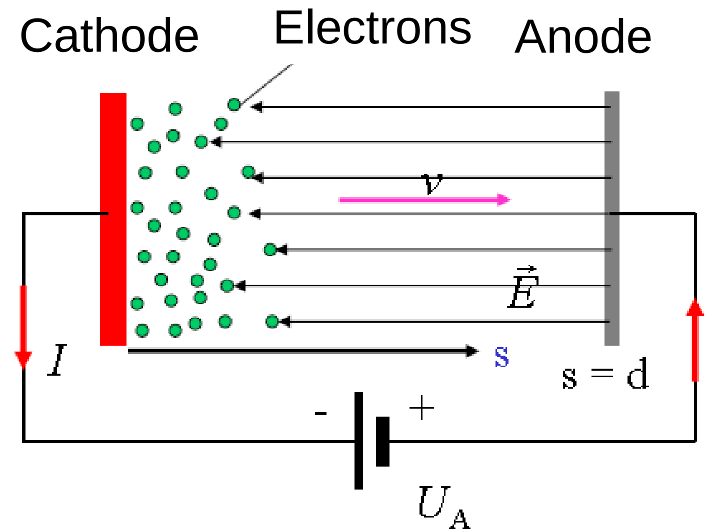
- **The $U^{3/2}$ dependency is characteristic of all tubes in the space charge limited region.**
- The space charge limited operation are not dependent on the operation temperature of the cathode or the work function of the emitter material.
- The operation depends on the applied voltage and the geometry of the emitter (d: distance between cathode and anode, A: emitter surface).

Calculation of the Child-Langmuir-Law …#1/4

The slow electrons emitted from the cathode create a space charge cloud whose charge density disturb the externally applied potential. This effect limits the electron flow.

Catchword: Space charge limited emission of electron ray tubes

The electrons starts at the cathode with v = 0 and will be accelerated by an electric field E(s). r(s) is the charge density.



$$\frac{\partial^2 U(s)}{\partial s^2} = \frac{-\rho(s)}{\varepsilon_0} \qquad \frac{dv(s)}{dt} = \frac{q}{m} E(s)$$

Poisson Equation   Equation of motion

The current density j of the electron beam is defined by

$$\vec{j}(s) = \rho(s)\vec{v}(s)$$

In addition, the continuity equation is valid at all places s.

$$div\vec{j} + \frac{d\rho}{dt} = 0$$

In the stationary case the charge density r(s) is temporally constant at all places. It is not allowed that the current density changes along s. With increasing particle velocity decrease the charge density ρ at a constant current density j.

$$\frac{dj}{ds} = 0 \quad \rightarrow j = j_0 = \rho v$$

….#3/4

The current density j_0 can be directly determined, because the density $\rho(s)$ via the poisson equation is coupled with the potential distribution.

$$-\frac{dE}{ds} = \frac{d}{ds}\,gradU = \frac{d^2U}{ds^2}$$

$$\frac{d^2U}{ds^2} = -\frac{\rho(s)}{\varepsilon_0} = -\frac{j_0}{\varepsilon_0 v(s)} = -\frac{dE}{ds}$$

$$\frac{dE}{ds} = \frac{j_0}{\varepsilon_0 v(s)} = \frac{j_0\,dt}{\varepsilon_0\,ds}$$

$$\frac{dE}{dt} = \frac{j_0}{\varepsilon_0} \quad \text{und} \quad E = \frac{j_0}{\varepsilon_0} t$$

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We solve the equation of motion in the usual way:

$$\frac{dv(t)}{dt} = qE(t) = \frac{q}{m}\frac{j_0}{\varepsilon_0}t \qquad v(t) = \frac{1}{2}\frac{q}{m}\frac{j_0}{\varepsilon_0}t^2 \qquad s(t) = \frac{1}{6}\frac{q}{m}\frac{j_0}{\varepsilon_0}t^3$$

The scalar potential or the voltage U(s) are derived by

$$U(s) = -\int_0^s E(s)ds = -\int_0^t E(t)v(t)dt = -\int_0^t \frac{1}{2}\frac{q}{m}\frac{j_0^{\,2}}{\varepsilon_0^{\,2}}t^3 dt = -\frac{1}{8}\frac{q}{m}\frac{j_0^{\,2}}{\varepsilon_0^{\,2}}t^4 = U(t)$$

We substitute t by the independent space variable s and get

$$U(s) = -\left(\frac{9}{4}\frac{j_0}{\varepsilon_0}\sqrt{\frac{m}{2q}}\right)^{2/3} s^{4/3}$$

By solving for the space charge limited current density we get finally the ***Child-Langmuir-Law*** dependent on the distance d (distance cathode - anode).

$$j_0 = \frac{4}{9}\sqrt{2}\varepsilon_0\sqrt{\frac{q}{m}}\frac{U^{3/2}}{d^2}$$

$$I_0 = \frac{4}{9}\sqrt{2}\varepsilon_0\sqrt{\frac{q}{m}}\frac{U^{3/2}}{d^2}\cdot\pi r^2 = \frac{4\pi}{9}\sqrt{2}\varepsilon_0\sqrt{\frac{q}{m}}\frac{r^2}{d^2}\cdot U^{3/2} = P\cdot U^{3/2}$$

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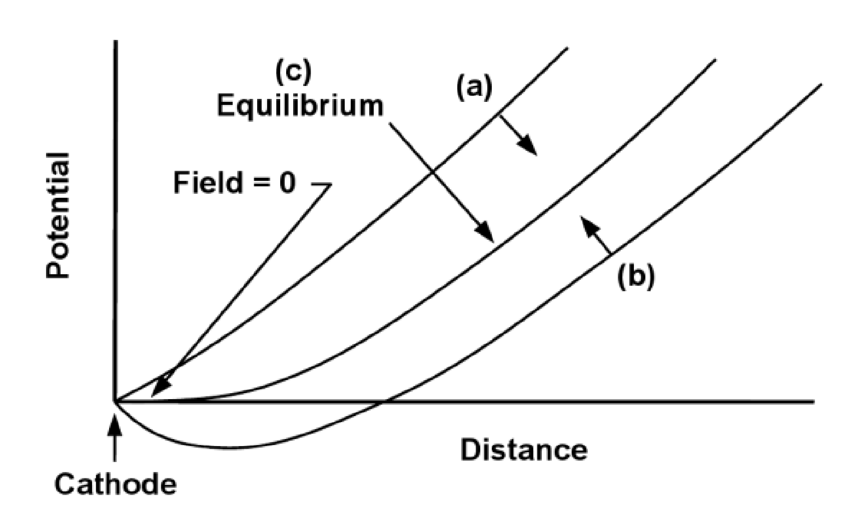
Space Charge Limitation

a) The electric field at the cathode surface causes all emitted electrons to leave the cathode

b) The electric field at the cathode surface forces electrons back to cathode surface.

c) The potential adjacent to the cathode surface is zero, that is, when the electric field at the cathode surface is zero (equilibrium condition). If the potential tends to become positive, more electrons flow from the cathode.

When the electric field at the cathode surface is forced to be zero by the electron cloud close to the cathode surface, the emission is said to be space charge limited.



Potential profiles near the cathode surface

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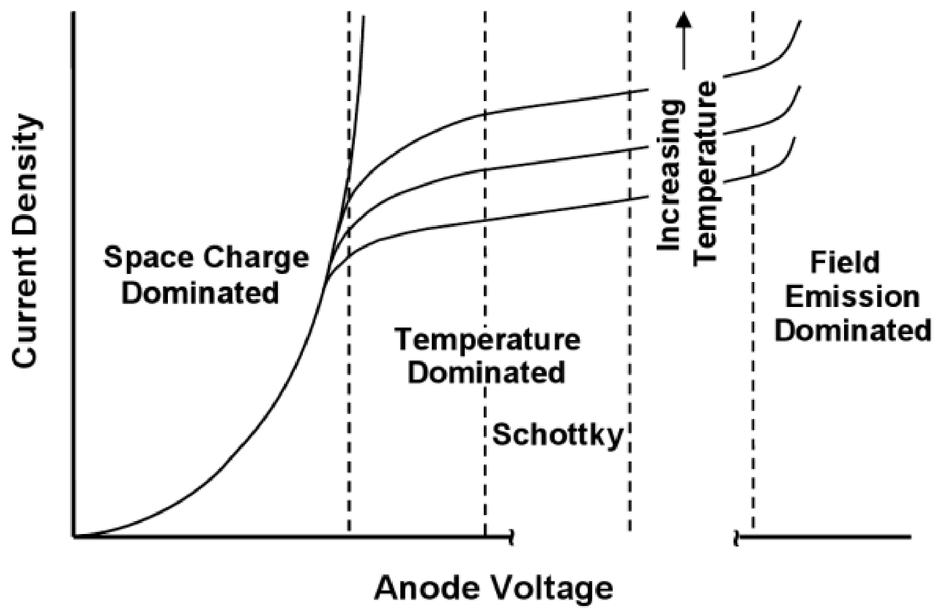
Summary of emitting Mechanisms

- At low voltages, current is space charge limited
- As voltage is increased, the emission limit of the cathode is reached and current becomes dependent on cathode temperature.
- Current continues to increase slowly with voltage, because of the Schottky effect.
- At high voltages, field emission causes current to increase rapidly



Summary of mechanisms dominating current flow in a thermionic diode.

History of thermionic cathodes

~ 1920 Tungsten (Wolfram) cathodes (e Φ = 4.6 eV)

~ 1935 Oxide coated cathodes

~ 1950 Dispenser cathodes

Reservoir cathodes (Ba diffuses through the porous tungsten)

CPD cathodes (controlled porosity dispenser)

Impregnated cathodes (Ba is included in pores)

~ 1990 Scandate cathodes

Commonly used in industrial gyrotrons:

Ba impregnated dispenser (tungsten) cathodes

In short pulse operation:

LaB_6 cathodes (not sensitive to poisoning)

(Lanthan-Bor-6)

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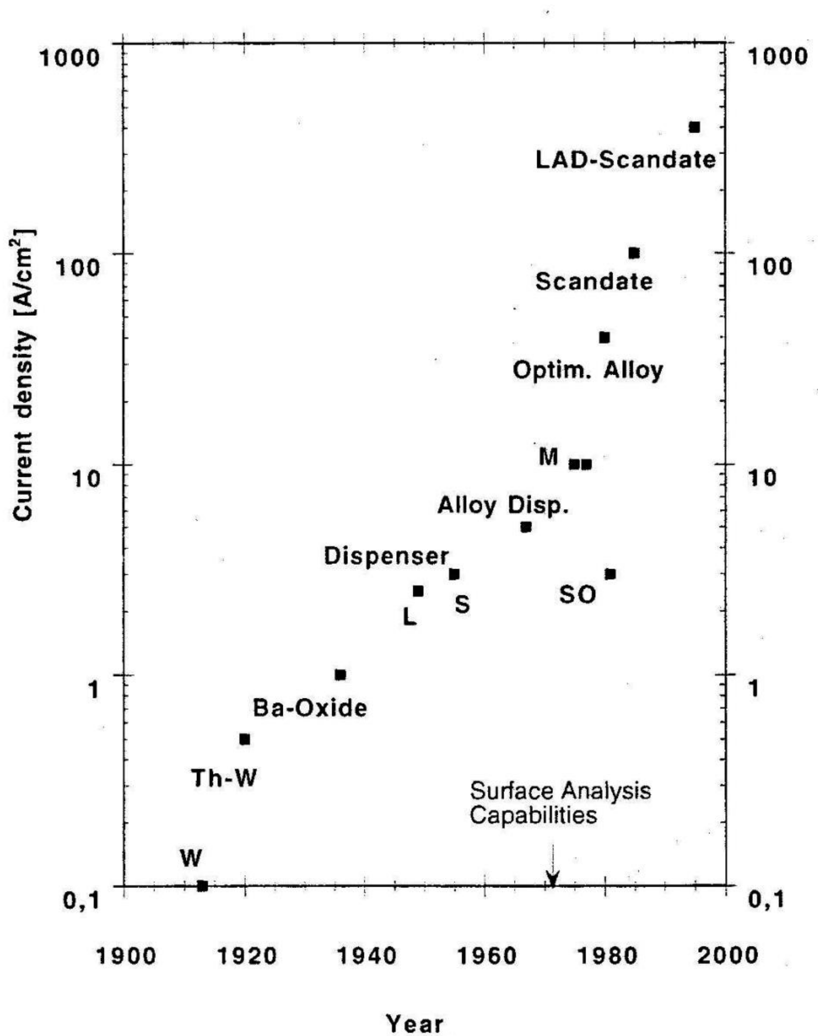


Cathode type	Φ (eV)
W	4.6
Th-W	3.2
Oxide	1.5
Dispenser (B – type)	2.1
Coated dispenser (M – type)	1.95
Optimum alloy (M – type)	1.85
Scandate	1.47

Emission capabilities of a Scandate cathode

T (^{0}C)	J (A/cm^2)
1030	400
930	115
830	26
730	4.6

Tungsten (Wolfram)-Cathodes

Tungsten (Wolfram, W, atomic number 74) is a hard, rare metal.
It was found naturally on the Earth only in chemical compounds such as tungsten oxide. Now, the most of tungsten mines was found in China.

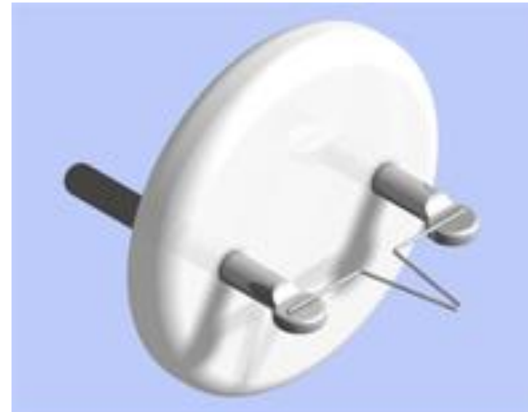
Tungsten was identified as a new element in 1781, and it was the first isolated as a metal in 1783. There are two important tungsten ores include wolframite and scheelite.

Tungsten has the highest melting point of all the non-alloyed metals and the 2nd highest melting point of all the elements after carbon.

Tungsten metal has high density of 19.3 g/cc which is comparable to that of uranium and gold, and it is much higher about 2 times than that of lead.

Most of tungsten chemical compounds are Tungsten oxides and tungsten

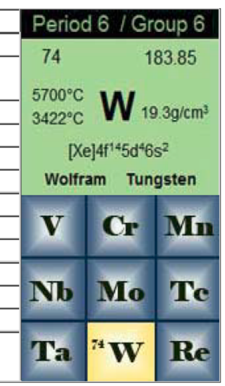
Trioxides (WO3). Tungsten oxides are always named tungsten intermediate Products. That are tungstic acid, ammonium paratungstate (APT, tungsten oxide content 88.5 %); ammonium metatungstate (AMT), sodium tungstate, yellow tungsten oxide (YTO), blue tungsten oxide (BTO), tungsten trioxide (WO3), violet tungsten oxide (VTO). The other tungsten chemical compounds are most often used industrially as tungsten catalysts, there are tungstic anhydride, pure tungsten oxide, extra pure tungsten oxide (refined tungsten oxide) yellow-green tungsten oxide, Tungstic acid anhydride (Wolframic acid anhydrous, Wolframic acid anhydride), puratronic tungsten(vi) oxide, etc.



Tungsten (W) Filament Cathode

中钨在线（厦门）科技有限公司
ChinaTungsten Online (Xiamen) Manu. & Sales Corp.

Cell Phone	tungsten alloy mobile cubes
Watch	tungsten alloy watch bobs
Computers	tungsten alloys heat sinks for PCB tungsten alloy heat base for PCB
Dart Sets	tungsten alloy dart billets, tungsten alloy dart barrels
Golf	tungsten alloy golf clubs
Yacht	tungsten alloy yacht balance,
Fishing	tungsten alloy fishing sinkers
Hunting Gun	tungsten alloy shots and hunting gun's bullets' balls
	tungsten alloy weights roller for meters,
Racing Car & Motors	tungsten alloy balances for racing car tungsten alloy crankshafts for motor & auto engines
Home	tungsten alloy Paper Weight.
Airplane	riveting bucking bars for airplanes,
Submarines	tungsten alloy seals for submarine tungsten alloy counterweigh , balance for submarine



Thoriated Tungsten (Th-W) Cathode

Thoriated Tungten (Th-W):

A small percentage of thoria in W .

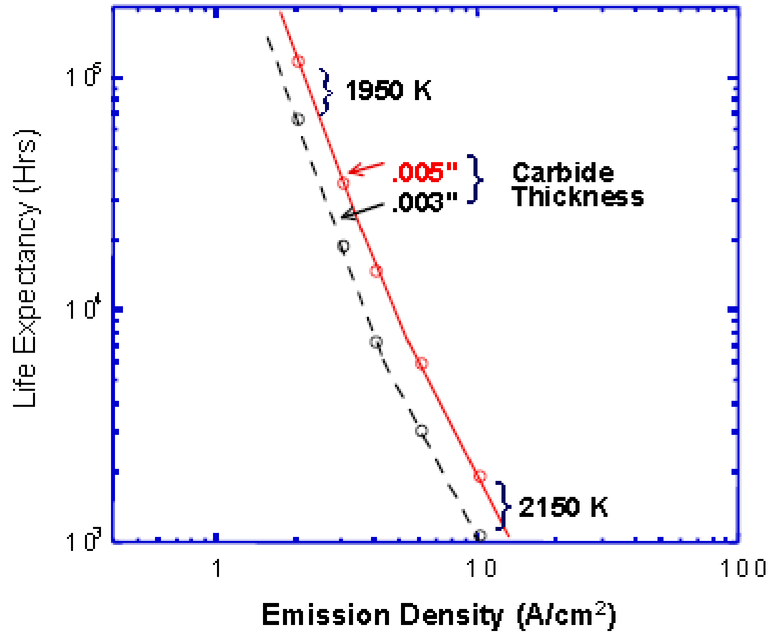
Thorium diffuses to the surface of the tungsten, and reduces the work function.

Carburization reduces the evaporation rate of the thorium.

Emitter	A amp/cm^2/deg^2	Work Function ϕ Volts	b_o degrees K
W	60-100	4.54	52,400
Ta	60	4.1	47,200
Mo	60	4.15	51,300
Th on W	3.0	2.63	30,500

Reference data for engineers: Radio,Electronics, Computer & Communications 8th Edition, p16-3, ed. M.Van Valkenburg, Newnes Press, Boston MA, 1993

Life Expectancy for a Switch Tube with a Th-W Cathode



T.E.Yingst, et al, Proc. IEEE, March 1973

Carburization - Kohlenstoffanreicherung

Quellen: W. E. Harbough, Tungsten, Thoriated-Tungsten, and Thoria Emitters,
A. Shih, High Emission Density Thermionic Cathode, Workshop on Cathodes for Relativistic Electron Beams, 2001

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Oxide-Coated Cathodes

	Φ (eV)	T (K)	J (A/cm²)
W	4.6	2608	1
Th-W Thoriated tungsten	3.2	1870	1
Oxide	1.5	942	1

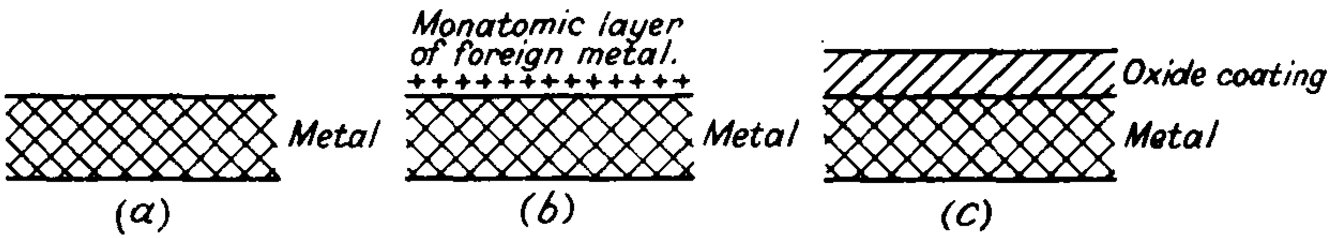
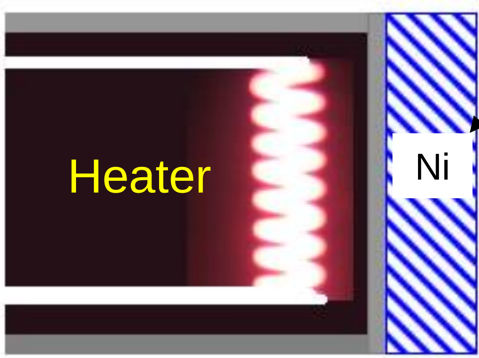


Fig. 1.—Section through (a) a Pure Metal Cathode, (b) an Atomic Film Metal Cathode, (c) an Oxide Cathode.

Quelle: S. Wagener, The oxide-coated cathode, 1951



Mixture of BaO, SrO, CaO
49%, 44%, 7% (atomic %)

Nickel substrate with an oxide layer:

Passive Ni, Ni without active impurity

Φ = 1.85 eV

Active Ni, Ni with impurities such as W

Φ = 1.5 eV

Oxide-Coated Cathodes

Activation mechanism:

Generation of oxygen vacancies, which shifts the Fermi-level E_F from the intrinsic level to above the donor level

Φ = 1.5 eV with active Ni substrate

Φ = 1.85 eV with passive Ni substrate

Poisoning mechanism:

Annihilation of oxygen vacancies.

Poisoning gases: O_2 , CO_2 , H_2O and S.

Disadvantage of oxide cathodes:

- Not robust against residual gas poisoning.
- Coating flakes off after air exposure.
- Low D.C. emission, < = 1 A/cm^2.

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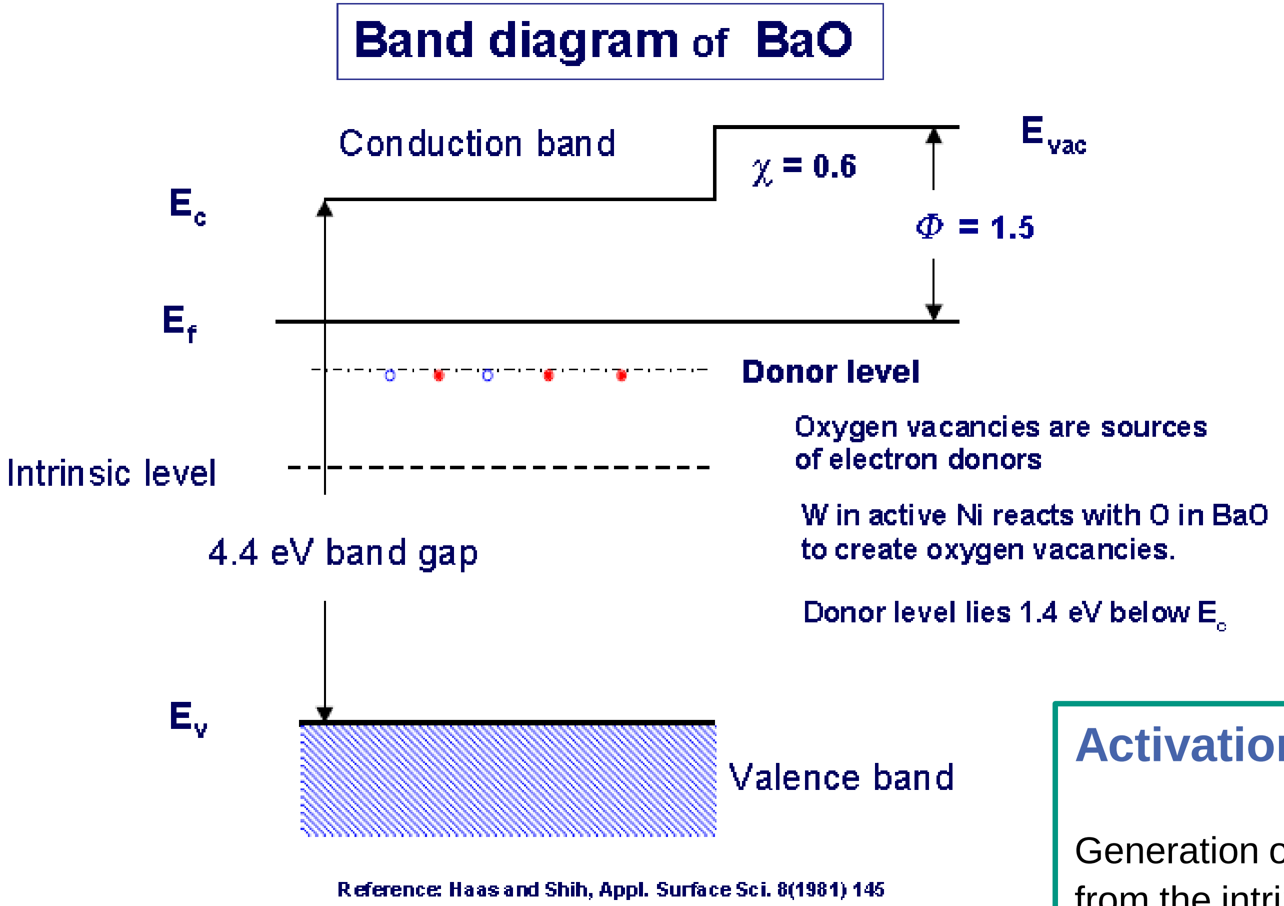
BaO-Oxide-Cathodes: Activation Mechanism

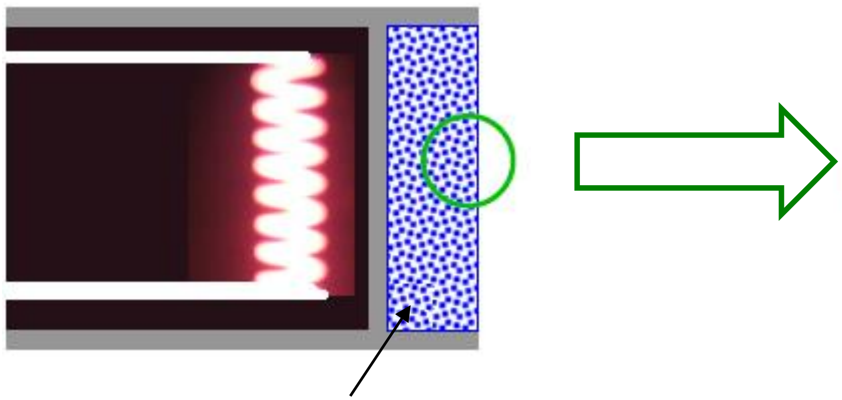


Activation mechanism:

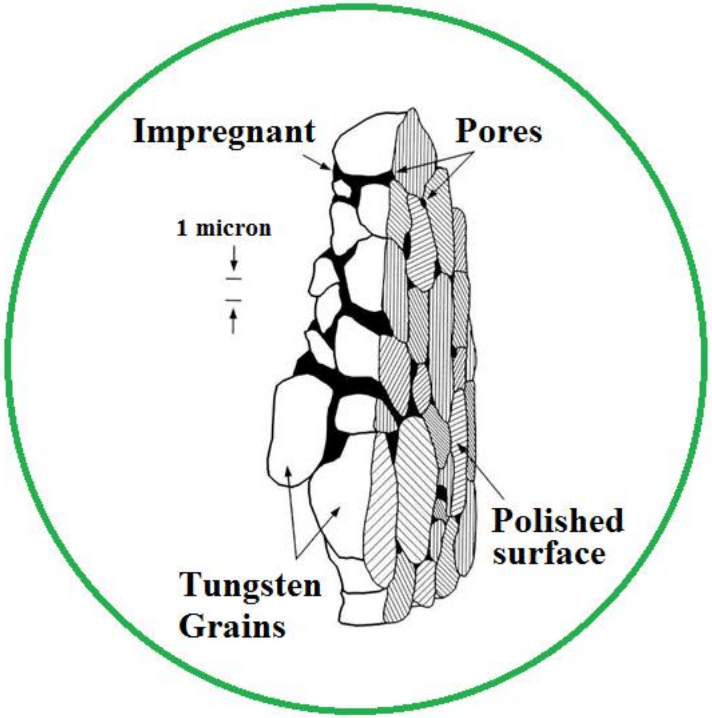
Generation of oxygen vacancies shifts E_F from the intrinsic level to above the donor level

Φ = 1.5 eV with active Ni substrate
Φ = 1.85 eV with passive Ni substrate

Dispenser-Cathodes



Matrix : Pressed W powder
20 % porosity



Impregnant:
4BaO, CaO, Al_2O_3 : [411], S-type
5BaO, 3CaO,$2Al_2O_3$: [532], B-type

W provides the electrical conductivity.
BaO lowers work function

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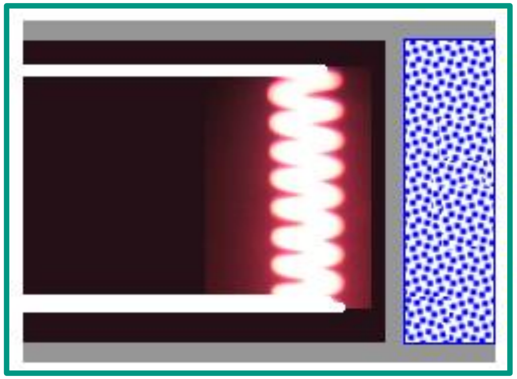
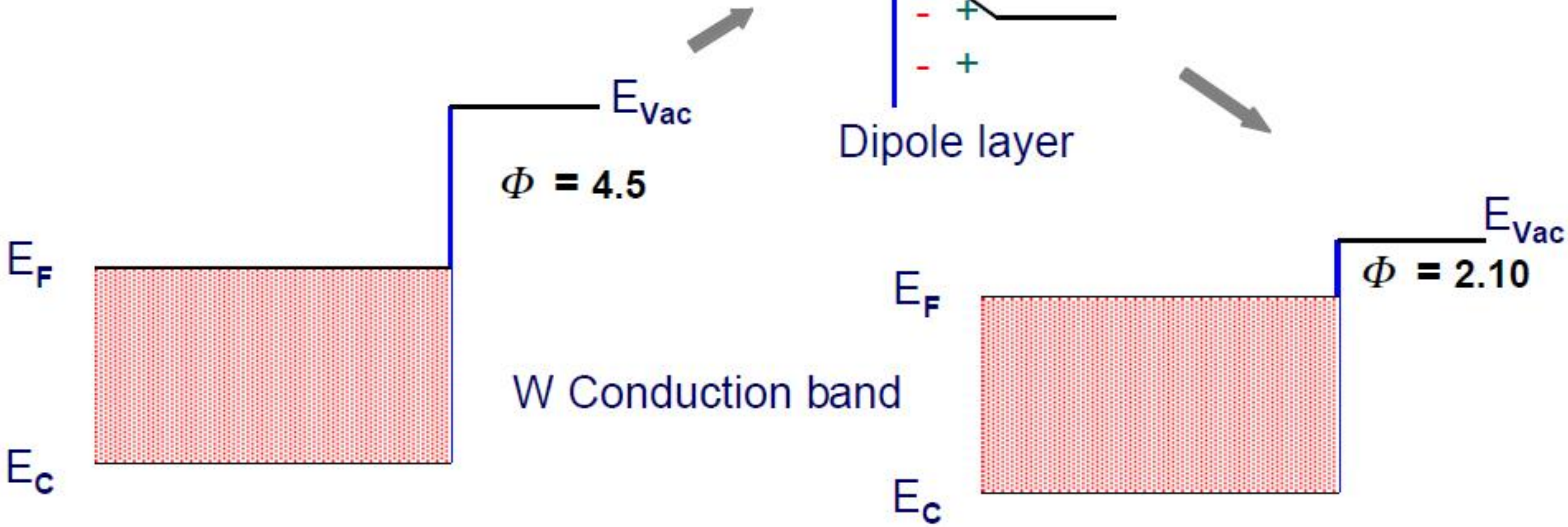
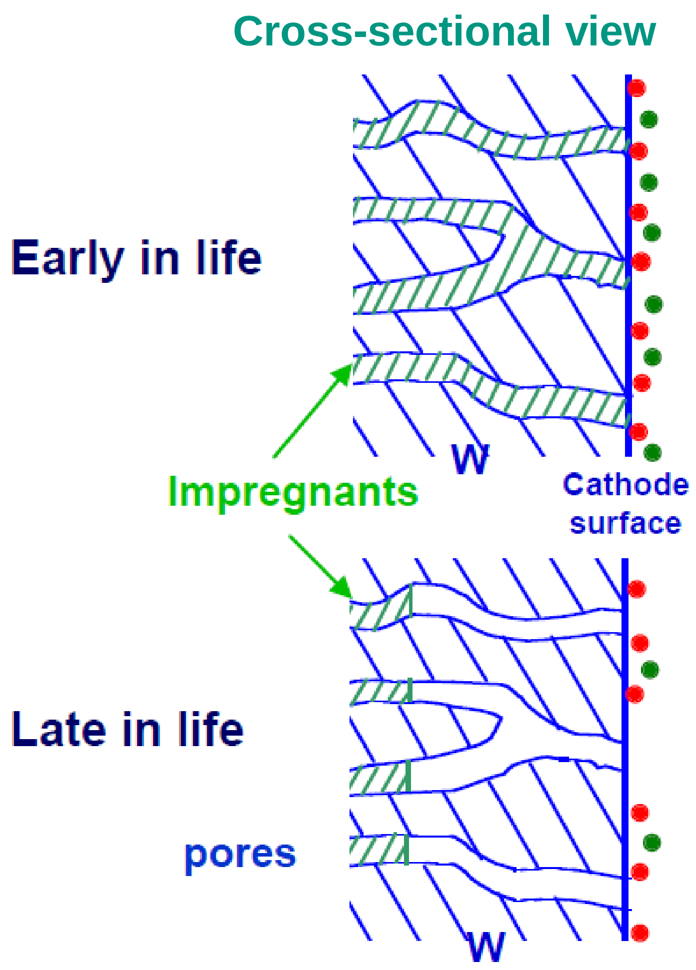
Work function of a BaO-Dispenser cathode





Life time of a dispenser cathode



Early in life, almost a full layer of Ba and O on the cathode surface.
Cathode surface

During operation, desorption of Ba occurs, but a supply of Ba from the pores maintains a full coverage on the surface.

Impregnants near the pore end depletes during life, resulting in low surface Ba coverage and poor emission.

J. Jelonnek

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Further characteristics

Cathode poisoning:

CO_2, O_2 or H_2O adsorption reduces dipole effect
CO, CH_4, H_2 or N_2 adsorption does no harm,
but C residue poisons cathodes.

Reactivation from poisoning:

Thermal desorption of the poisoning gases.
Impregnant replenishes the surface Ba.

Compared to oxide cathodes:

More robust against gas poisoning.
Reusable after air exposures.
Higher work function.
No DC emission limitation

	Φ (eV)	T (K) ($J=1A/cm^2$)
Oxide	1.5	942
Standard	2.1	1277
Os-coated	1.95	1194

Modifications

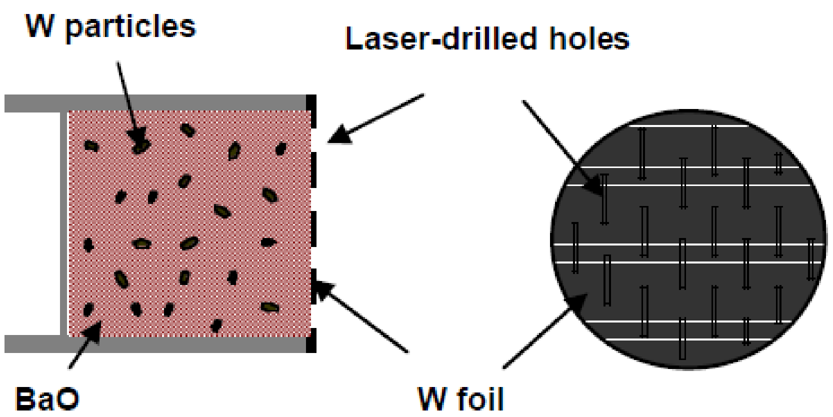
Coating: Strengthening BaO dipole

	Φ (eV)
Os-coating (M-type)	1.95
Os-W alloy-coating	1.85
Ir-W alloy-coating	1.85

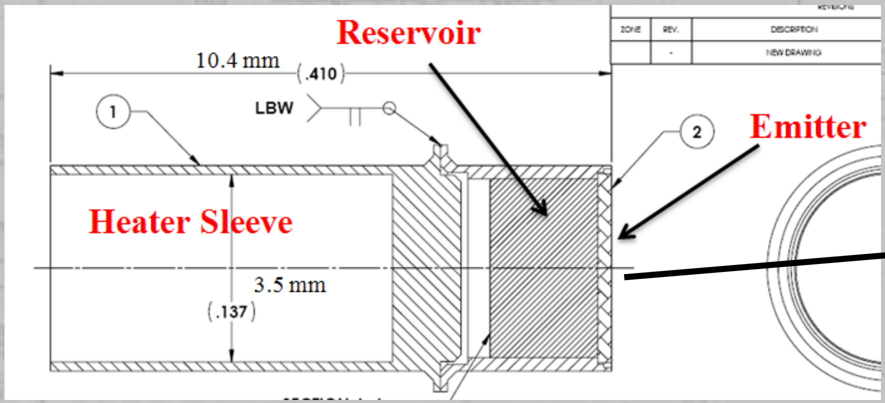
Structure: Improve life or uniformity

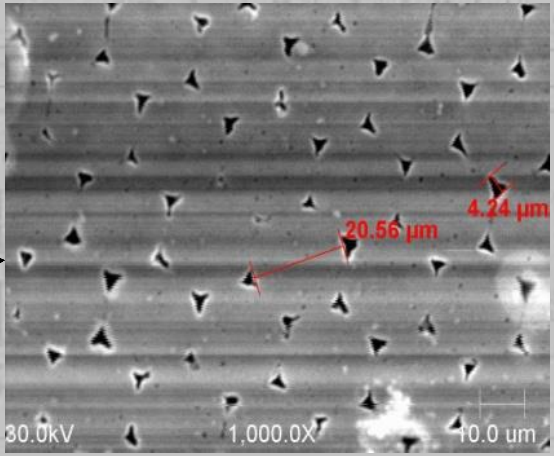
Reservoir of Ba: **RV cathodes**
Long life

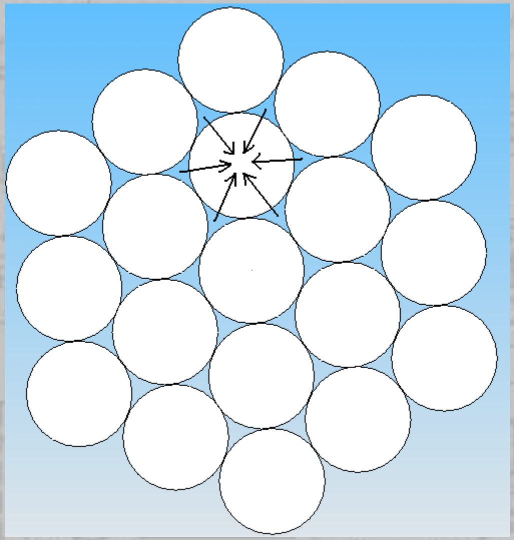
Controlled pores: **CPD cathodes**
Uniform emission

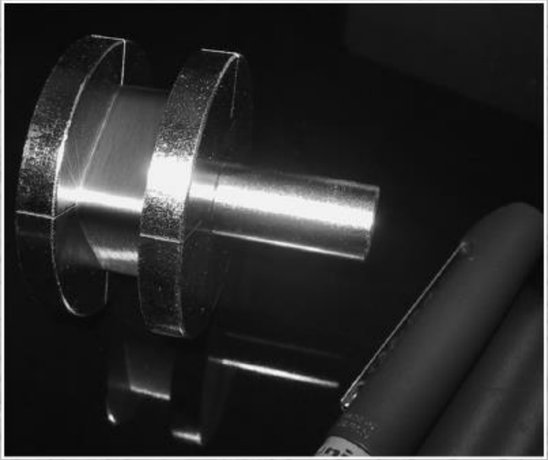


Controlled Porosity Reservoir (CPR) Cahodes









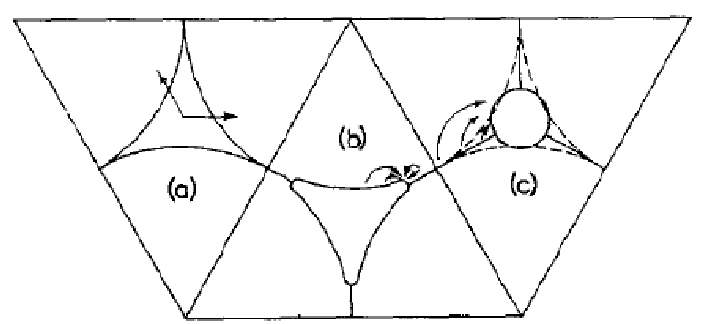
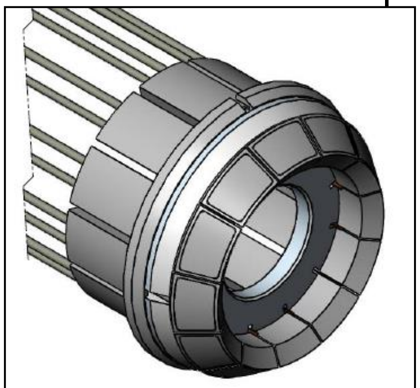
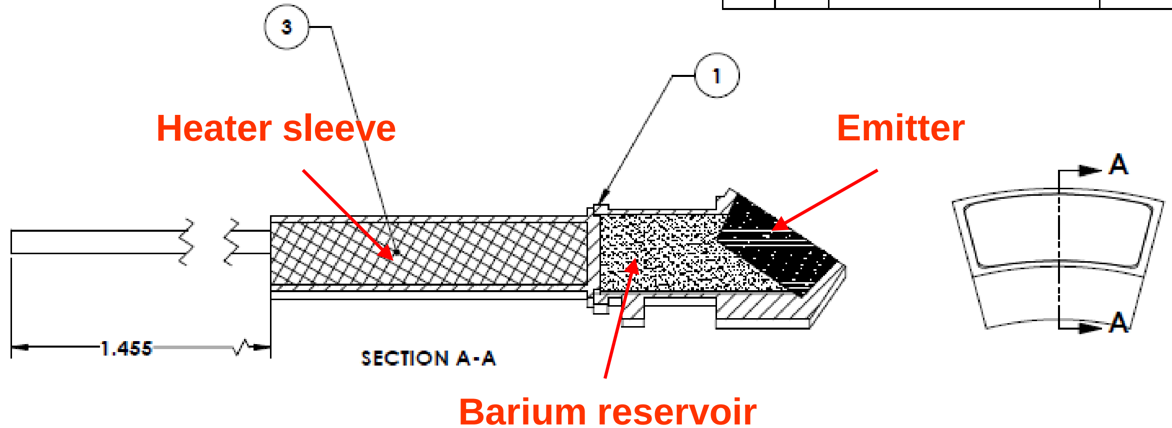
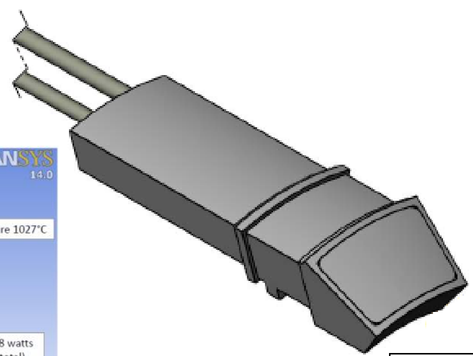


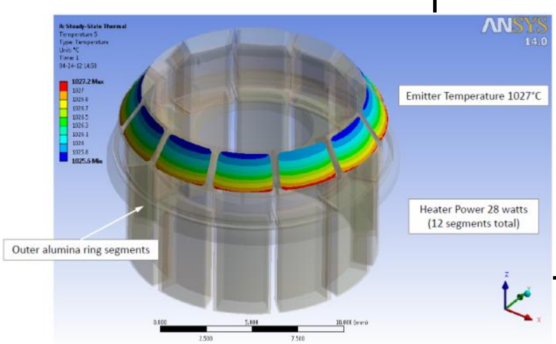
Figure 2. Stages of sintering. Image (a) is prior to sintering showing wires forming a pore. Image (b) is and intermediate stage and image (c) is when the material is fully sintered.

New Research: Segmented Emitter Configuration









REVISIONS				
ZONE	REV.	DESCRIPTION	DATE	APPROVED
	-	NEW DRAWING		

ITEM NO.	Part Number	DESCRIPTION	QTY
1	CCR-5621	Cathode Sub-Assy	1
2	TBD	Heater	1
3	TBD	Heater Potting	1

LIST OF MATERIALS

PROPRIETARY DATA. USE OR DISTRIBUTION IS PROHIBITED WITHOUT PERMISSION OF CALABAZAS CREEK RESEARCH, INC.

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES
DEC: 1PL ±.1 | 2PL ±.02
3PL ±.005 | FRAC±1/64
ANG ± 1° | SUR 125
MATERIAL
NOTED
SPEC NO. N/A

DR D.Marsden 3/24/11
ENG -
FAB -
ASSY -
PI -
CUSTOMER APPROVAL N/A

KIT MIG
USED ON
APPLICATION
PROJECTION

Calabazas Creek Research, Inc.
San Mateo, Calif

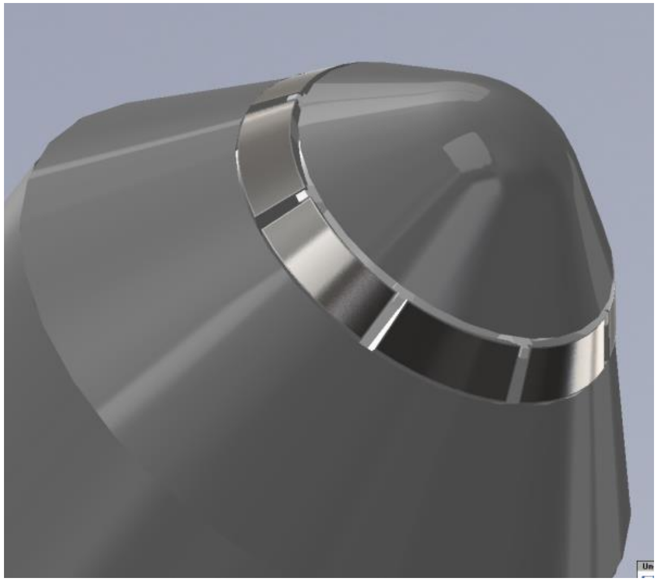
Cathode Assy

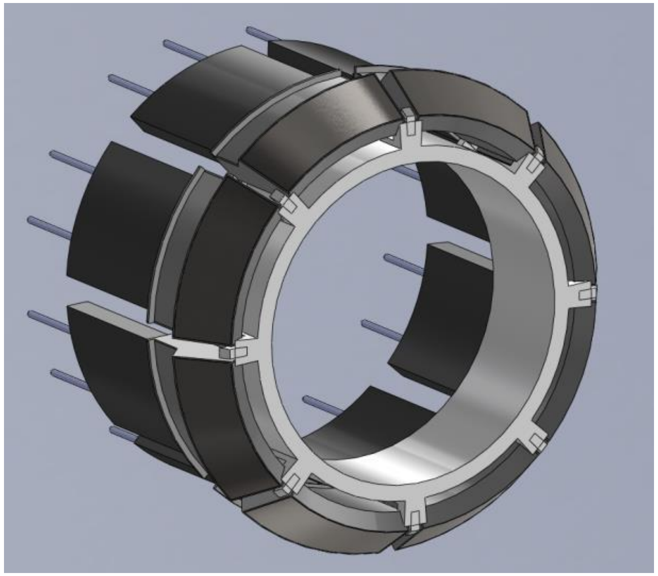
SIZE B | CAGE CODE 1QRA6 | CCR-5620 | -
SCALE 16:1 | SHEET 1 OF 1

Motivation

Build a Gyrotron with segmented emitter using CPR type cathode, to examine

- impact of inhomogeneous electron emission
- capabilities of CPR cathodes in gyrotron operation





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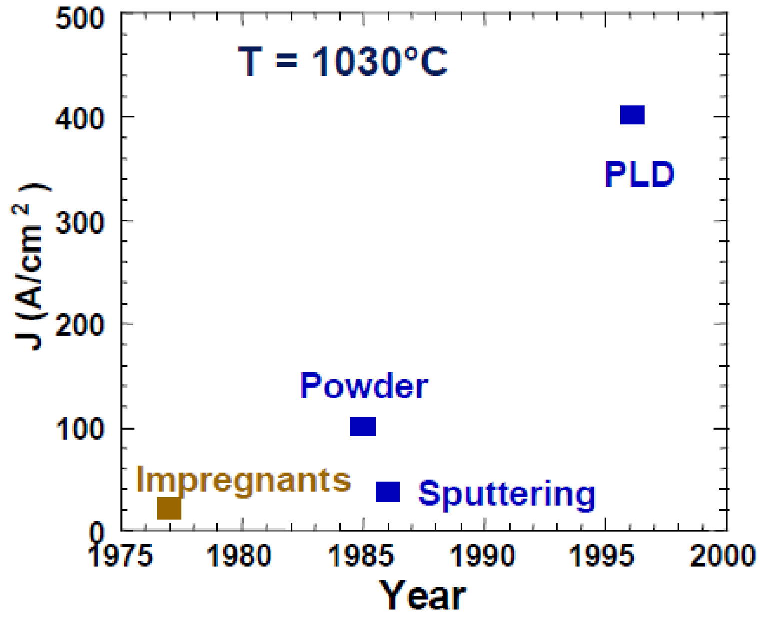
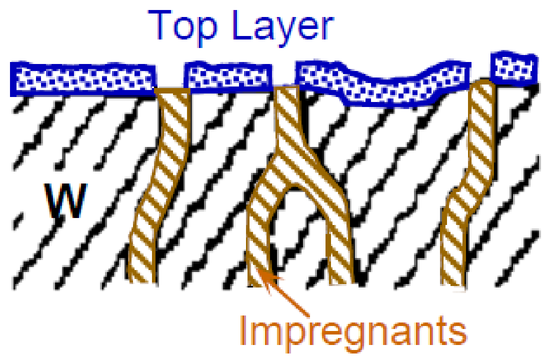
Cathodes with scandium (Scandate Cathodes)

Scandate cathode types	J A/cm² (T = 1030°C)
Pressed W + $Ba_3Sc_4O_9$	5 - 10
Sc – in the impregnant	20
Top layer types (powder, sputtering, pulsed layer deposition)	30-400





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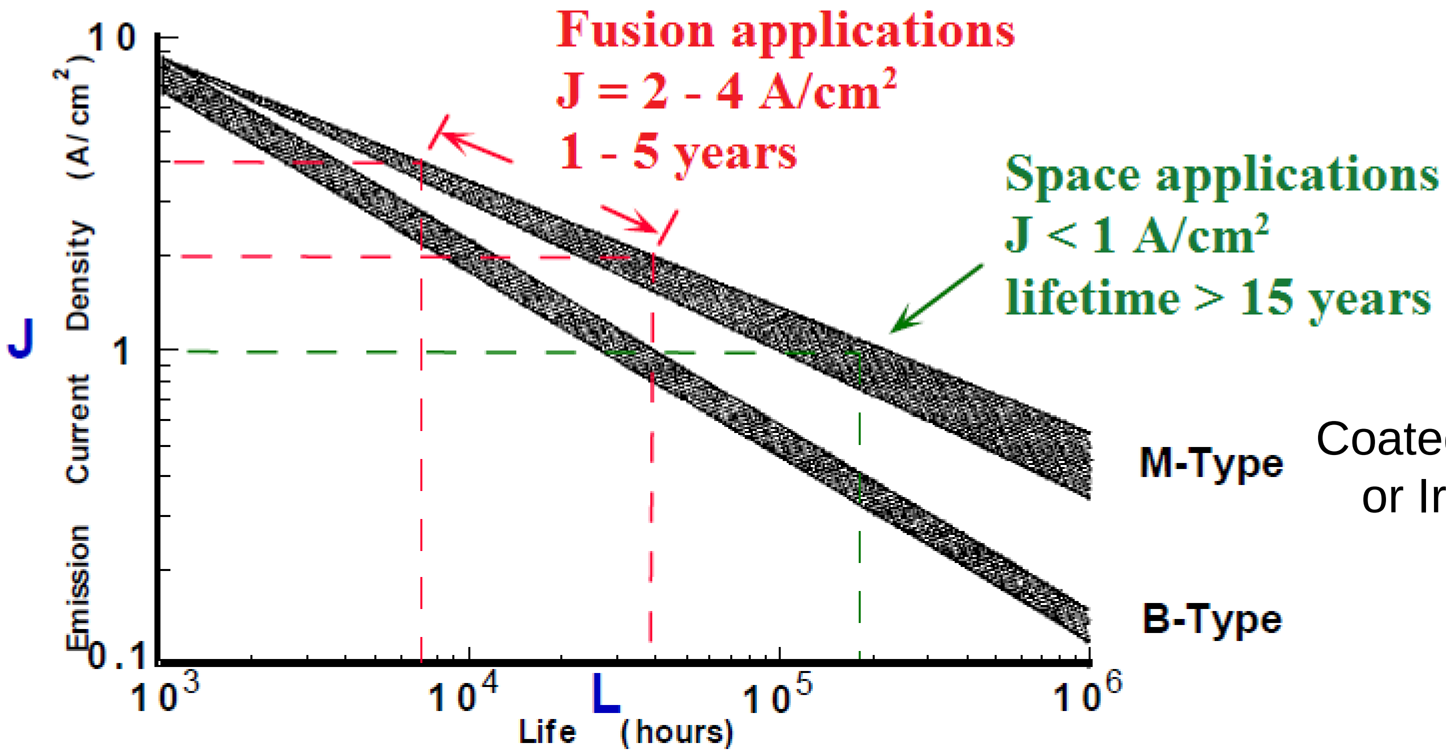
Trade-Off between current density and live time

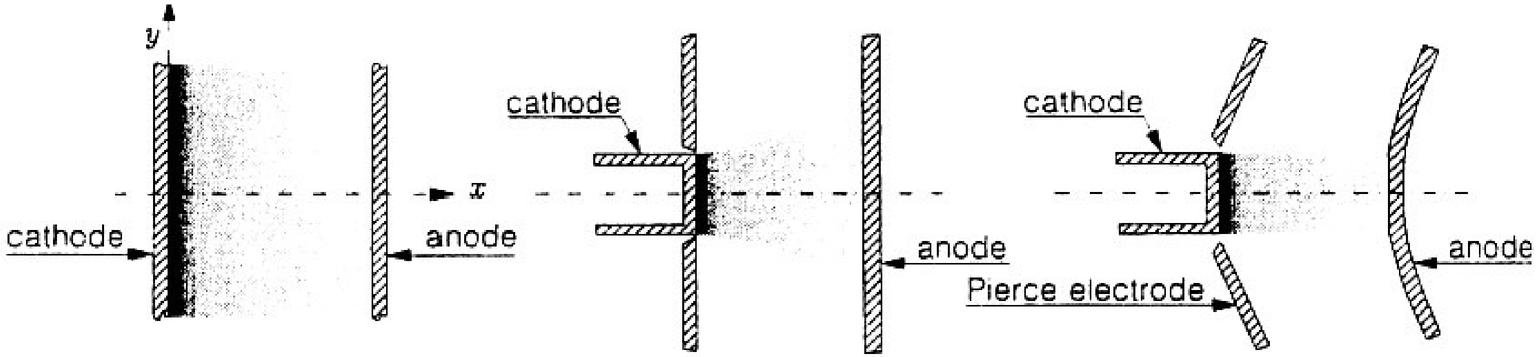


Coated with Os or Ir B-type

A.S.Gilmour,"Microwave Tubes", p132, (1986) Artech House, Inc.

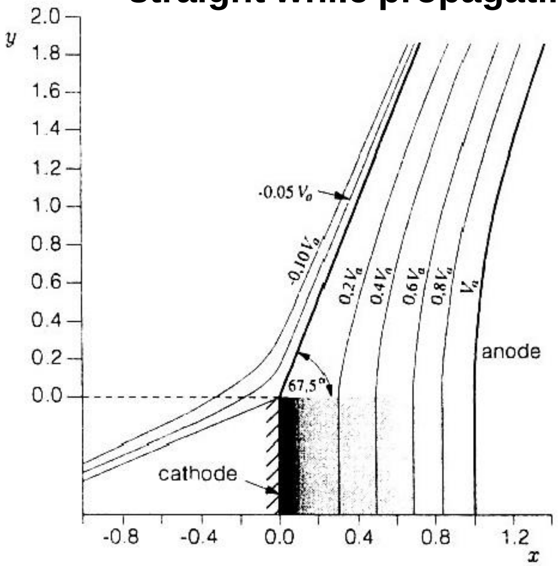
Life test at very high J:
B-type cathode 45 A/cm2, 50 hours at 1620K, LLNL

Example for Space charge Limited electron Gun: Pierce-type Electron Gun

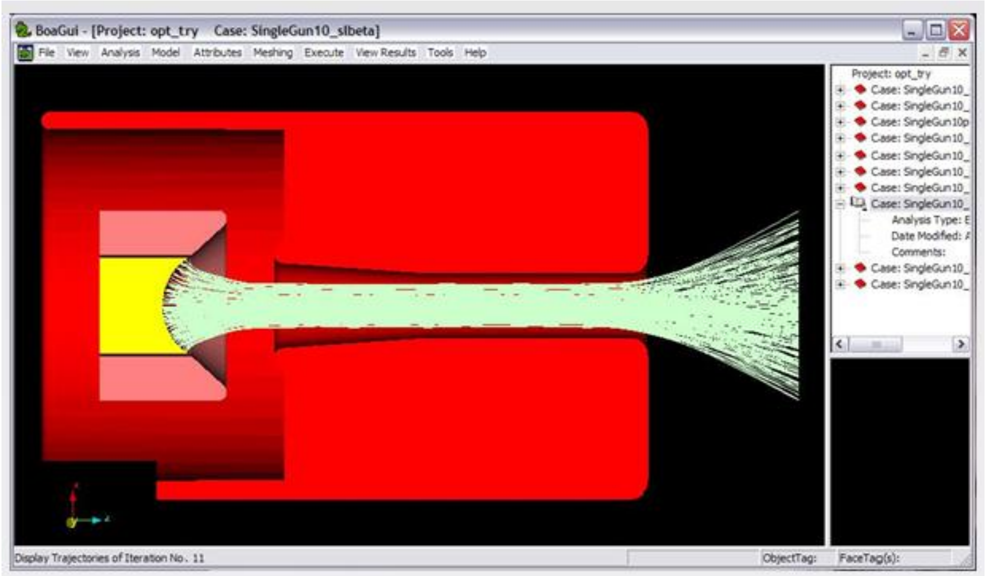


“Infinite” Diode | “finite” Diode | Pierce Diode

Optimum angle for the focusing electrode is 67.5^0 for keeping beam straight while propagating



Pierce gun for a real device



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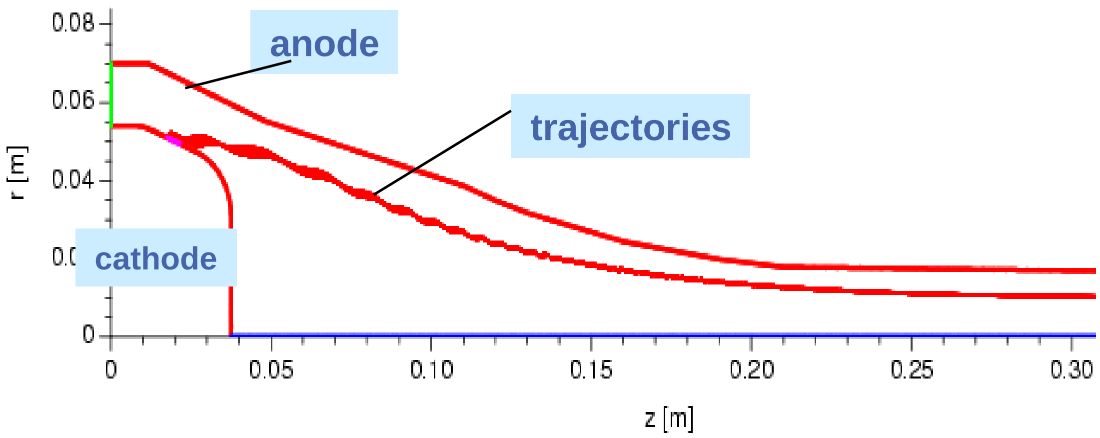
Example for temperature Limited electron Gun: Magnetron Injection Gun for Gyrotrons

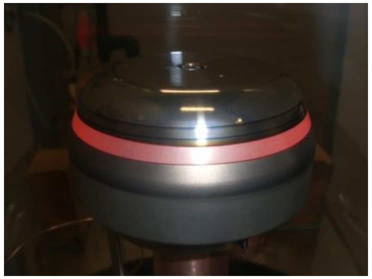


Gun

operating parameters:

beam voltage, U_b	80 kV
beam current, I_b	40 A
emitter current density, j_e	2.2 A/cm^2
velocity ratio α	1.4
emitter radius R_e	50 mm
beam radius in the cavity	10 mm

Cathode with emitter ring



Heated emitter
T=1050^{0}C

Configuration of the electron optical System

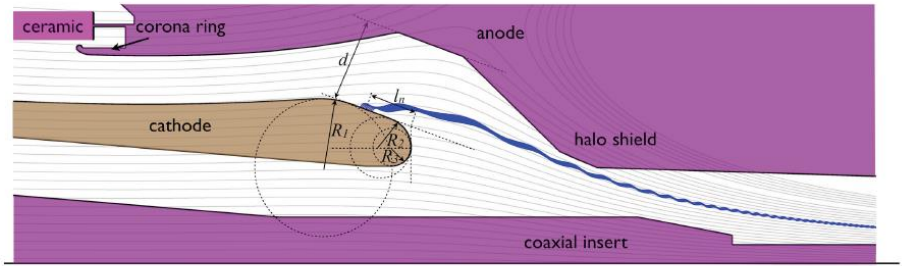
ITER gyrotron for fusion

Cavity mode	$TE_{34,19}$
Output frequency	170 GHz
mm-wave output power	2 MW
Beam current	75 A
Accelerating voltage	90 kV
Cavity magnetic field	6.87 T
Output efficiency (w/o SDC)	33 %
Output efficiency (with SDC)	50 %

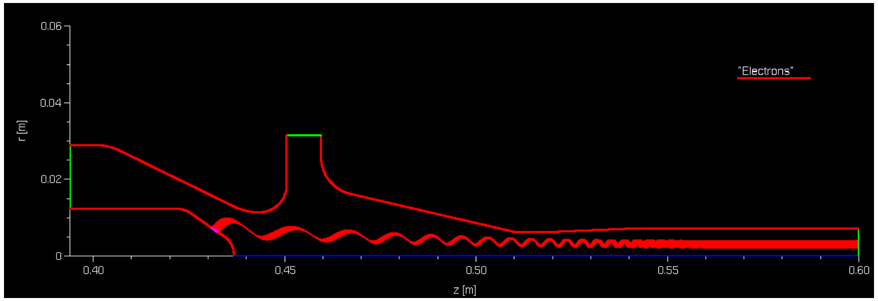
Technological gyrotron for materials processing

Cavity mode	$TE_{1,2}$
Output frequency	28 GHz
mm-wave output power	10kW
Beam current	2.2 A
Accelerating voltage	20 kV
Cavity magnetic field	0.513 T
Output efficiency (w/o SDC)	30 %

Diode magnetron injection gun for 1MW/170GHz coaxial gyrotron



Triode magnetron injection gun for 10kW/28 GHz conventional gyrotron



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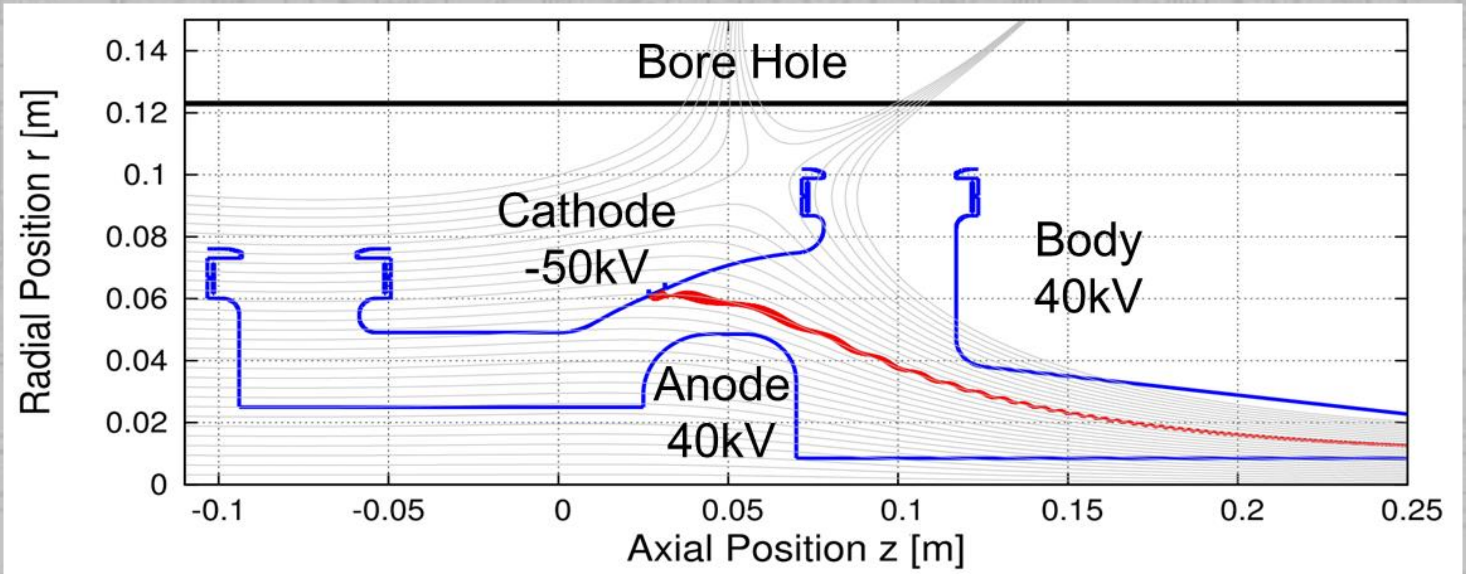
Developing Process of a Modern Gun Design

1. Definition of the physical Gun geometry in Matlab or C++
   a) Parameterization of the whole geometry with length, radii and angles
   b) Definition of the boundary conditions (potentials)
   c) Definition of the emitting structure
   d) Definition of the magnet adjustment
2. Creation of output files which are compatible to the simulation tool (Ariadne, Daphne, …)
3. Calculation and simulation of the beam parameters with the Simulation Tool
4. Possibly adjustment of the physical geometry and repetition of the steps 1-4 till the satisfied criteria and goals are achieved.
5. Simulation of the thermal expansion.
   → Appointment of the usable material (Molybdenum, Copper …)
6. Development of the cooling system.

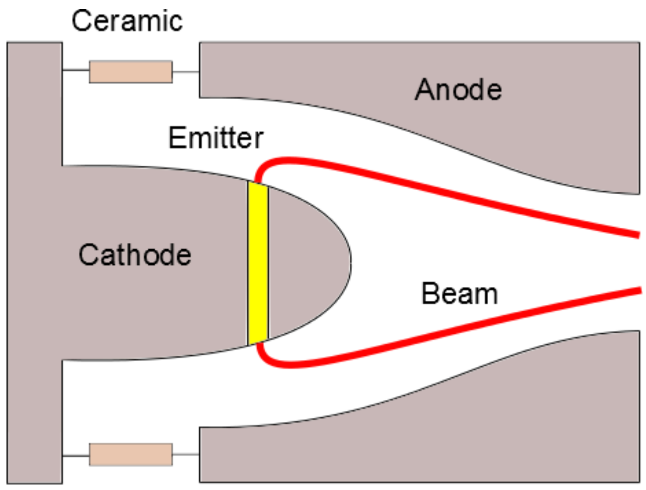
Final physical Design of a Magnetron Injection Gun



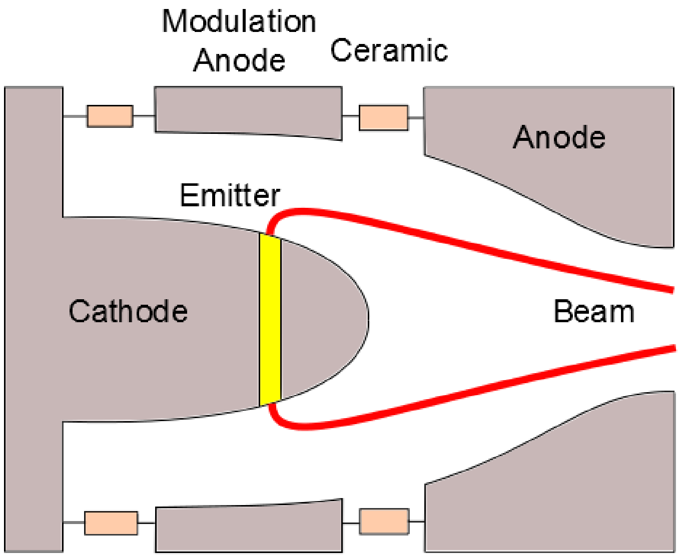
The gun design simulation is finished if:

- the simulated beam parameters satisfy the demanded parameters.
- the magnetic coil currents are in a realizable range.
- the electric field strength are below the limitations.

Different Types of Gun



diode gun



triode gun

- Diode Gun
  - Consists of the cathode and anode
  - Only 2 power supplies are necessary
- Triode Gun
  - Consists of the cathode, anode and modulation anode
  - →increase the control of beam parameters

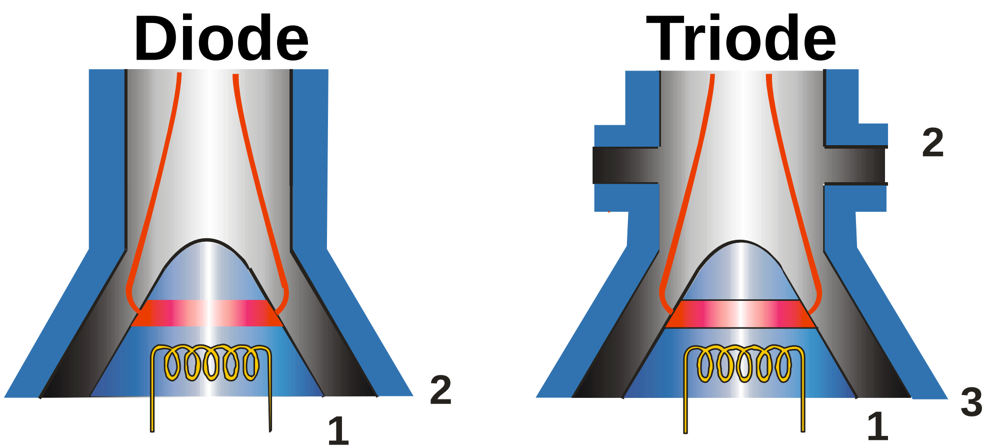
Diode- / Triode configuration

Gyrotrons need hollow beam with transverse velocity.
To produce transverse velocity, a radial electric accelerating field has to be applied.

→ **Magnetron Injection Gun (MIG)**

The transverse velocity is given by with the applied voltage Uc.

$$v_{\perp gun} \propto \frac{U_c}{B_{gun}} \cos \varphi_{EB}$$

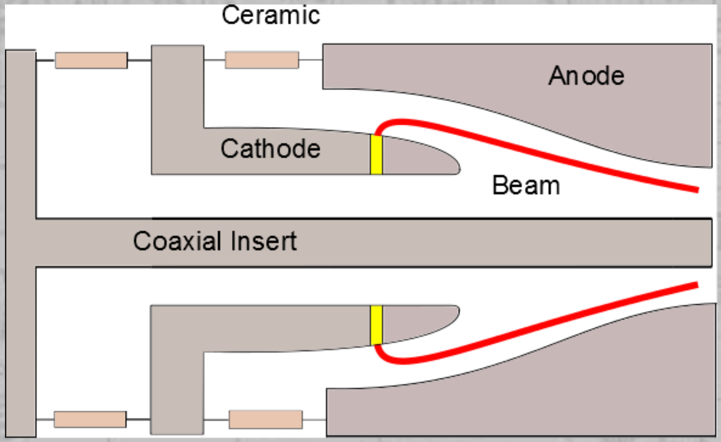


1 cathode
2 anode
3 intermediate anode

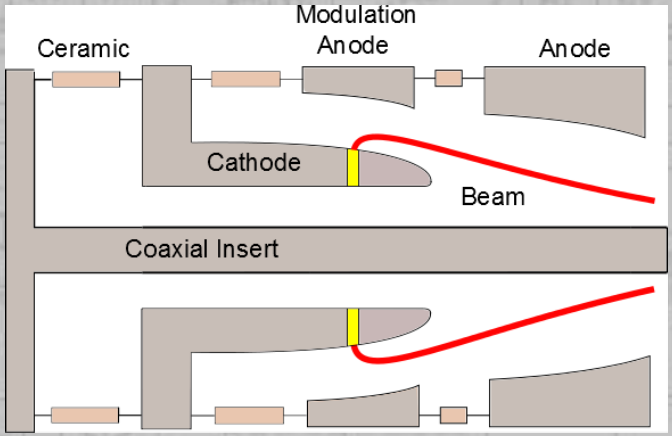
Advantage of triode:
Transverse velocity can be varied by the choice of voltage to intermediate anode without effecting the overall energy

Disadvantage of triode:
Additional power supply necessary

Different Types of Gun



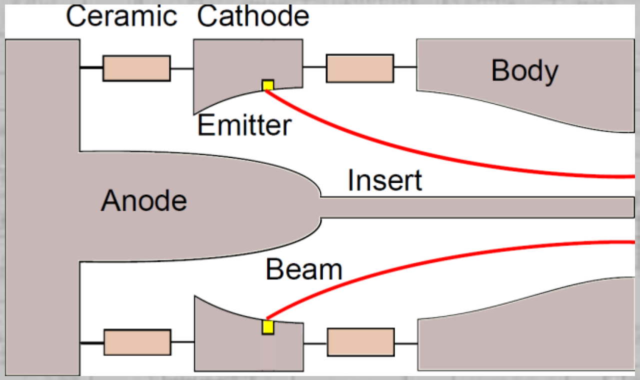
diode gun with coaxial insert



triode gun with coaxial insert

- Used in high power and high frequency gyrotrons
- Better mode competition
- Higher order modes
- Higher current → Higher output power
- Used in the 2 MW 170 GHz coaxial cavity gyrotron at IHM

Different Types of Gun



inverse gun with coaxial insert

- Emission takes place inwards instead of outwards
- The insert plays the role of the anode
- Advantages:
  - Larger emitter radius is possible or smaller bore hole (more cost efficient)
  - Simpler geometry