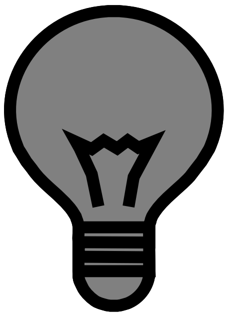
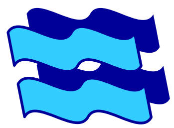
The Linac Klystrons Aging and Associated Problems

- The cathode. Structure and operation
- Lifetime vs. Heater power
- Operating point
- "Good" and "Bad" current
- Emission jumps
- Summary

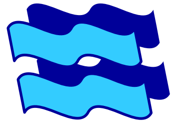
Instead of Introduction





If a light bulb fails, it’s easy to get through and to buy a new one.

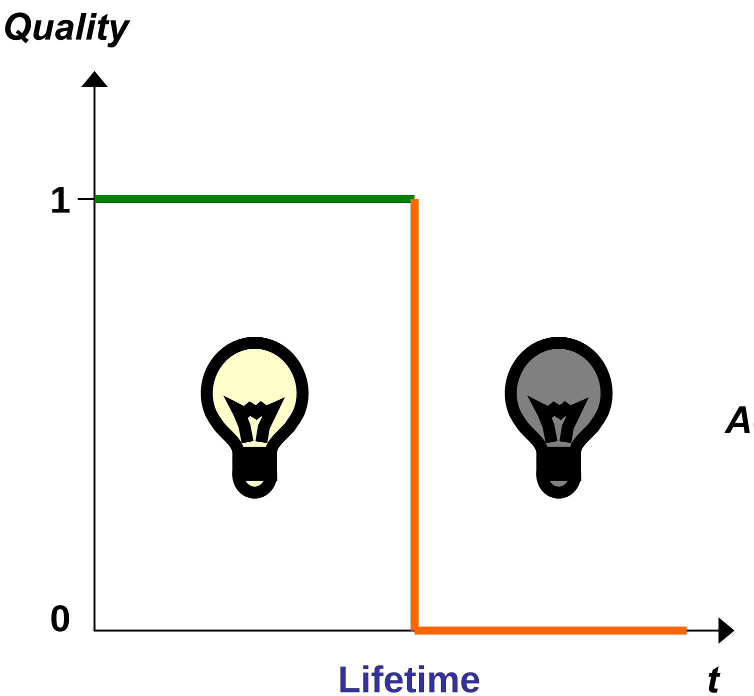
In case of the klystron, things are much different.



Klystron Quality

A light bulb fails suddenly, once and forever. In some sense it is a digital component:

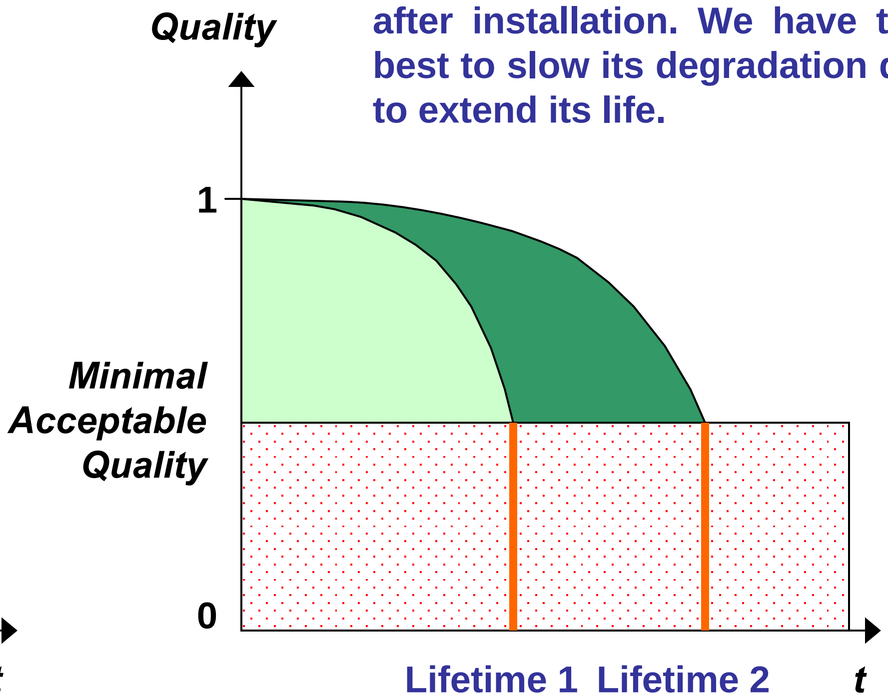
- Yes/No,
- Works/Doesn't



A klystron may be characterized in terms of quality as a combination of various parameters:

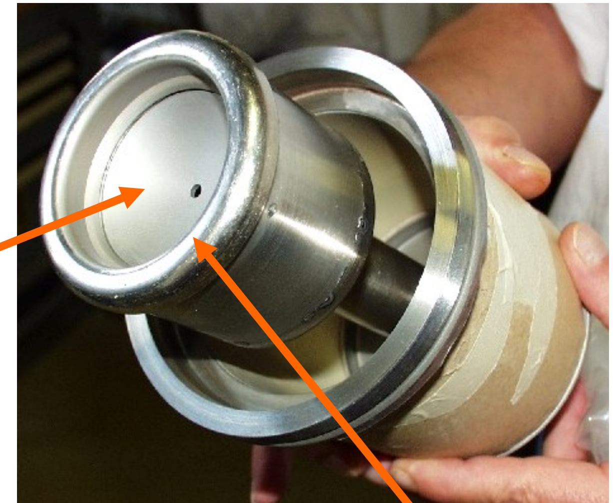
- Gain,
- Efficiency,
- Stability, etc.

Klystron quality starts falling right after installation. We have to do our best to slow its degradation down and to extend its life.



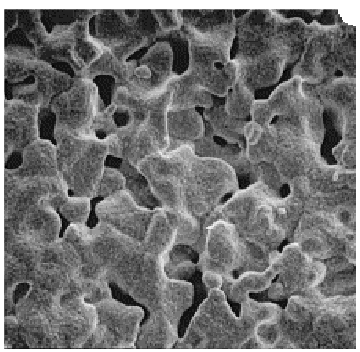
Klystron Gun

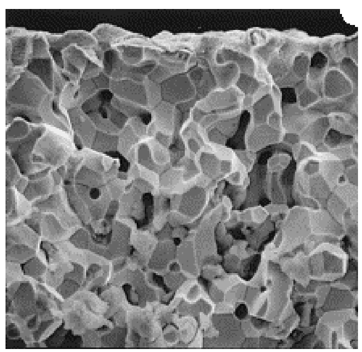
The part whose aging affects overall performance of the tube more than any other part is the electron gun.



The main part of the gun is the ***cathode*** that is made of porous tungsten impregnated with mix of barium oxide and some other substances. The cathode is a several millimeters thick parabolic cup.

Also, it contains a *wehnelt*, a metal ring under cathode's potential that participates in initial focusing of the beam.



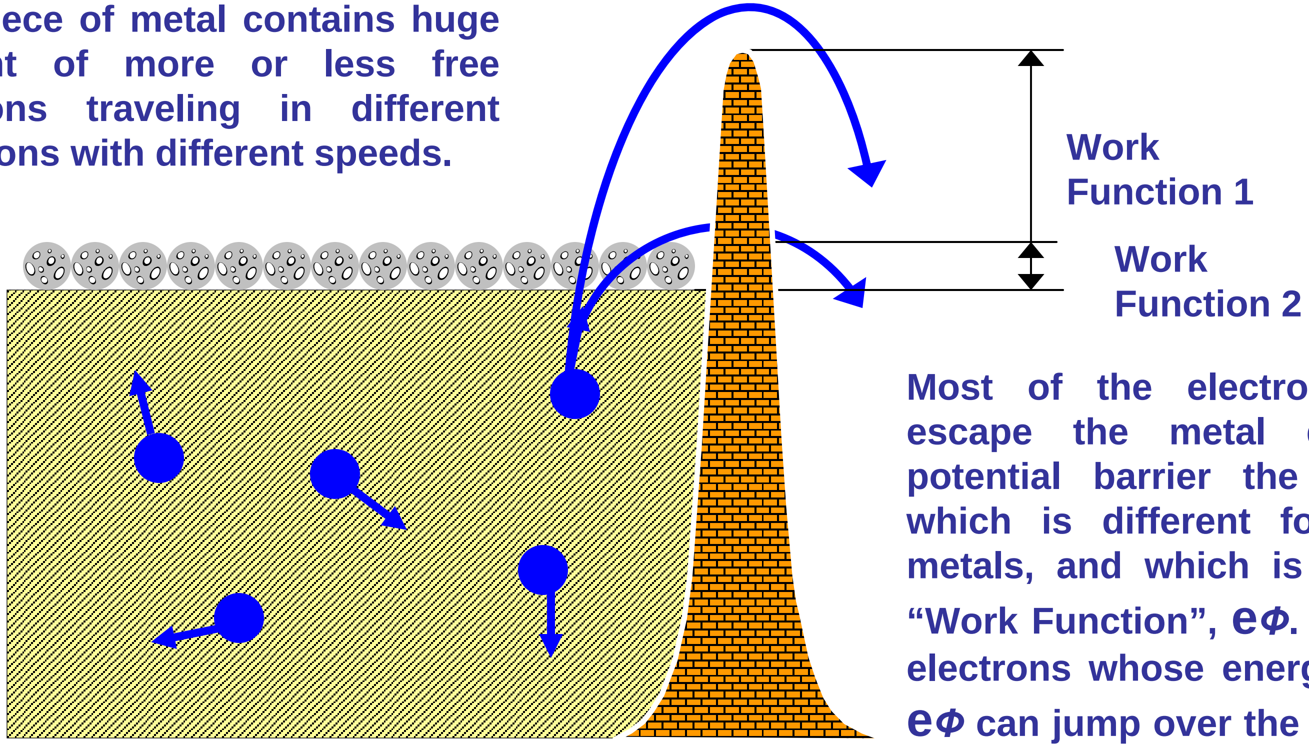


Top- and cross-section microscopic view of a porous tungsten cathode body.

The heater filament.

Leaving the Cathode

Any piece of metal contains huge amount of more or less free electrons traveling in different directions with different speeds.

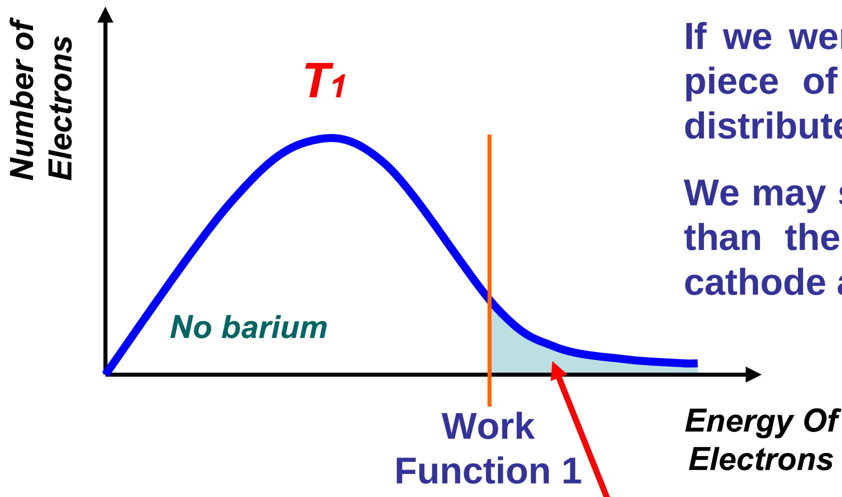


Most of the electrons cannot escape the metal due to a potential barrier the height of which is different for different metals, and which is called the "Work Function", $e\Phi$. Only those electrons whose energy exceeds $e\Phi$ can jump over the barrier and escape.

Placing even one-atom thick layer of such a metal like barium on the surface of tungsten significantly lowers height of the barrier and increases amount of electron that are capable of leaving the cathode surface.

Electric field also affects the height of the barrier.

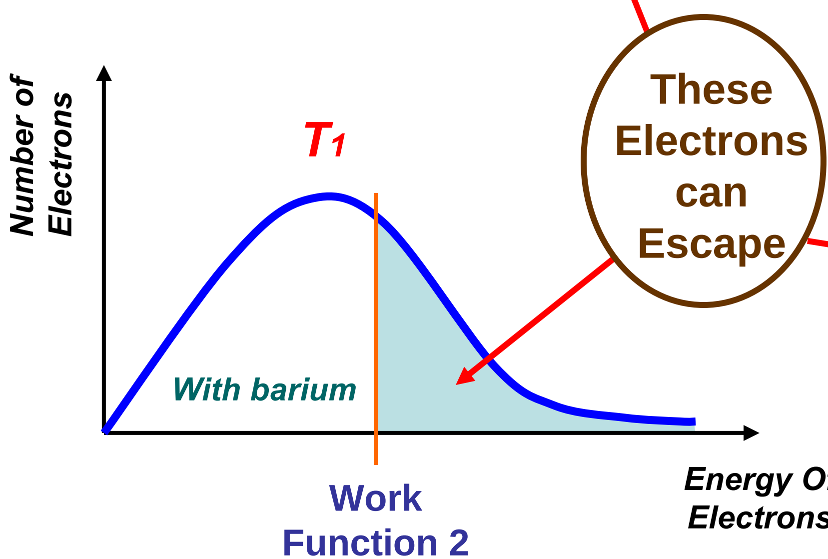
Leaving the Cathode - 2

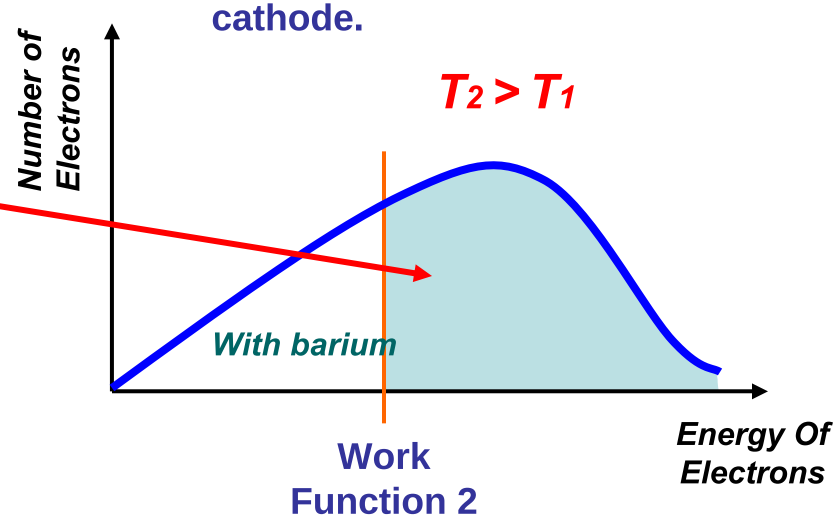


If we were able to measure energy of all electrons in a piece of metal, we would find that the electrons are distributed one way or another along the Energy axis.

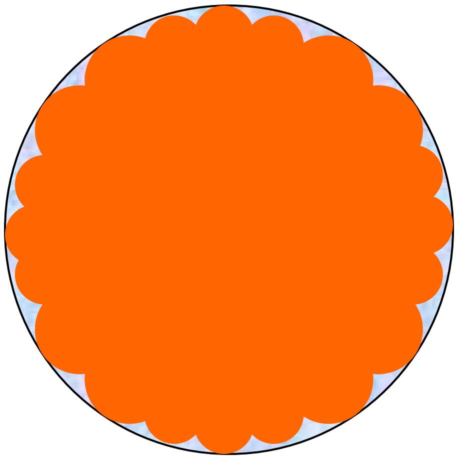
We may say that only those electrons with energy higher than the Work Function are able to escape from the cathode and participate in creating klystron beam.

Warming the cathode to higher temperature does not change the Work Function, but increases amount of electrons with higher energy that are able to leave the cathode.

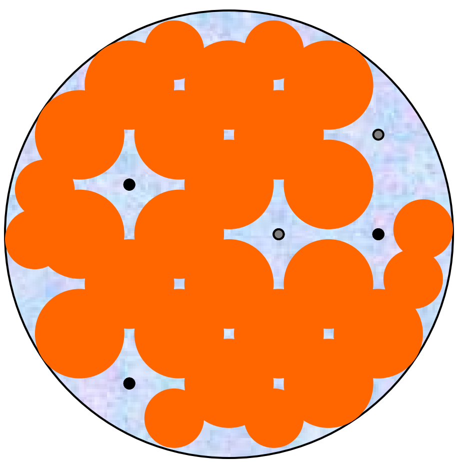




Covering by Barium



Cathode



The gun heater has to perform two functions:

1. **To help release barium from the cathode's interior and spread it over the surface;**
2. **To increase amount of electrons with energy high enough to escape from the cathode surface.**

As the cathode worms up, the area covered by barium increases.

At some temperature, almost entire surface becomes covered by barium.

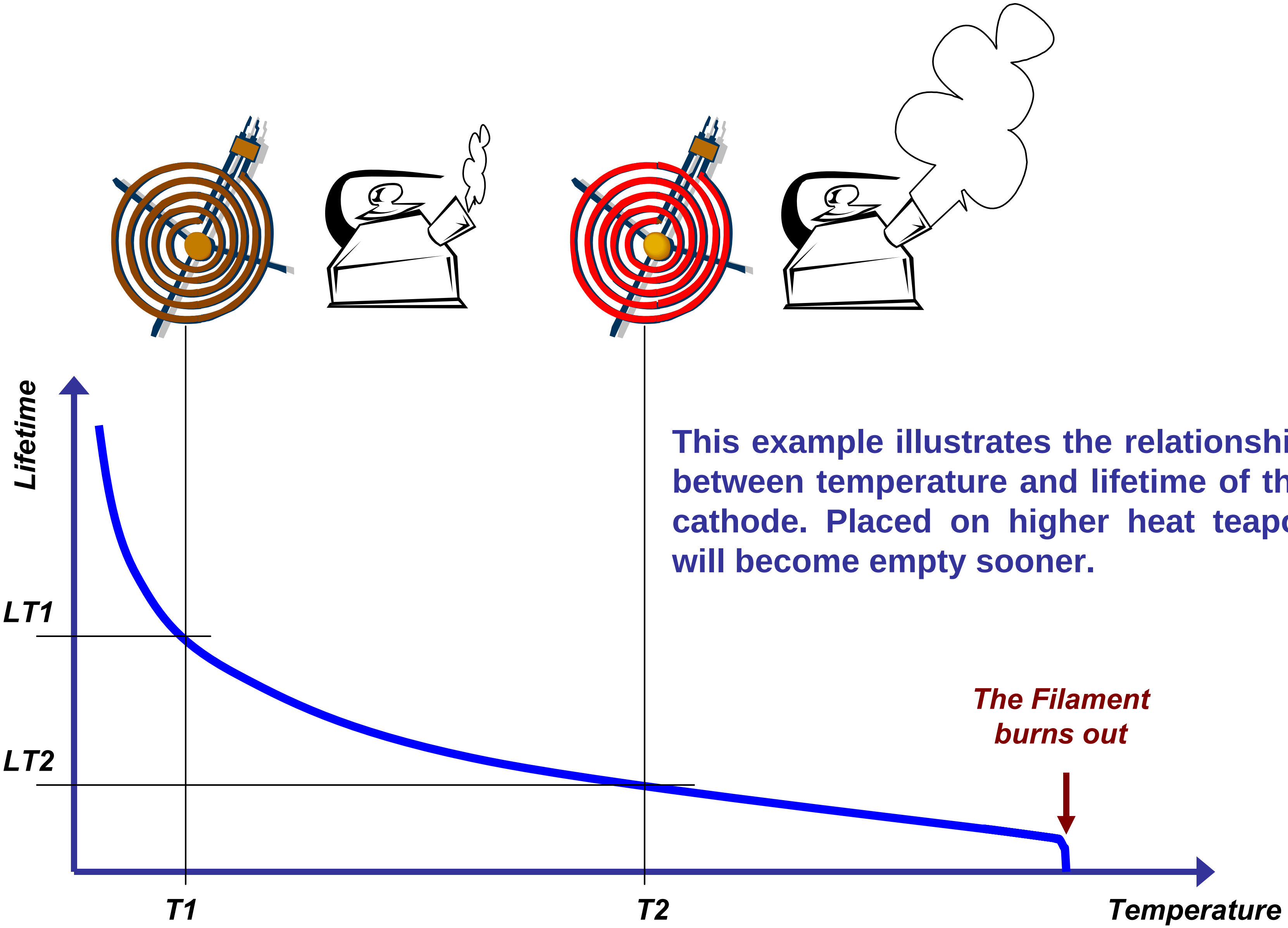
Because of high temperature of the cathode, barium keeps evaporating from the surface. Evaporated atoms are replaced with the atoms that continue migrating from the cathode interior.

As the cathode ages and the pores in the cathode are depleted and/or choked, the covered by barium area becomes smaller.

This causes reduction of cathode emission (and beam current!) and forces us to increase filament power.

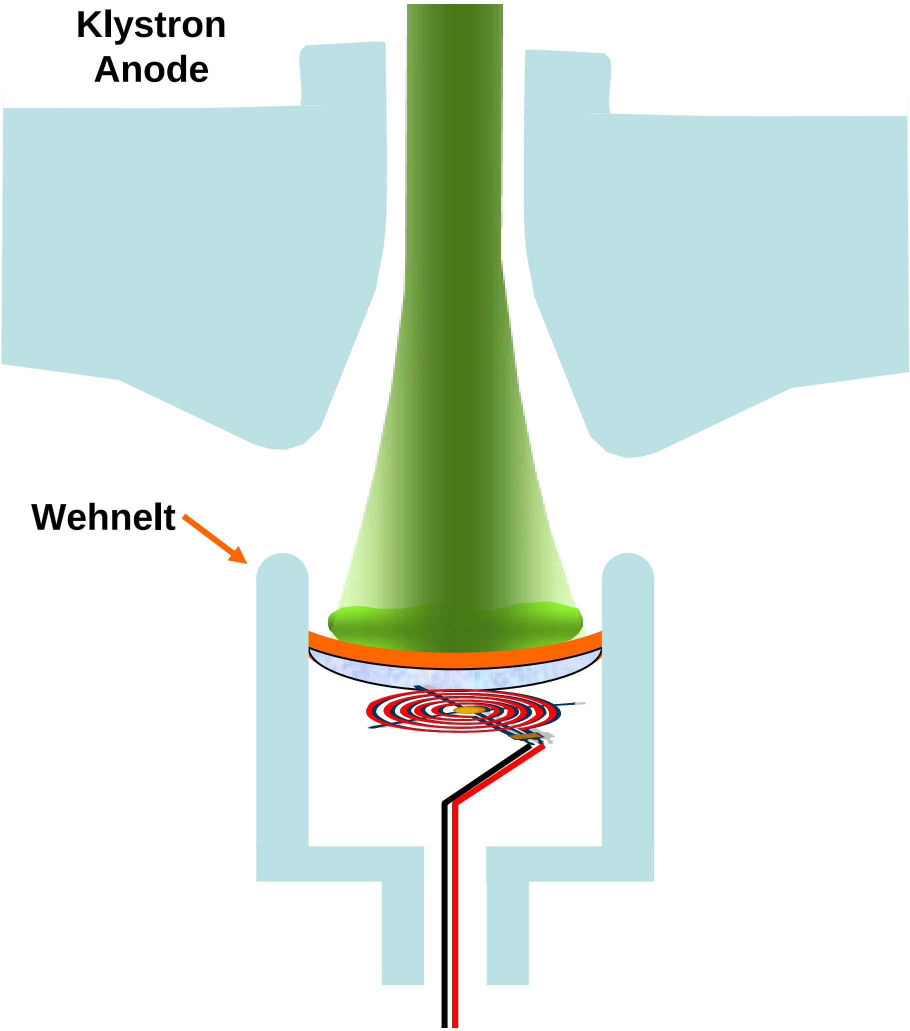
Higher filament power heats the cathode to higher temperature that, in turn, increases barium evaporation rate that, in turn, speeds up depletion of the pores that, in turn, etc., etc., etc…

Temperature and Lifetime



This example illustrates the relationship between temperature and lifetime of the cathode. Placed on higher heat teapot will become empty sooner.

Producing the Beam



After the filament is turned on and the cathode is warmed up, an electron cloud develops near the cathode surface. Some electrons fly away, some return to the cathode, and new electrons replace them. We can talk about dynamic equilibrium of the cloud.

When negative voltage is applied to the cathode, electrons from the cloud form the klystron beam.

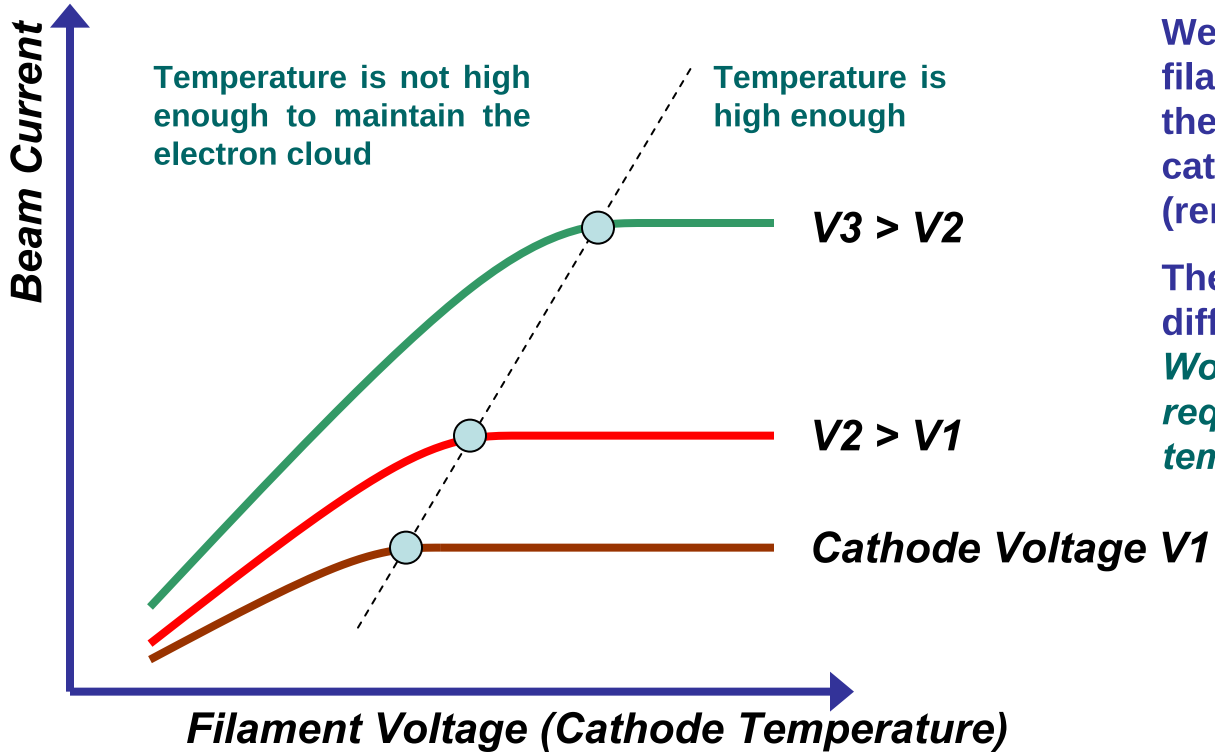
If filament power and cathode voltage are set up correctly, the cloud does not disappear. The electrons which have gone with the beam are immediately replaced with the new ones emitted by the cathode.

Filament Operating Point

As mentioned above, the beam is formed from the electrons that present in the cloud. Density of the cloud depends on temperature of the cathode.

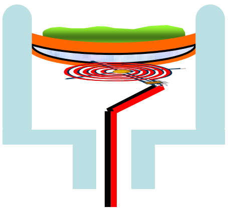
If the temperature is high enough to make up for the electrons used to form the beam, beam current depends ONLY on cathode voltage (the area to the right from the dashed line).

If cathode temperature is too low, then the cloud disappears, and the electrons are carried away immediately after they leave the cathode. In this case, beam current depends on filament power, barium migration uniformity, variation of the cathode surface coverage, etc.



We have to keep such a filament operating point where the beam is stable, but the cathode is not overheated (remember the teapot?)

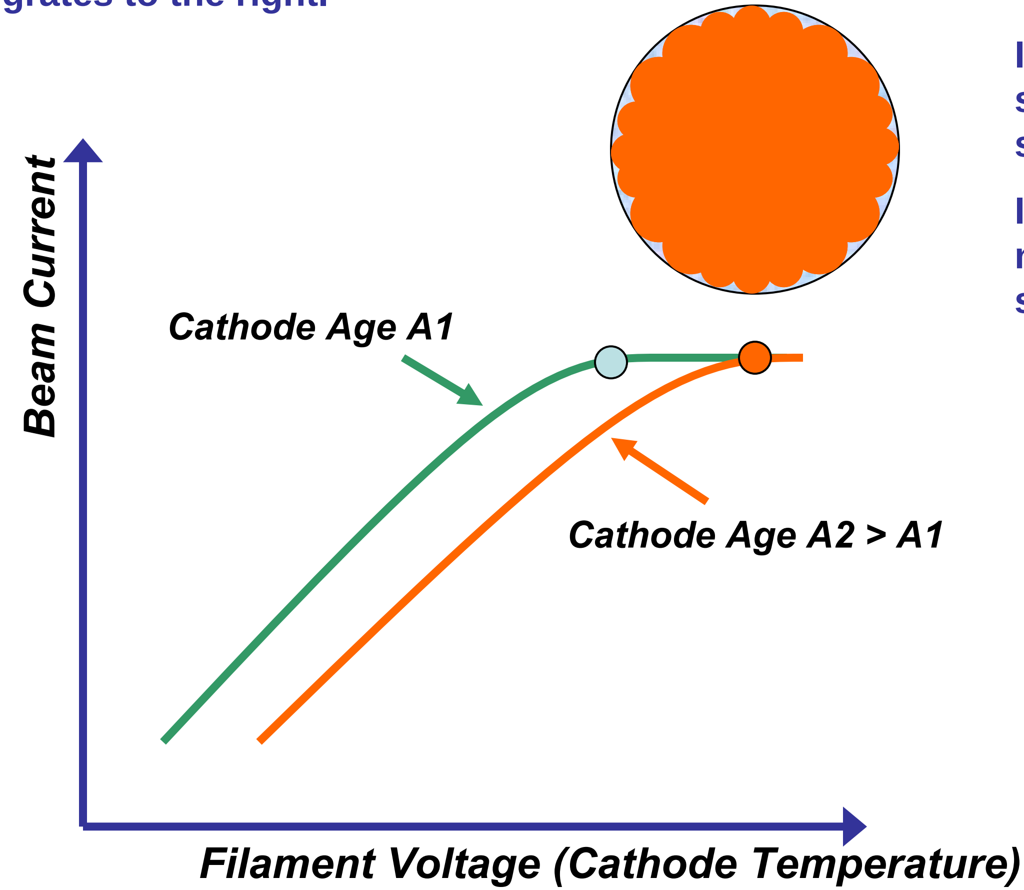
These points are different for different voltages (bluish dots). ***Working with higher voltage requires higher cathode temperature.***



Filament Operating Point and Aging

As the cathode ages, its ability to emit electrons declines, and the cathode requires higher and higher temperature to operate. Filament power operating point migrates to the right.

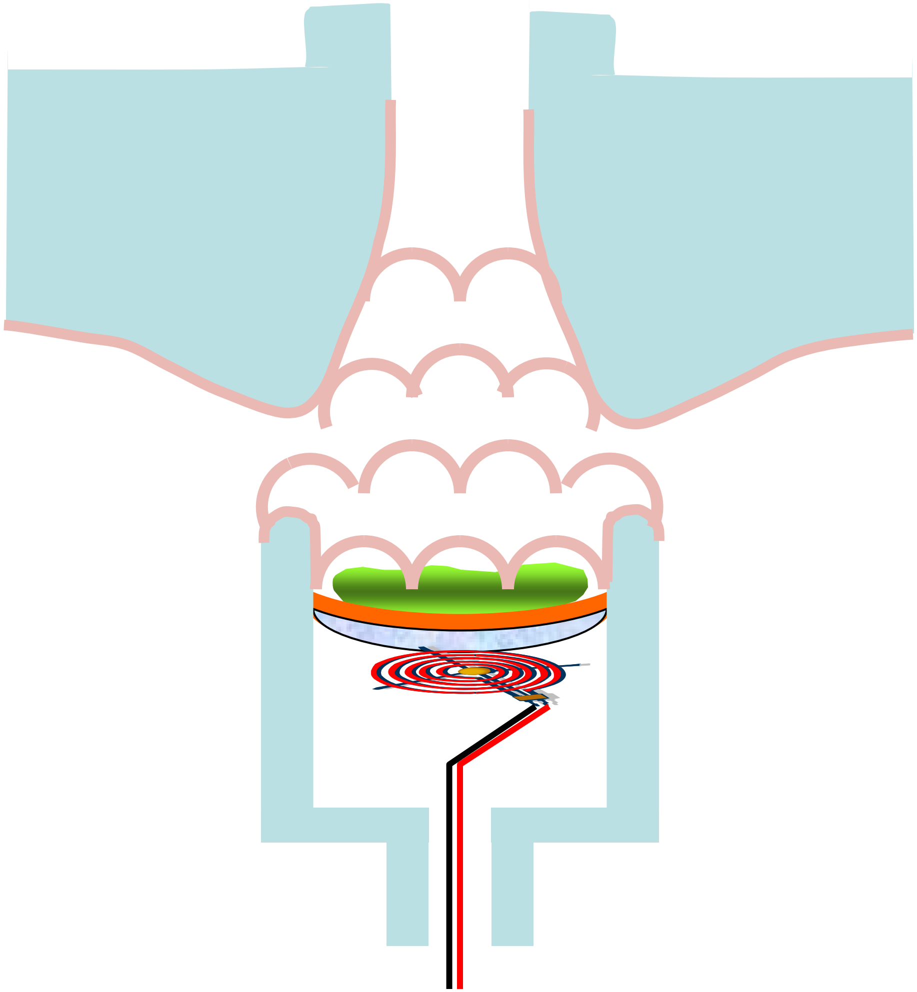
In order to optimize performance of the cathode (and the klystron!), the filament operating point needs to be reviewed every shutdown.



In some sense, the cathode is similar to a filled with water sponge:

If the sponge is half empty, we need to apply stronger force to squeeze water out.

Barium Evaporation and Surface Pollution

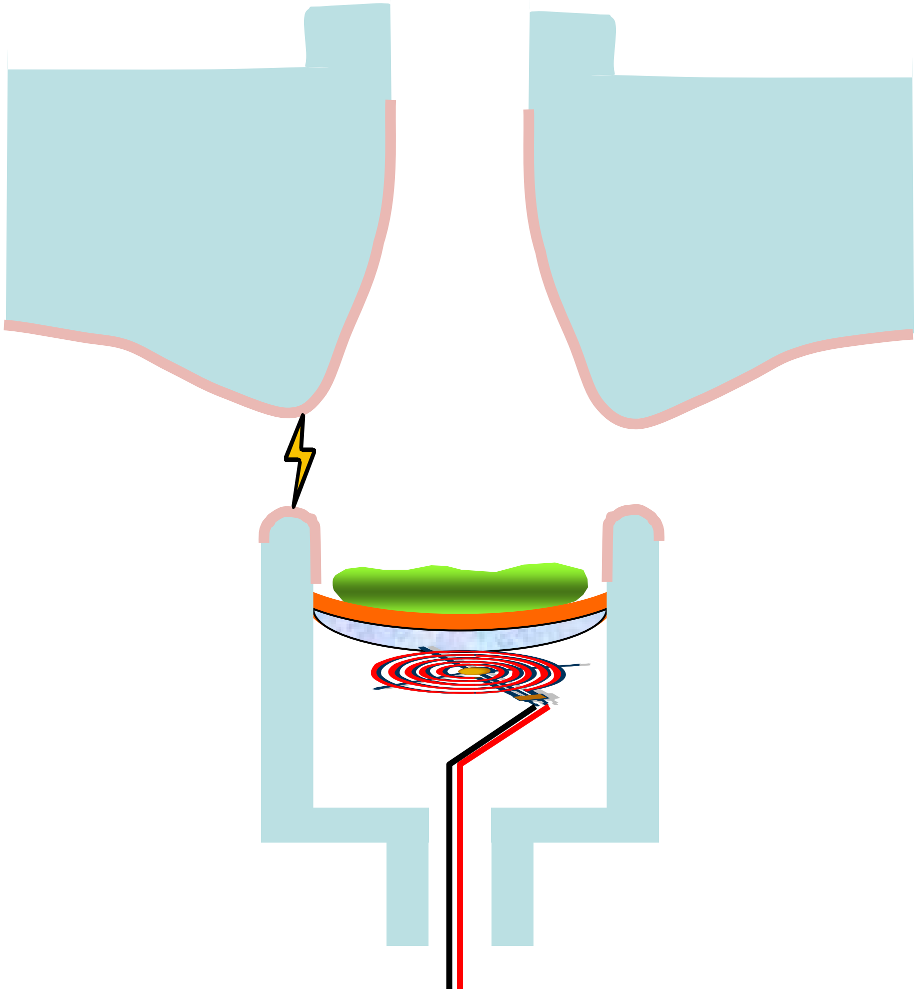


Barium keeps evaporating from the cathode continuously when the filament power is on.

Eventually, all nearby surfaces become covered by barium.

Shown on the photograph below is the Thales' cathode test set. We can see the glass jar cowered by barium.

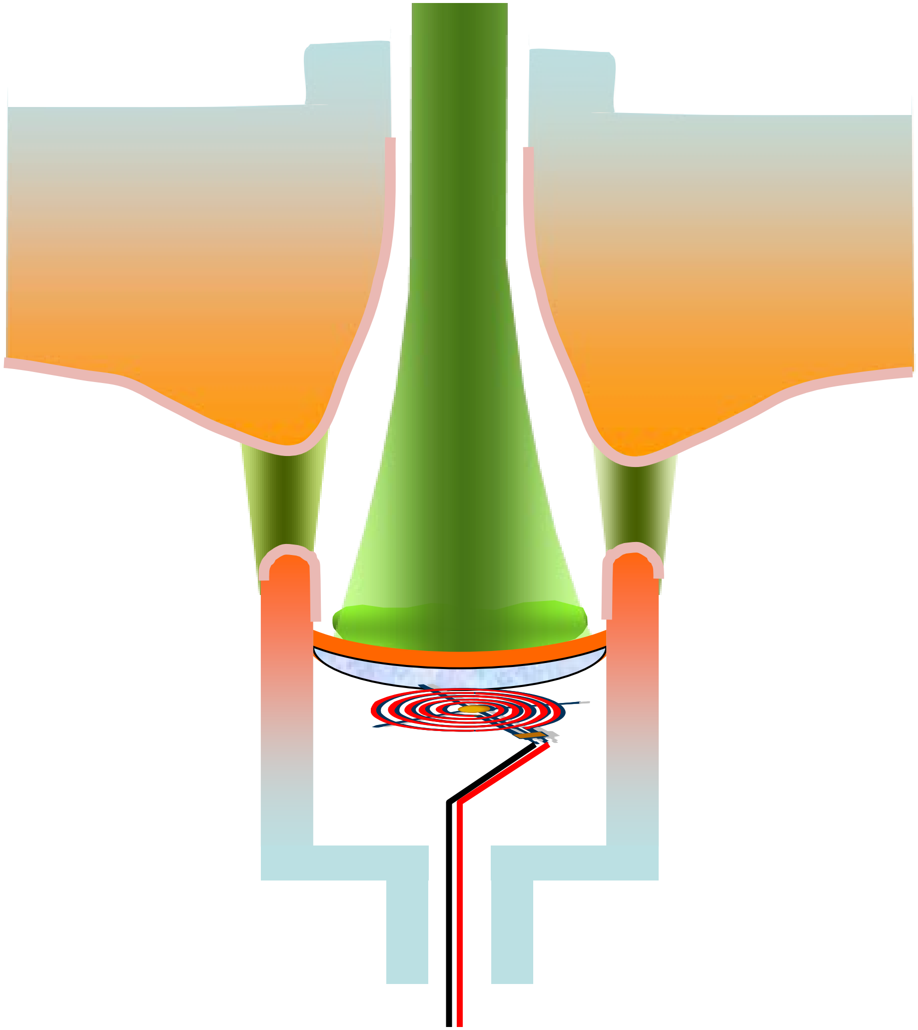
Secondary Barium Pollution



Certain amount of barium may be delivered to the wehnelt from the anode during the arcs which usually occur between these two surfaces.

The older the klystron is, and the more barium is deposited on the anode surface, the more barium may be delivered to the wehnelt.

The “Good” and “Bad” Beam Currents



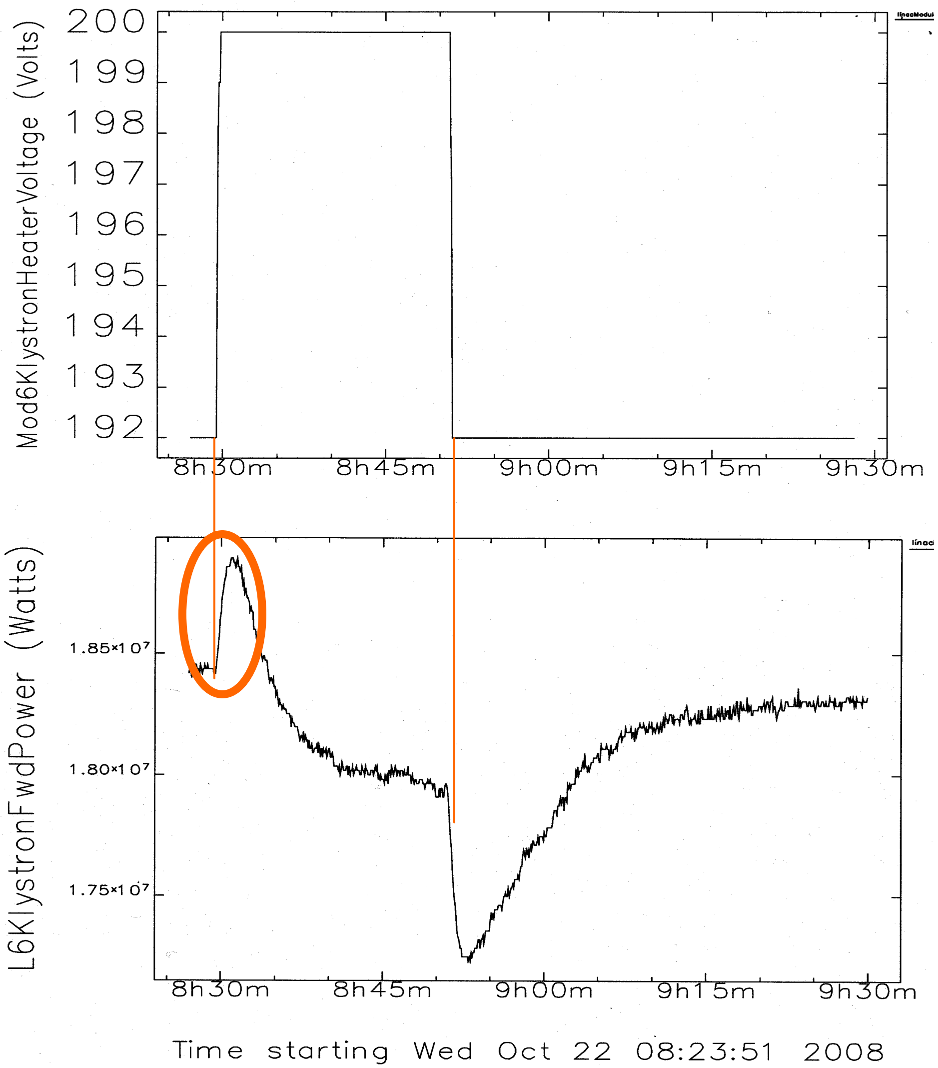
If the wehnelt is cool and voltage is not too high we have a good, normal beam.

But if for some reason the covered by barium wehnelt gets hot, a parasitic (“bad”) beam is developed in addition to the main one.

This “bad” beam hits the anode and warms it up. As a result:

- **Body differential temperature rises.**
- **X-ray radiation may increase.**
- **The “bad” beam loads modulator, cathode voltage slightly drops, the main (“good”) beam current also drops, as well as forward RF power, gain, efficiency, etc.**

The “Good” and “Bad” Beam Currents - 2

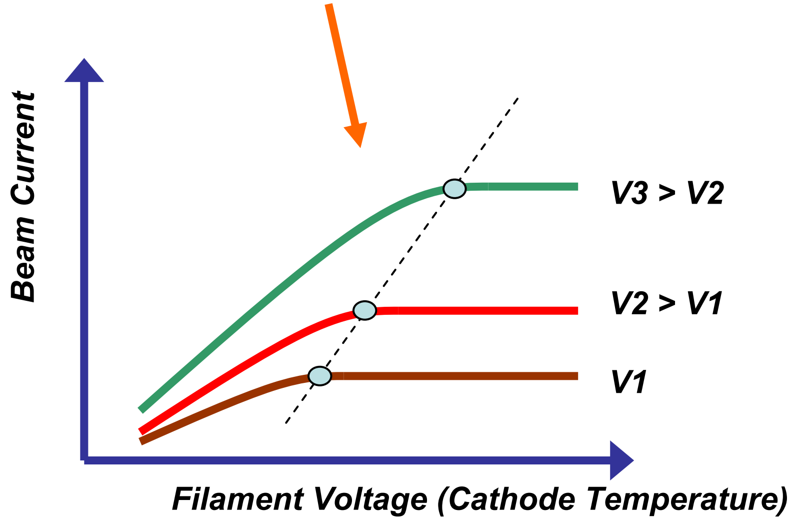


These plots illustrate what just was said.

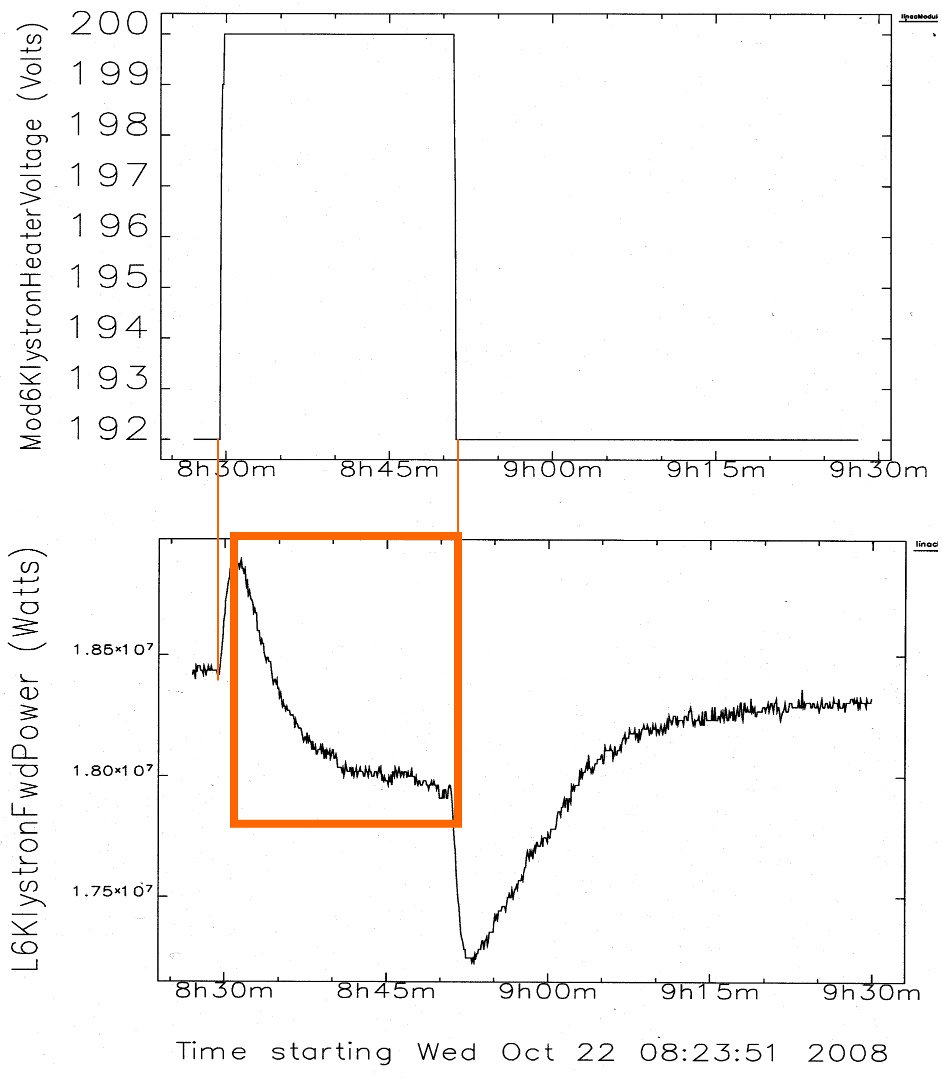
The upper plot shows how filament power was changed in L6.

The lower plot is very interesting. It represents changes of klystron forward power.

Right after filament power was increased, forward power started growing. It tells us that filament power was initially set incorrectly: neither beam current, nor forward power shall increase in this situation (see Slide # 9).



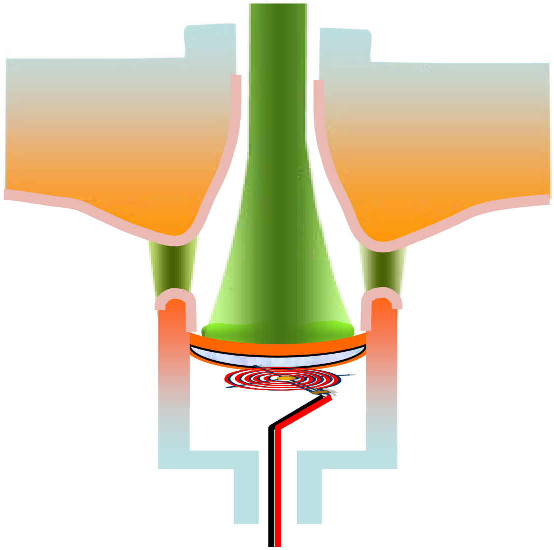
The “Good” and “Bad” Beam Currents - 3



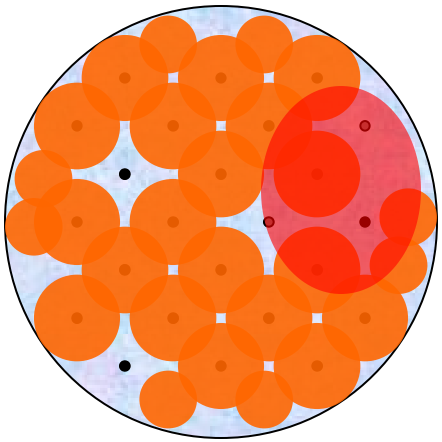
But surprisingly, very soon, forward power stops growing and even noticeably drops!

This means that the wehnelt warms up, emits the “bad” beam that loads the modulator, cathode voltage drops, “good” beam current drops, forward power is getting lower.

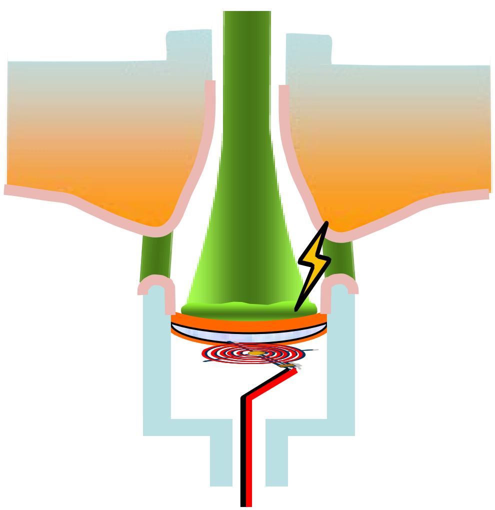
After filament power was returned to the original value, everything eventually returned to the initial levels.



Emission Jumps



Cathode



As the cathode ages, the area covered by barium shrinks, the "good" beam weakens, while the "bad" one intensifies increasing body differential temperature.

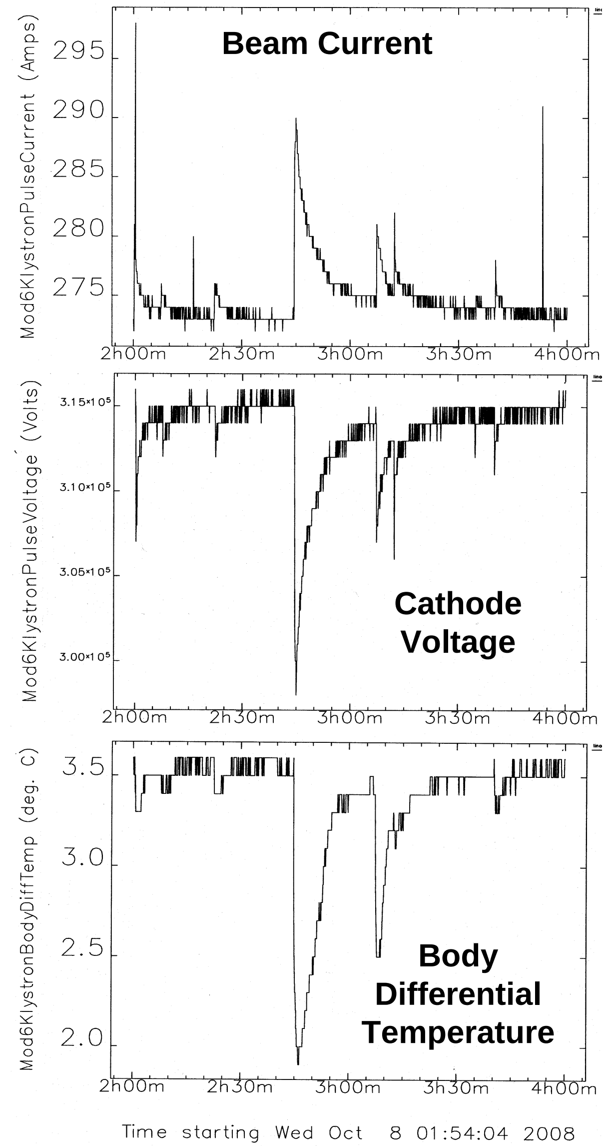
It seems possible that the arcs that usually occur between the anode and wehnelt, sometimes hit the cathode itself spreading certain amount of barium over the cathode surface (red oval).

Active area suddenly gets larger, and the "good" beam current and forward power jump up.

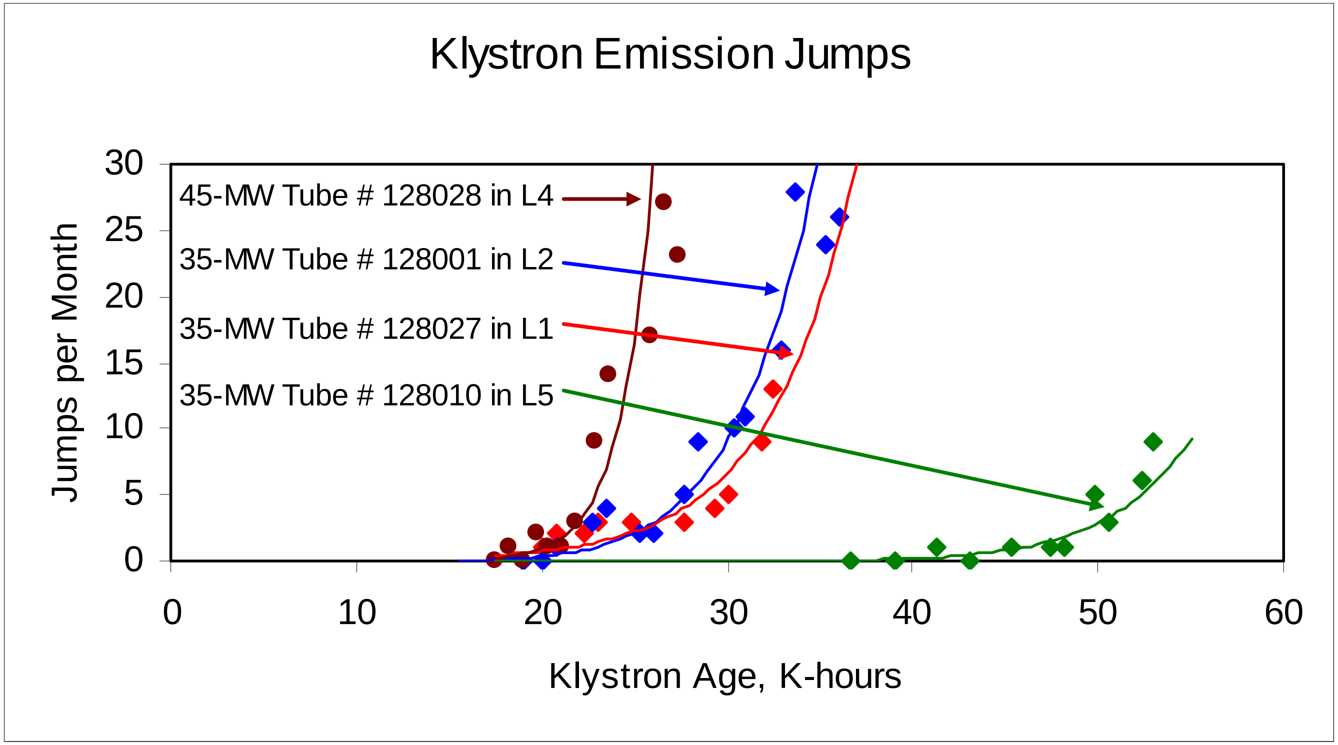
Higher beam current loads the modulator causing some voltage drop.

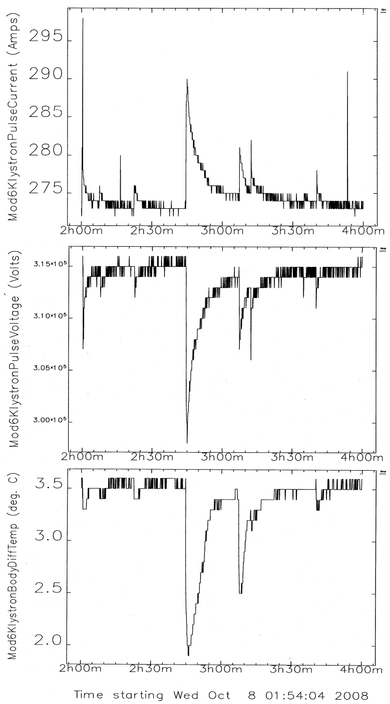
Due to lower cathode voltage, the "bad" current weakens, and body differential temperature gets lower.

In some while, extra barium evaporates from the cathode, and all parameters return to where they were before.



Emission Jumps - 2

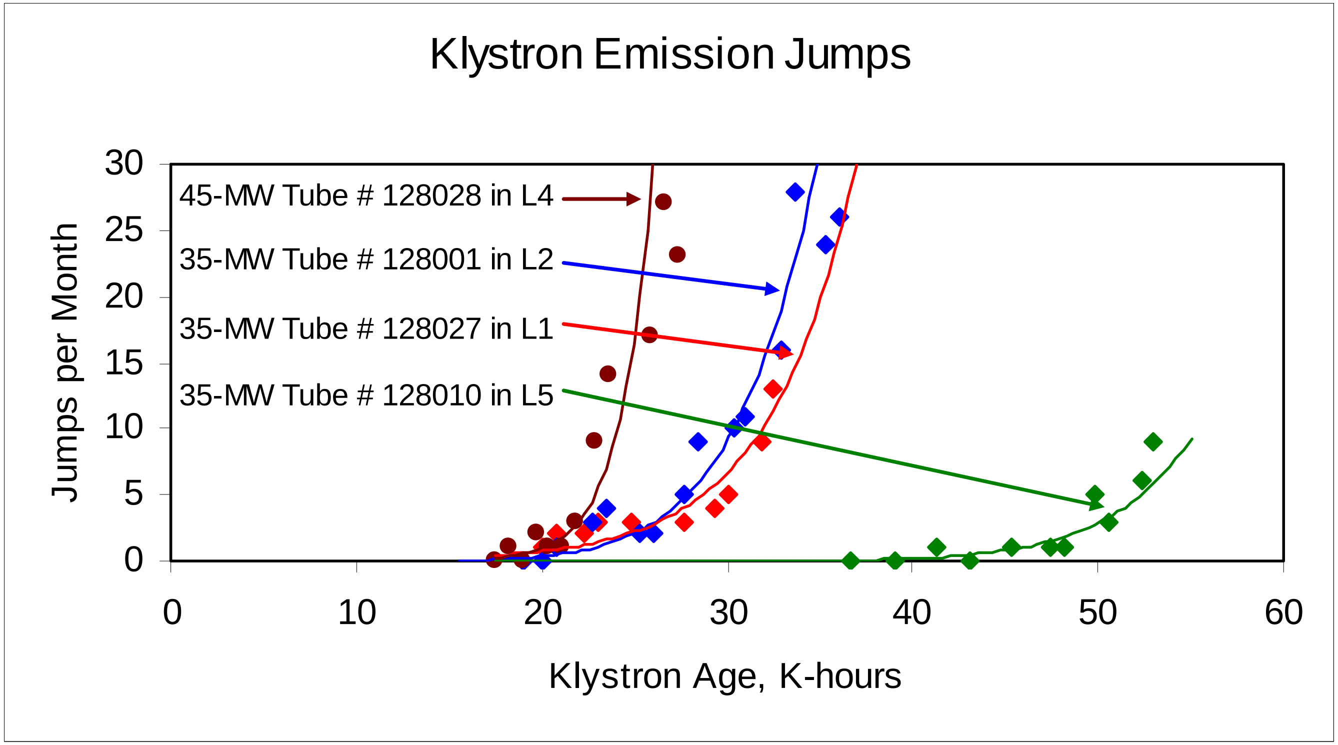


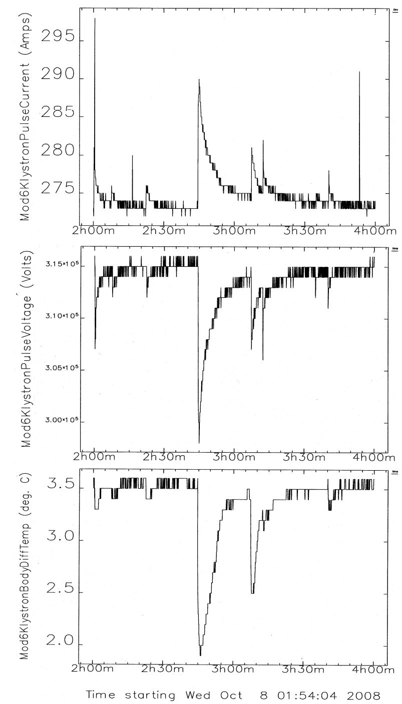


Cathode emission jumps were observed in all klystrons older than about 20,000 hours with only one exception, tube # 128010. The reason why that tube was better than all others is unknown.

The only (as of today) old 45-MW klystron (# 128028) demonstrated very fast degradation after 20,00 hours of operation, so we had to replace it at the age of about 29,000 hours.

Emission Jumps - 3

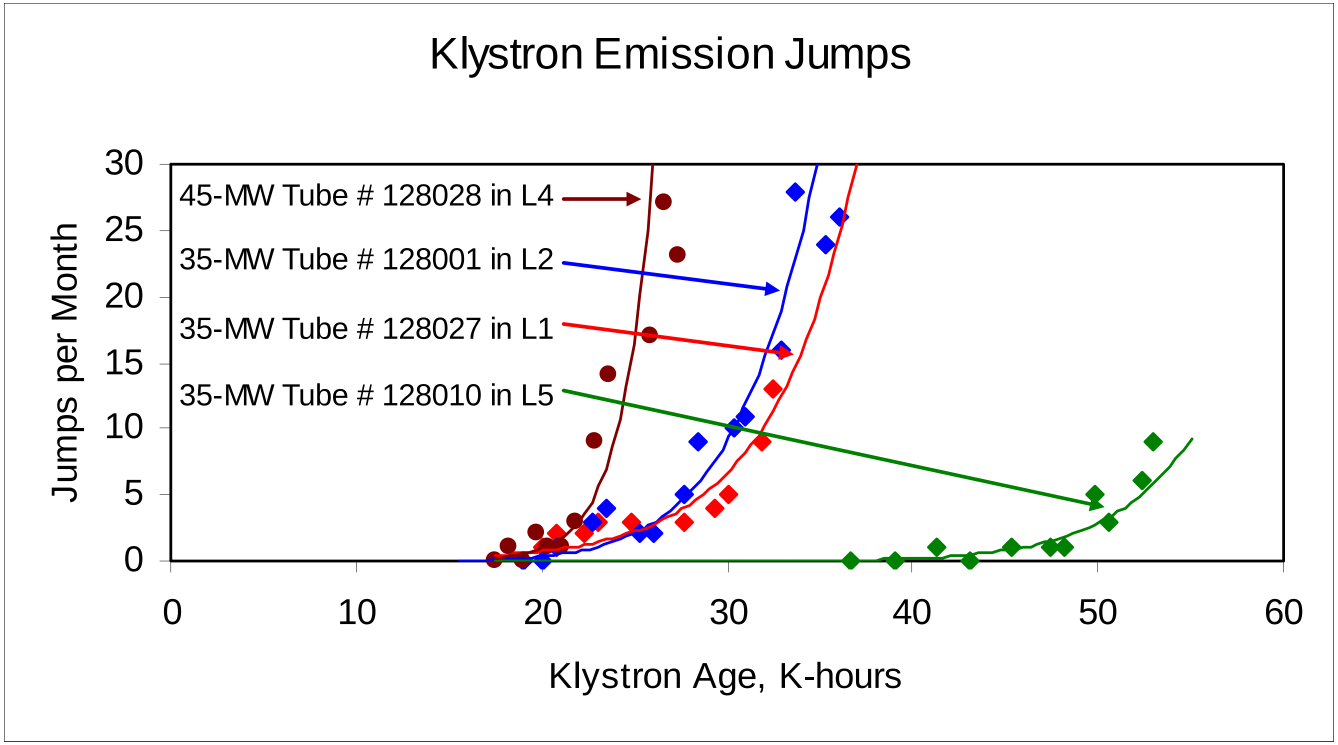


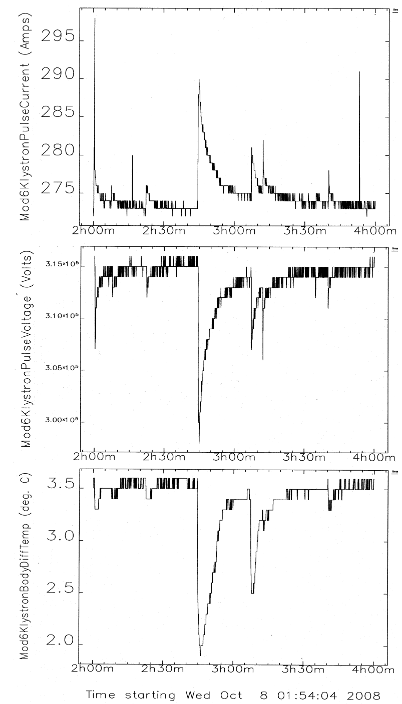


If the way these jumps happen was described correctly (it was just the *hypothesis*; neither Thales' experts nor the experts from other companies I spoke with were able to explain this phenomenon), the only way to eliminate the jumps could consist of lowering cathode voltage down to the arc-free level, which corresponds to PFN voltage of about 28-29 kV.

The problem is that this voltage is too low to produce the RF power levels required in L2 through L6. Only L1 can work properly with this low voltage, because L1 never needs to produce more than 10 to 12 MW.

Emission Jumps - 4



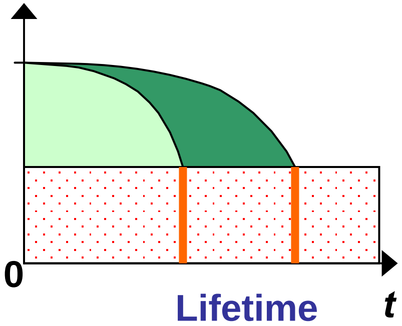


Also, since the emission jumping is *possibly* associated with cathode depletion and with increasing the area that is free of barium, we have one more reason to save barium in the cathode body and to keep cathode temperature as low as possible.

It means that if the klystron needs to produce, for instance, 10 MW during almost entire run, there is no reason to keep filament voltage as high as required for producing 30 MW.

Instead of the Summary

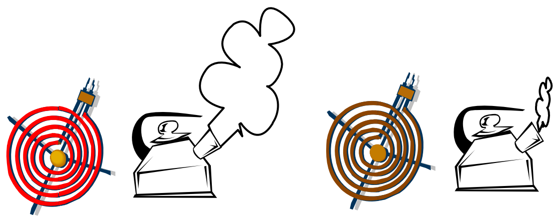
The klystron is a very expensive toy.



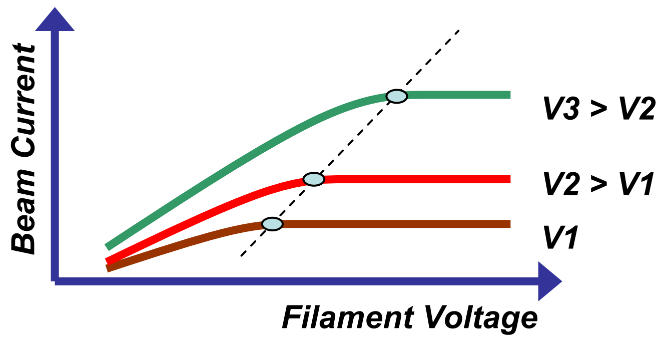
We have to do whatever possible to extend its life.

Klystron aging and degradation is, first of all, the aging and degradation of its cathode.

Instead of the Summary



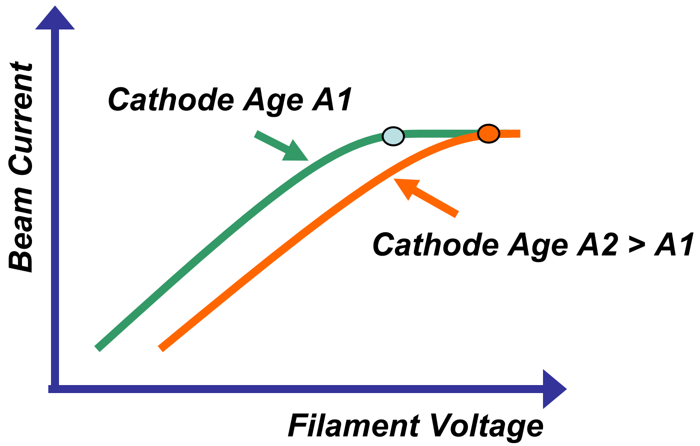
Amount of barium in the cathode is limited. The cooler cathode lives longer.



Lower operating cathode voltage level requires cooler cathode and lower filament voltage.

The dashed line is the border between longer life and stable operation.

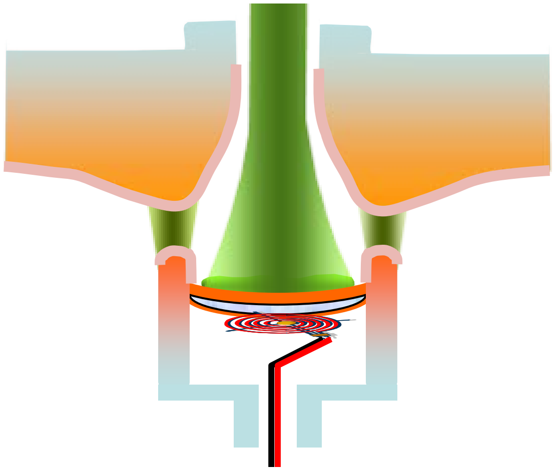
Stay on the border!



The older cathode needs higher filament voltage.

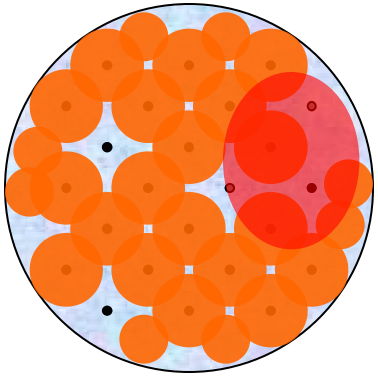
Adjust the filament operating point every shutdown!

Instead of the Summary

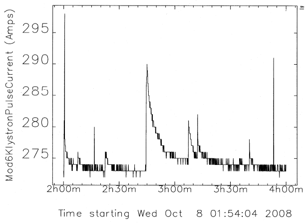


In some cases, the wehnelt becomes an additional cathode that emits the beam (the “bad” beam) which does not participate in amplifying RF, but hits the anode, increases body temperature, X-ray radiation, and loads the modulator.

If it is possible, try to lower cathode voltage and filament power; try to adjust focusing currents, it may help reduce body differential temperature and radiation level.



Extra barium delivered from the anode during an arc may cause emission jumps. This phenomenon inherent in the tubes older than 20,000 hours. ***So far, there is no known effective way to fix the problem.***



Try to keep filament and cathode voltage as low as possible and during as long time as possible.

The End