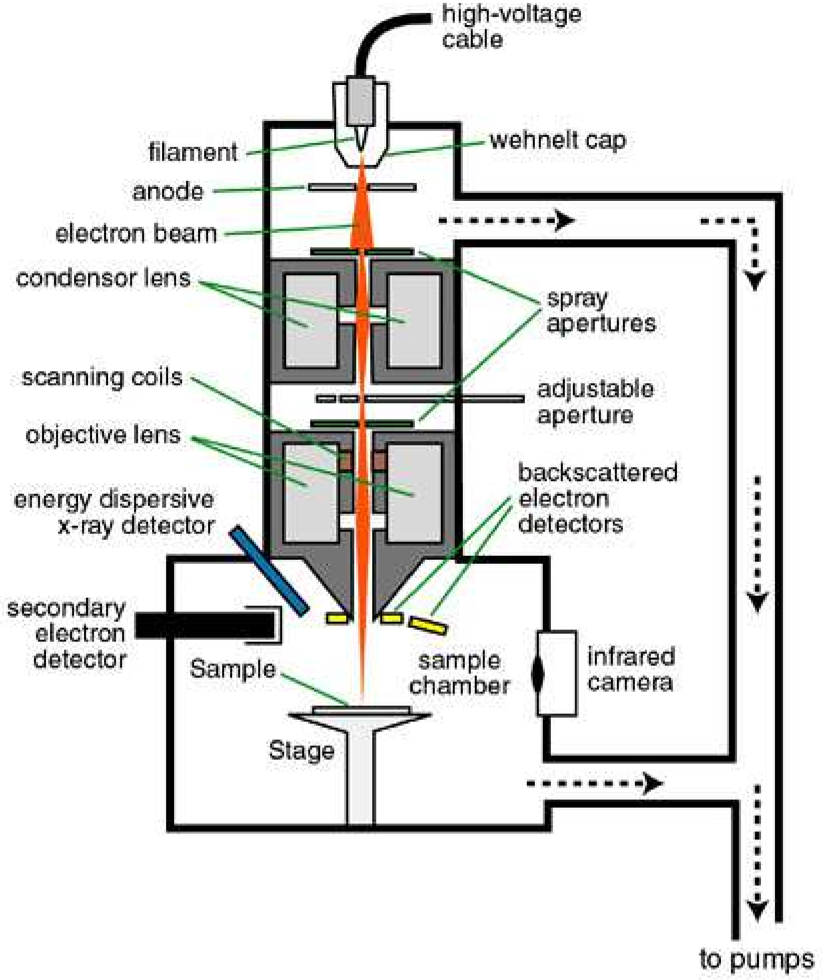
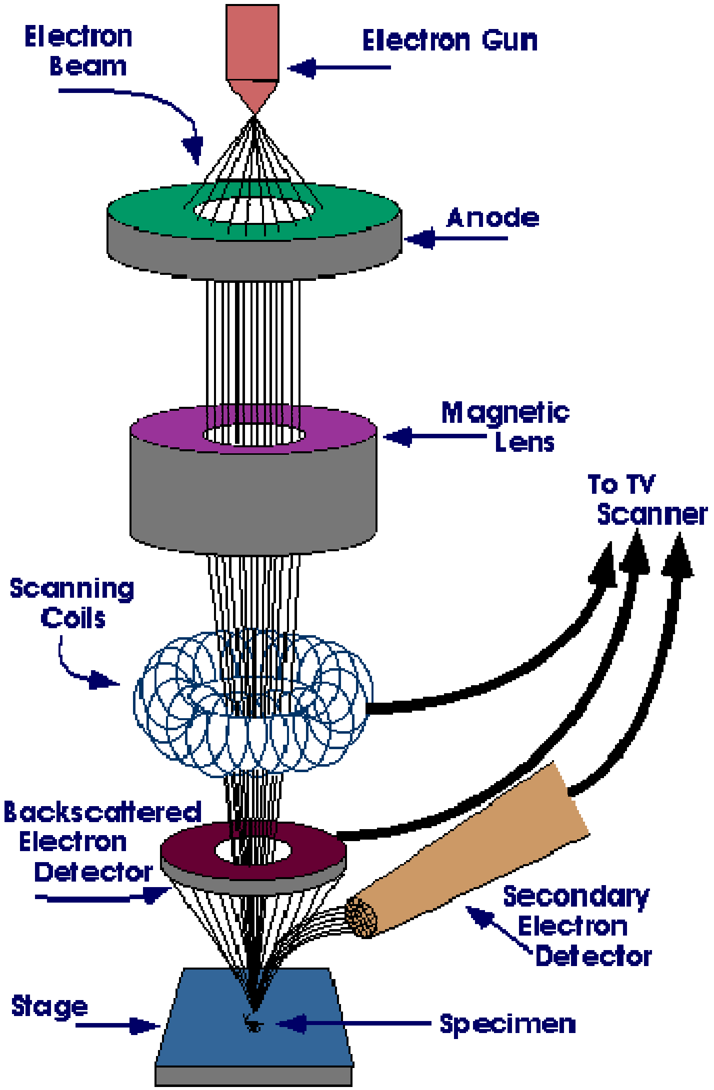
The SEM Column





The illumination source: the electron beam

The probe of the electron microscope is an electron beam with very high and stable energy (10-100 keV) in order to get images with high resolution.

There are different electron beam sources which are different for the lifetime, for the beam intensity and so on.

In principle, there are two methods for the electron extraction:

Thermoionic electron emission

A **tungsten** or **lanthane esaborate**

(LaB_6) filament are heated by Joule effect.

The increasing temperature of the filament gives energy to the electrons enough to overcome the working function of the material becoming free electrons.

Field emission

A very high electric field is applied to the cathode in order to extract the electron by tunneling effect. Some sources are covered by a low working function material such as zirconium oxide (which emits electrons by Schottky effect).

Thermoionic electron emission

The tungsten filament

The Richardson equation gives the current density emitted from a material for thermoionic effect:

$$J_c = AT^2 \exp(-E_W / kT)$$

A is a constant of the emitter material [A/cm^{2}K^2]

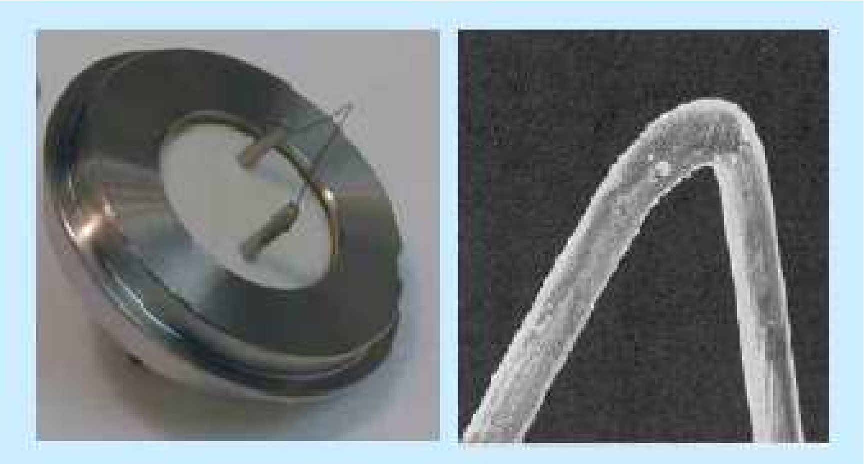
T is the absolute temperature emission [K]

E_W is the working function of the material [eV] (for the tungsten is 4.5 eV)

K the Boltzmann constant [eV/K]

Thermoionic electron emission

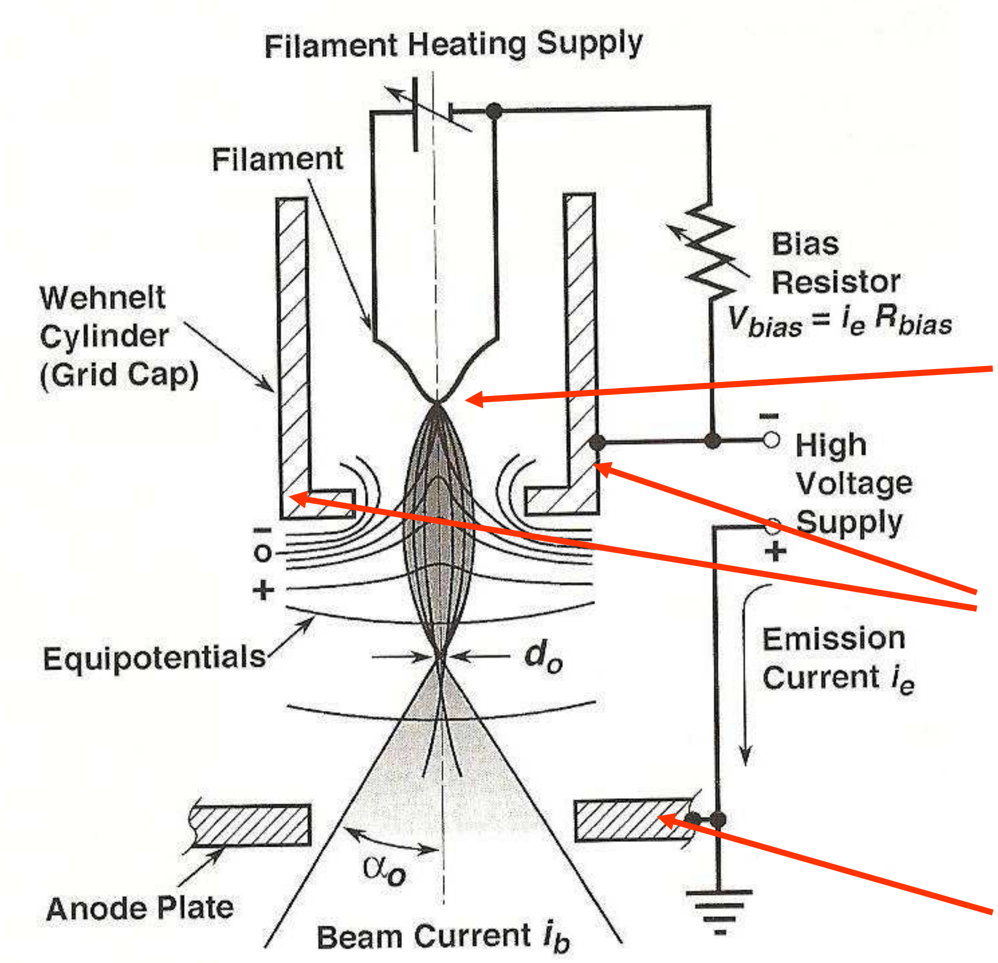
The tungsten filament



At high temperature (higher than 2700 K)
the electrons gain energy enough to overcome the tungsten E_W producing a high electron current

The tungsten filament has a diameter of 100 μm and it is usually folded with a V shape with a curvature ray of about 100 μm. The electron emission occurs from the tip of the filament (in a area of about 100 μm x 150 μm)

The electron gun by thermoionic electron emission



The electron gun is characterized by three main parties:

The filament.

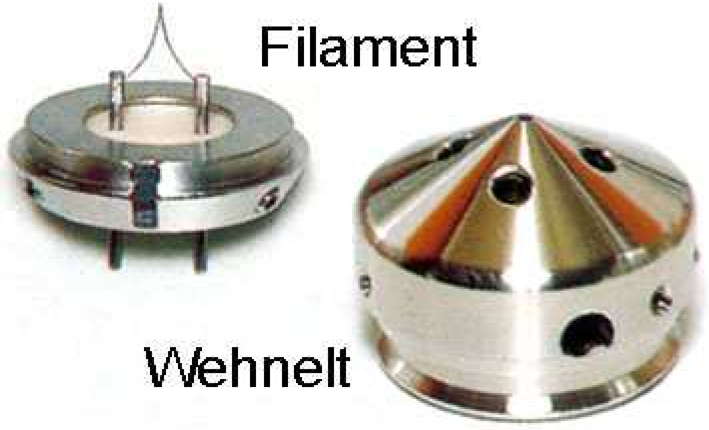
Wehnelt cylinder at negative bias with respect to the filament.

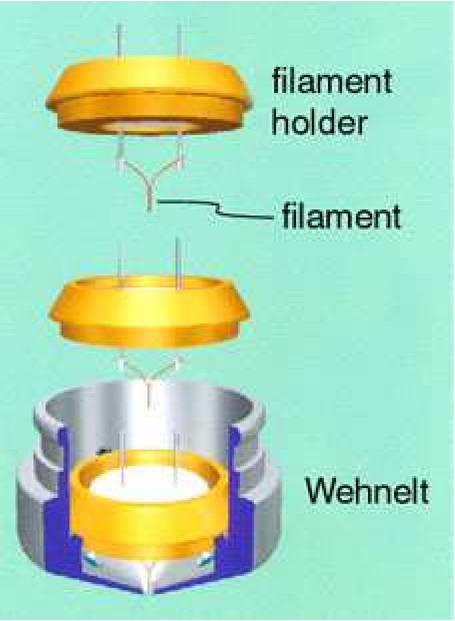
The hole anode at positive bias of the high voltage of a power supply.

Wehnelt cylinder

The filament electrons are emitted at a very large angle.

The Wehnelt cylinder focuses the beam as well as controls the electrons emission from the filament.

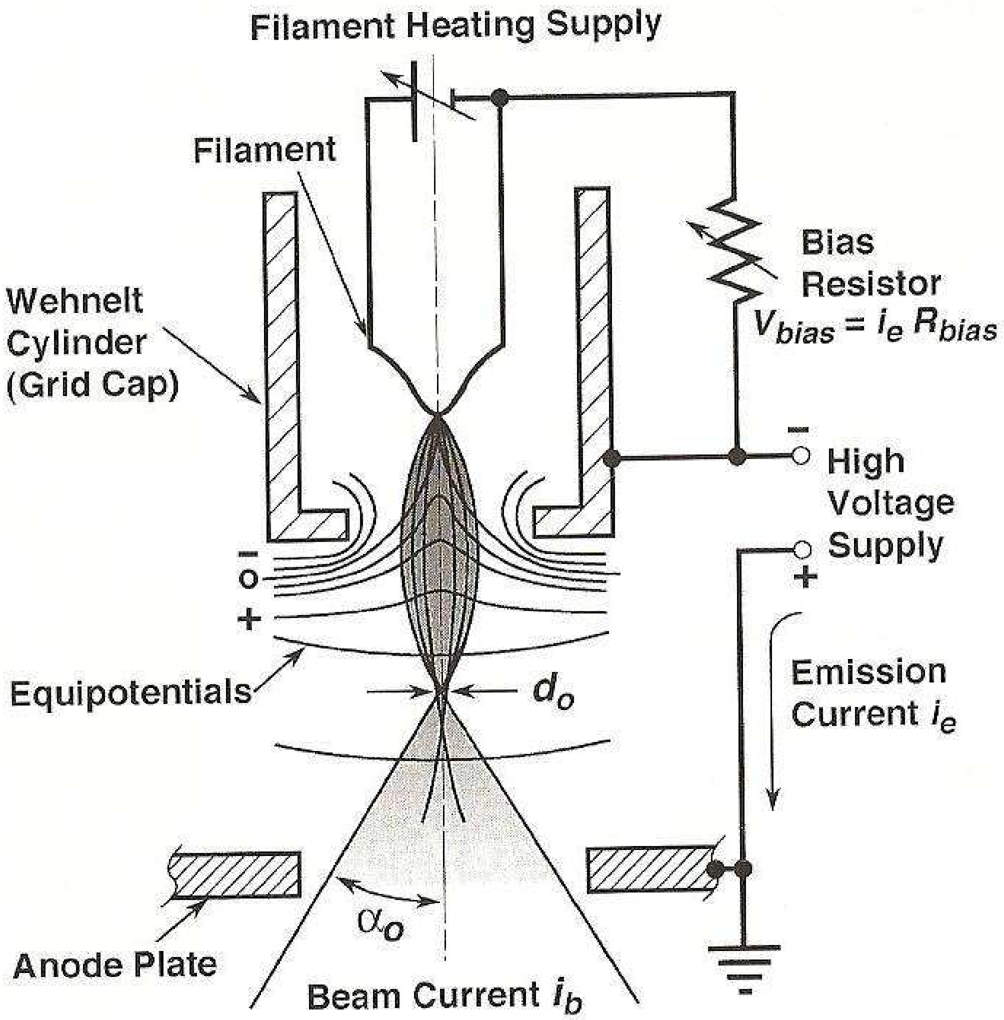


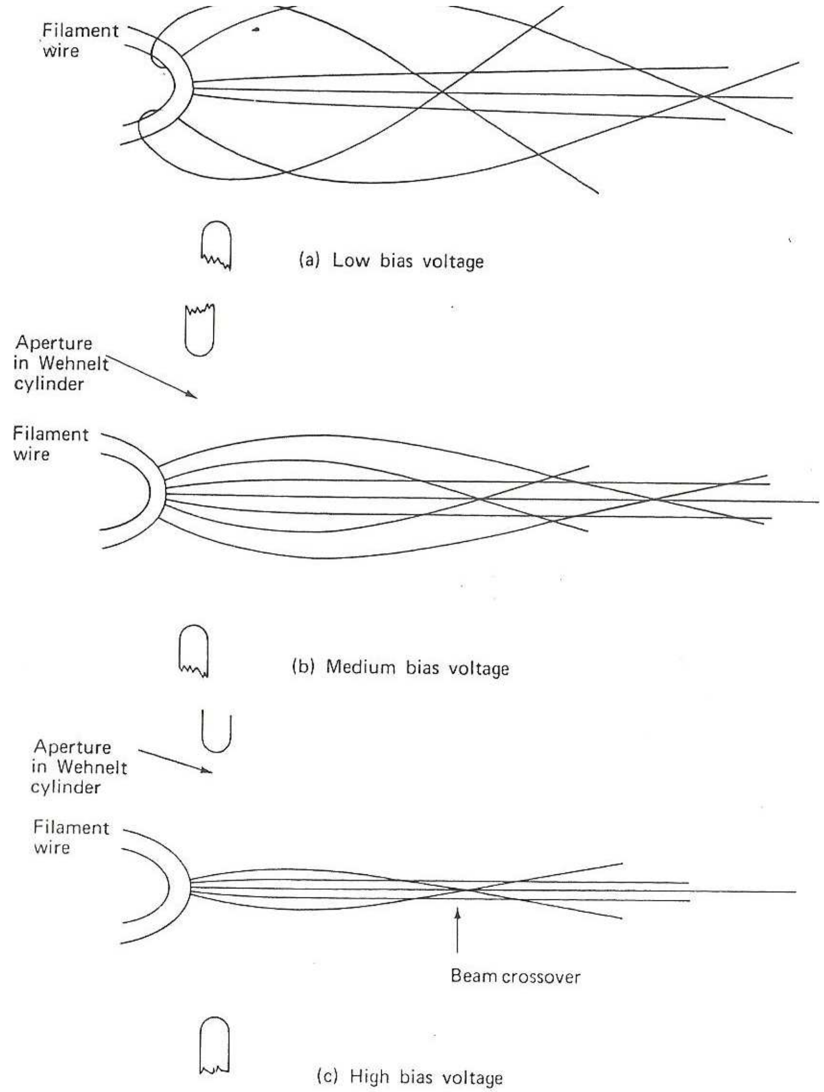


Wehnelt cylinder

The presence of an electrostatic field between the filament and the Wehnelt region focuses the beam as an electrostatic lens.

The result is an image formation between the Wehnelt and the anode (crossover), with d_0 of diameter and α_0 of angular aperture (divergence).





(a) Low bias voltage

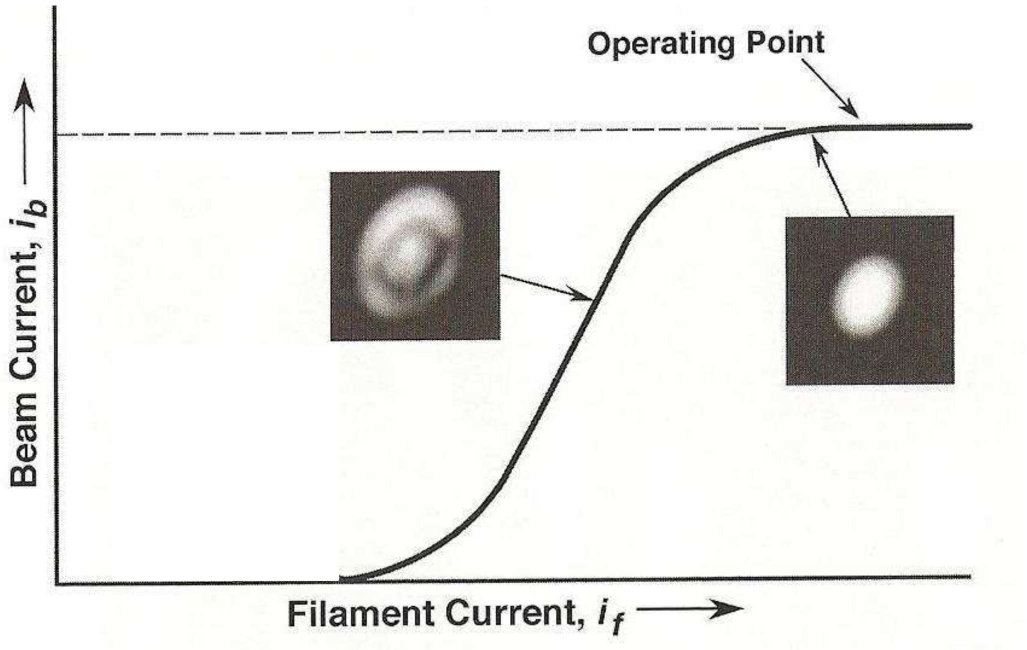
(b) Medium bias voltage

(c) High bias voltage

Fig. 1.15. Magnified diagrams of the filament and the aperture in the Wehnelt cylinder to show the general form of electron beam trajectories under conditions of increasing beam current and increasing bias voltage. (a) Low bias – multiple beam spots. (b) Medium bias voltage – spots converging. (c) High bias voltage – single high intensity crossover.

A proper SEM operation requires a stable current probe on the sample which has to be time constant and the same in every point of the sample.

In order to obtain a stable current, the filament current, $i_{f,}$ has to reach the saturation condition: it means that a small variation of i_f doesn't induce a variation of the beam current, i_b.

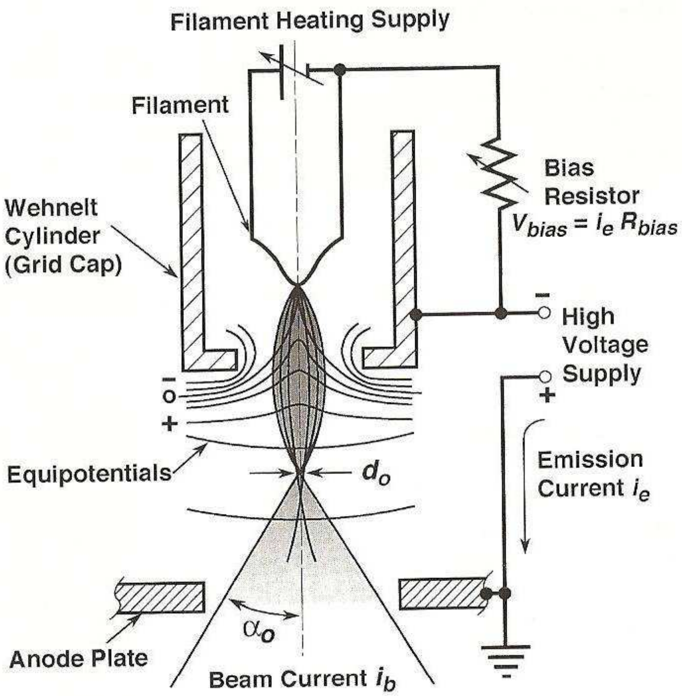


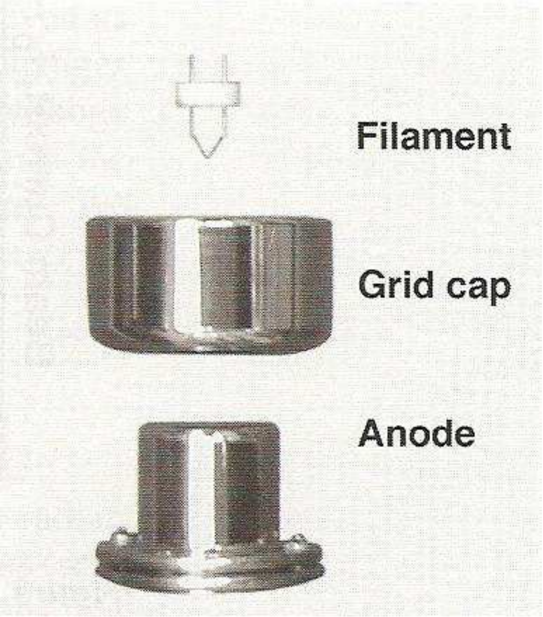
At the saturation regime, the electrons are emitted only from the tungsten filament tip.

The anode

The electrons emitted from the filament are then accelerated in the region between cathode (Wehnelt) and anode.

An electron fraction deriving from the filament goes through the anode hole going to the electromagnetic lenses. Generally the electron current deriving from the anode, i_b, is called beam current.

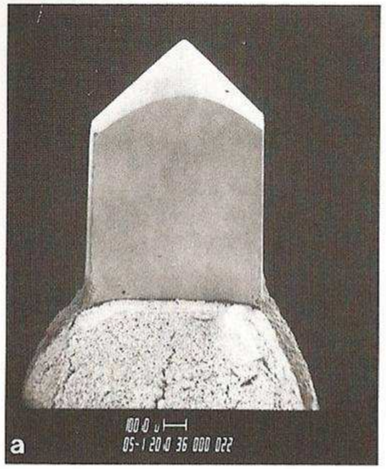




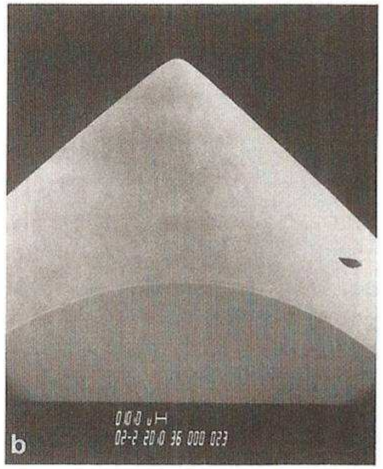
During the path of the electrons inside the SEM column, a fraction of the electrons is stopped due to the lens aperture. For this reason the current arriving on the sample (i_p – probe current) is lower than the beam current.

The electron source of LaB_6

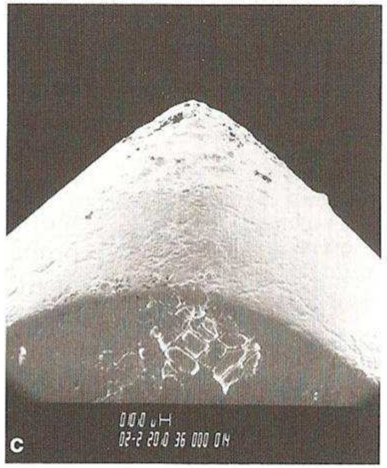
The LaB_6 (2.4 eV) has a working function lower than that one of W (4.5 eV), for this reason, with the same temperature, much more electrons are emitted from the source.



Tip of LaB_6 mounted on the holder

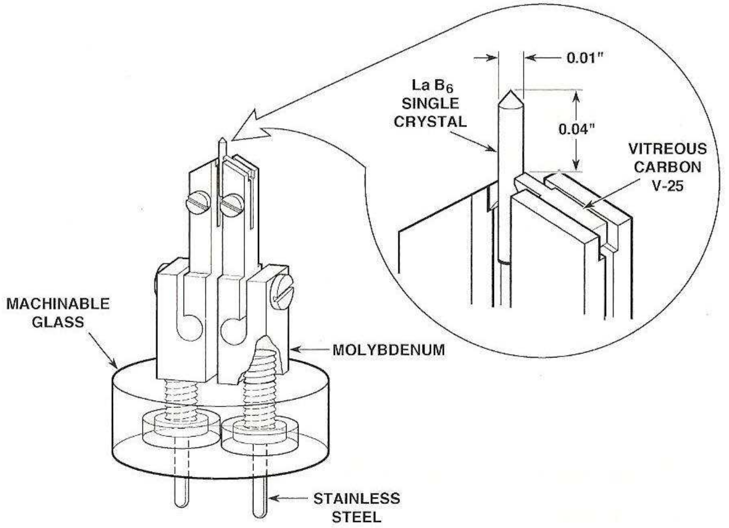


Magnified tip of LaB_6



Tip of LaB_6 ruined from the evaporation and from the oxide formation

The electron source of LaB_6



It is a single crystal of about 100 µm and it is about 0.5 mm lenght and it is heated by a graphite or renio support. These materials don't react chemically with the LaB_6 filament.

The crystal tip is of about 1 µm in diameter. The very high electric field on the tip favours the electrons emission. The high sharp crystals have a higher brightness but a lower lifetime of the source. Blunt crystals have a lower brighteness but a longer lifetime.

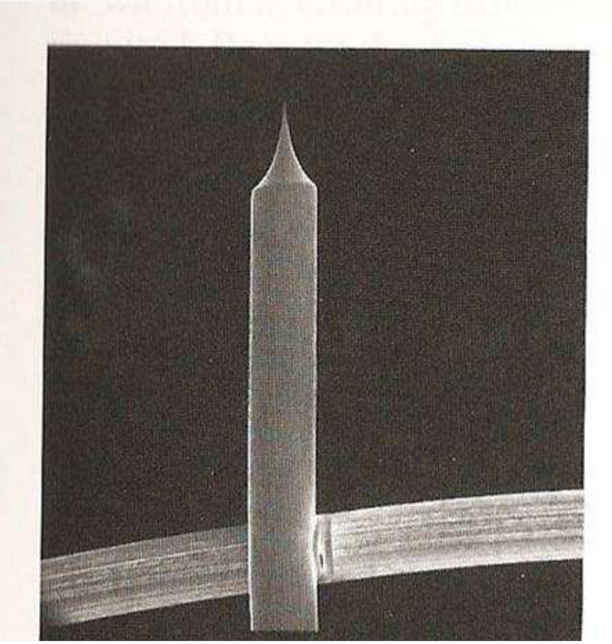
A LaB_6 source needs, with respect to a W filament, a high vacuum level of 10^{-4} Pa because the source could be easily affected by contaminations. For this reason after the air exposion, the temperature of the crystal should be increased slowly. In this way the degasing of crystal material is induced.

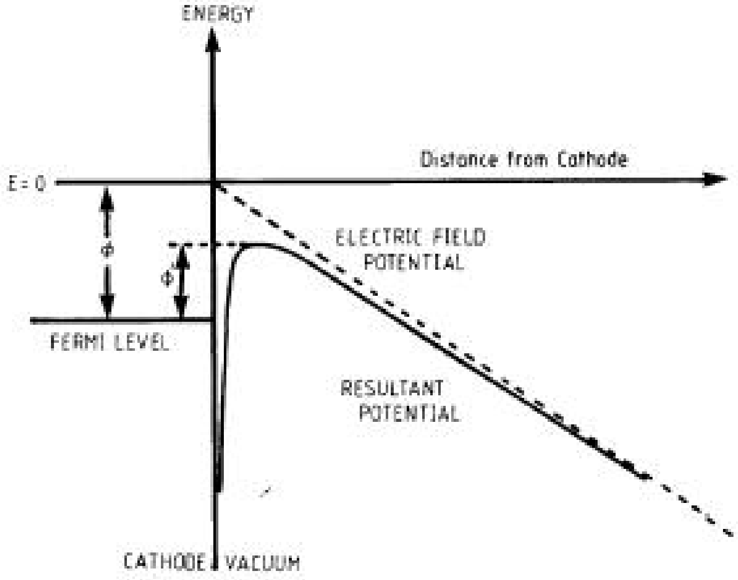
Field emission guns (FEG)

High electric fields induce the electrons emission.

A field emission cathode is a tungsten needle (ray ≤ 100 nm) settled on a W hook. A negative bias voltage is applied on the cathode which is very intense on the tip. When the electric field arrives to a value of 10 V/nm, the electric field potential decreases and the electrons are able to go out by tunnelling effect.

By these sources, it is possible to obtain a current density of 10^5 A/cm^2 (for a thermoinic source only 1-3 A/cm^2).





Field emission guns (FEG)

The current density, emitted from a field emission gun, depends strongly by the applied electric field *F* according to the Fowler-Nordheim equation:

$$J = 6.2 \cdot 10^{-6} \frac{\left(\frac{E_F}{E_W}\right)^{1/2} F^2}{E_F + E_W} \exp(-6.8 \cdot 10^{-9} E_W{}^{9} / F) \qquad [\mathrm{A/m^2}]$$

For $F > 5 \times 10^9$ V/m, the current density is of 10^5 A/cm^2 (for a thermoinic source only 1-3 A/cm^2) and the brightness is hundreds times higher with respect to a thermoinic source.

Field emission guns (FEG)

Usually in common SEMs, there are the following field emission gun emitters:

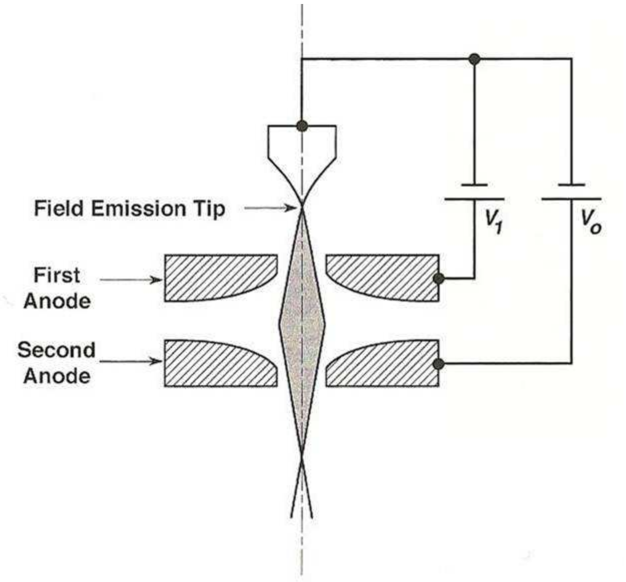
Cold Field Emitters (CFE)

Thermal Field Emitters (TFE)

Schottky Field Emitters (SFE)

Cold Field Emitters (CFE)

- The emission derives from a few nanometers area and it is indipendent from the source temperature. Even if the total current is relatively small (1-10 μA), the brightness is particulary high (10^8 A/cm^{2}sr @ 20 kV) thanks to the very small beam dimensions.
- The beam is focused and accelerated by two anodes.
- The bias voltage between the first anode and the cathode (3-5 kV) determines the electric field to extract the electrons.
- The bias voltage between the second anode and the cathode (from some hundreds of Volts to 30 kV) accelerates the electrons.



(ELECTRON GUN OF A CFE)

Scheme of the Butler's triode

Cold Field Emitters (CFE)

The proper operation of a CFE requires a very clean enviroment, for this reason a vacuum level of 10^{-8}-10^{-9} Pa is needed.

Before working, the emitter is hitted for few seconds at very high temperature (2500K).

This procedure damages slowly the emitter tip. Nevertheless, even if cleaning procedure is performed every day, the tip damage occurs at very long time.

Advantages:

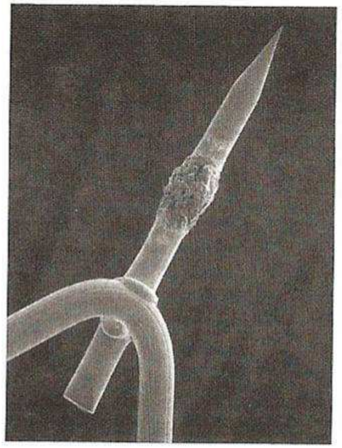
- the very small dimensions of the beam (3 nm) requires a very small focusing process (by the electromagnetic lenses) to reach the proper dimension of the spot (1 nm).
- low energetic spread.
- since the beam source is changed rarely, the system (source-lenses) remains allaigned and clean for long time, assuring reproducibility and stability in the measurements.

Thermal Field Emitters (TFE)

TFE have the same properties of CFE, but they work at high temperatures. For this reason the tip is always clean reducing the noise and the instabilities even at not perfect vacuum conditions. Moreover, the tip becomes sharp, due to the high electric field, improving the performances. TFE are able to operate as CFE at low temperatures for short periods.

Schottky Field Emitters (SFE)

The electric field on the tip of SFE is applied to decrease the material working function . For this reason such field emitters are coated with low working function materials such as ZrO_2.
Even if SFE is a thermoinoic emitter, the brightness and the current density are comparable with that ones of CFE.
The electron gun of a SFE is quite similar to that one of CFE.
SFE guns include a suppressor grid to eliminate unwanted thermionic emission from regions outside the tip.



Schottky Field Emitters (SFE)

The emission currents are of about 30-70 μA.

Useful lifetime of a SFE is about 12-15 months, so it must be replaced on a regular basis.
Vacuum level, required for successful Schottky operation, is not as demanding as that one of CFE, but in practice an ultrahigh vacuum aids long-term stability, prevents poisoning of the ZrO_2 cathode, and maximizes brightness.

The spot dimension of CFE and TFE are almost equal, whereas that one of SFE is bigger because bigger is the curvature ray. Nevertheless such thing could be an advantage when bigger spots are required.

Finally, the energetic spread could be bigger because the cathode is hitted.

Parameters of the electron gun

Brightness, β (A/cm^2/steradiant) is defined as the beam current for unit area and solid angle.

$$\beta = \frac{current}{area \cdot solid\_angle} = \frac{i_p}{\left(\frac{\pi d_p^2}{4}\right)\pi\alpha_p^2} = \frac{4i_p}{\pi^2 d_p^2 \alpha_p^2}$$

The brightness is constant and it is the same in all the column points. For this reason the brightness on the sample is almost the same of the brightness close to the source.

The defects and the aberrations of the lenses decrease the effective value of the brightness.

Parameters of the electron gun

The operation of a thermoinic electron gun was studied in a model system by Haine and Einstein (1952).
The brightness is given by:

$$\beta = \frac{J_c \cdot eV}{kT} = \frac{AT \cdot \exp(-Ew / kT)}{k}$$

The brightness is proportional to the accelerating voltage, while rapidly increases with the temperature of the filament, even though T also appears as a factor in the denominator.

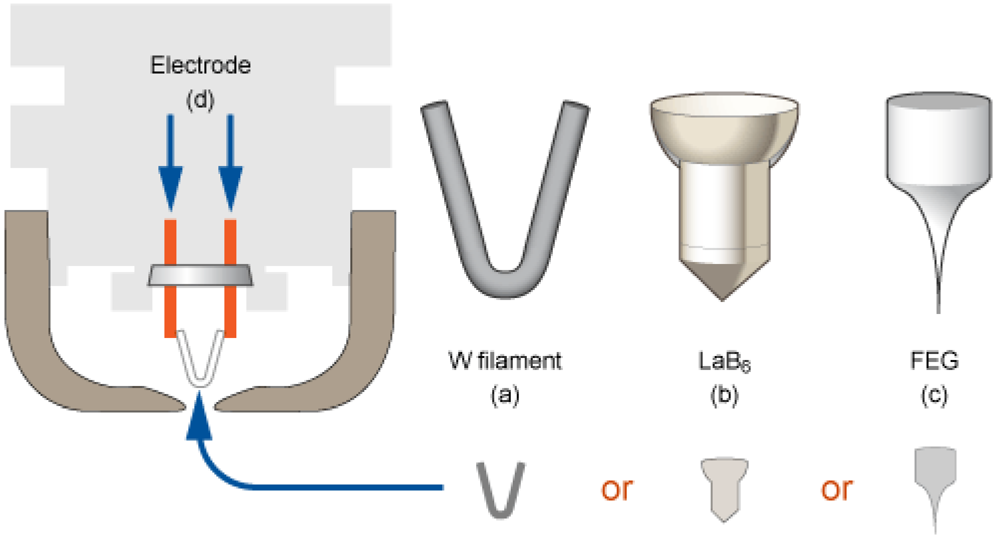
Parameters of the electron gun

Lifetime: a W filament evaporates gradually on time due to the high temperature of the operation: the filament makes thin and stops working. Increasing the filament temperature (oversaturation), the evaporation rate increases and induces a fast break of the filament.

Source dimensions: the beam dimension at the crossover, for a W source, is tipically ~ 50 µm (it depends on the gun configurations and the work conditions). Such relatively high dimensions need of an high electro-optical reduction of the images to obtain a small electron beam enough to obtain a good resolution. The new generation of electron microscopes has smaller beam dimension: for the LaB_6 source the dimension of the beam in the gun is of ~ 5 µm, while for the field emission sources is of 5-25 nm .

Energetic Spread, ΔE: this is the energetic dispersion of the electron emitted from the filamet. For the W is ~ 3 eV, for the LaB_6 is ~ 1.5 eV and for the field emission sources is ~ 0.3 – 1 eV.

Stability: this indicates how much the electron emission is constant in the working time. The Schottky sources are the more stable; the termoionic sources have good stability too, in comparison with the field emission sources.



Comparison among the different electronic sources operating @20kV

Source	Brightness (A/cm^2 sr)	Lifetime (h)	Source size	Energy spread ΔE (eV)	Beam current stability (%/h)
Tungsten hairpin	10^5	40–100	30–100 μm	1–3	1
LaB_6	10^6	200–1000	5–50 μm	1–2	1
Field emission					
Cold	10^8	>1000	<5 nm	0.3	5
Thermal	10^8	>1000	<5 nm	1	5
Schottky	10^8	>1000	15–30 nm	0.3–1.0	~1