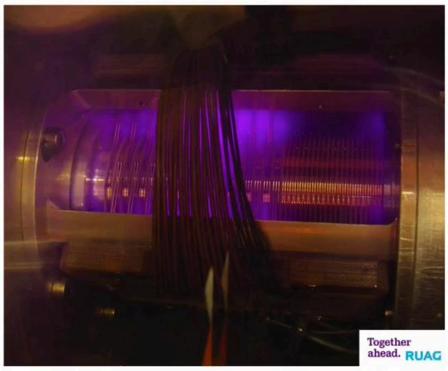
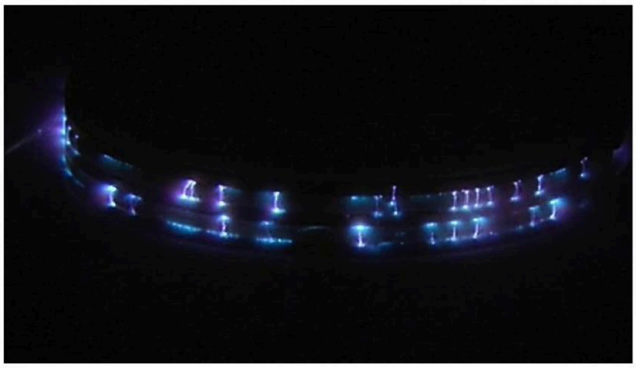


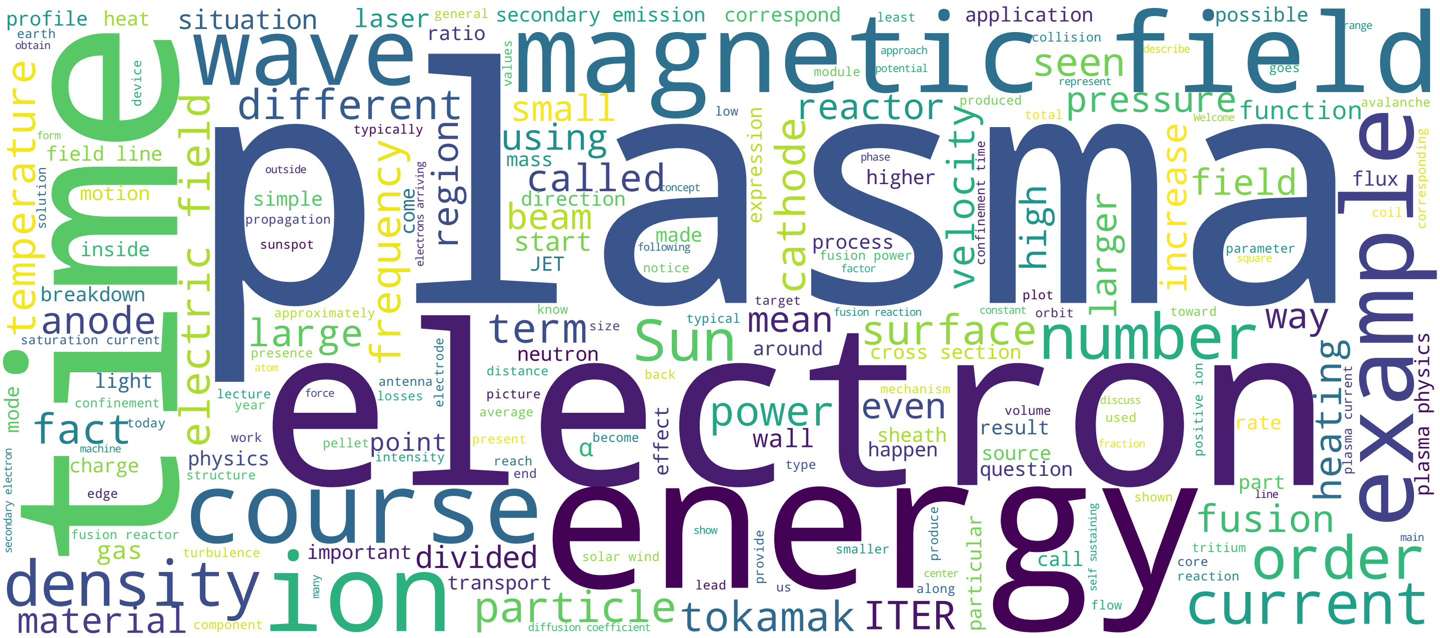


Breakdown in low pressure gases: part I

Plasma Physics and Application to Fusion Energy, Astrophysics and Industry

Lecture 5b

Alan Howling



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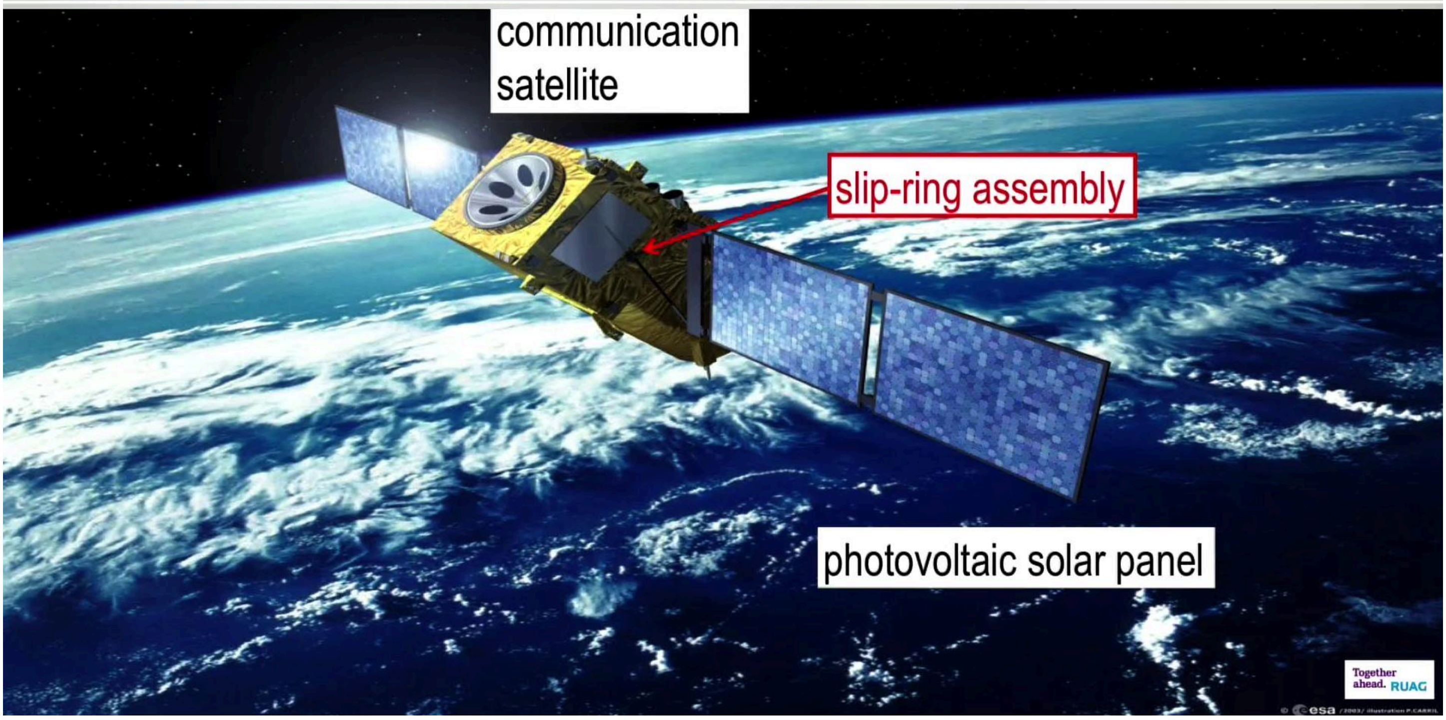
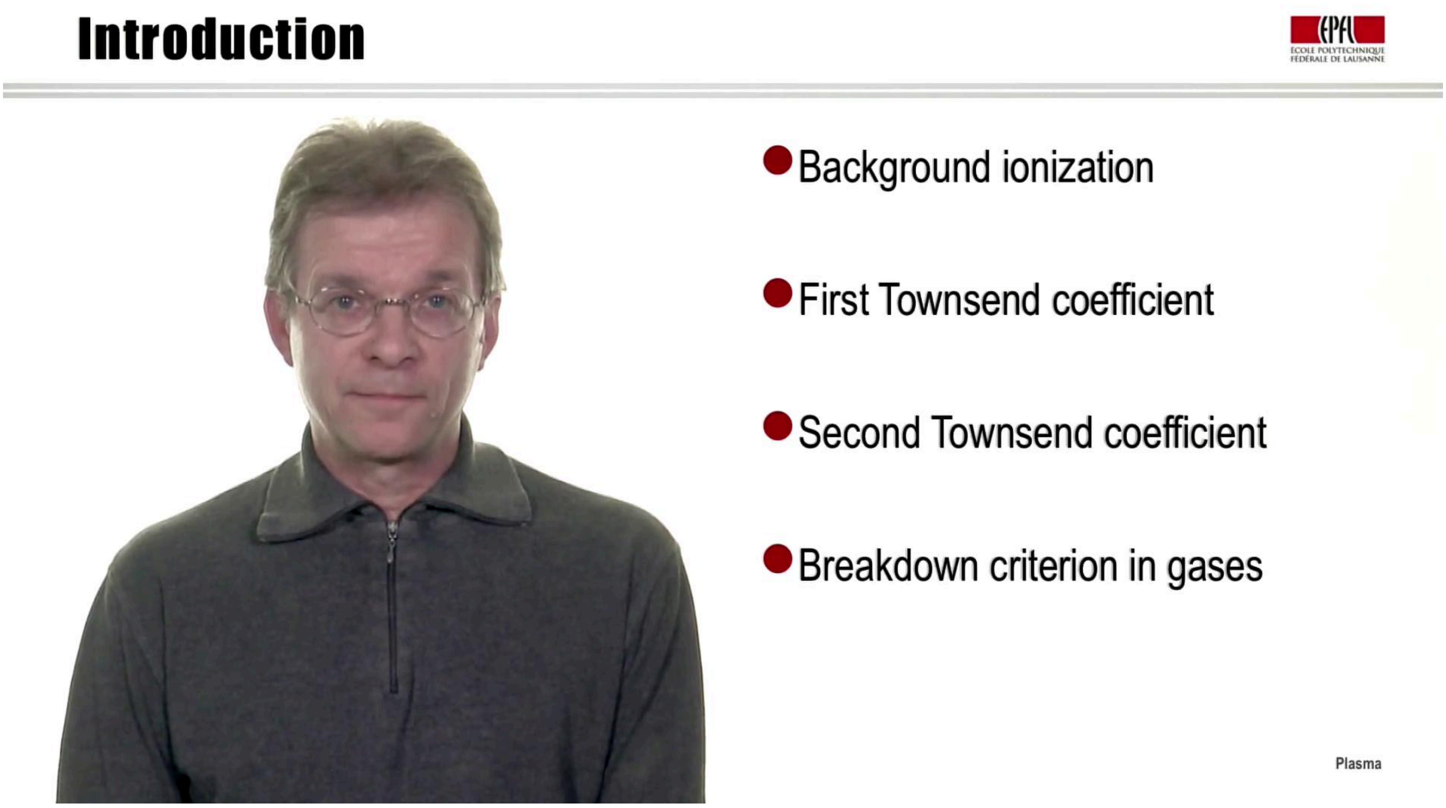


Welcome to the course in Plasma Physics and Applications. In the next two modules, we will consider electrical breakdown in low pressure gases. As an example, we will consider a communication satellite orbiting the earth, which is powered by photovoltaic solar panels. Now the communication satellite is aimed at the ground and the photovoltaic solar panels are aimed at the sun. And therefore, there has to be some relative rotation, which is guaranteed by a slip-ring assembly. Now in this example of breakdown, this is an application where we want to design the slip-ring assembly to avoid electrical breakdown. Therefore, we have to consider the physics of electrical breakdown in low pressure gases.

Notes

Summary

0m 05s



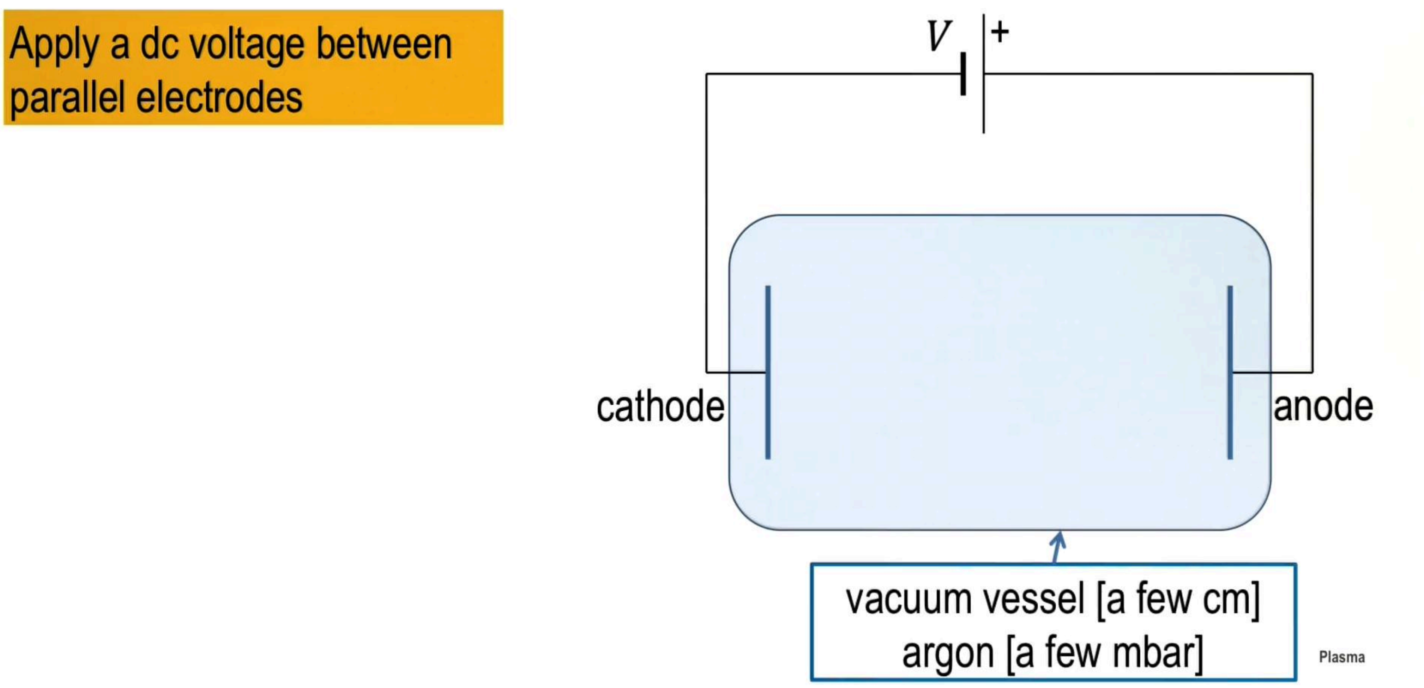
In this course, we will first consider background ionization and then the first and second Townsend coefficients and then we will come to breakdown criterion in gases.

Notes

Summary

0m 55s

Background ionization



As an example, we will take a vacuum vessel here with electrodes of a few centimeters dimensions and the vessel is filled with argon to a pressure of a few millibars. We will apply a *dc voltage* between a cathode and the anode and the question is: does a plasma form immediately?

Notes

Summary

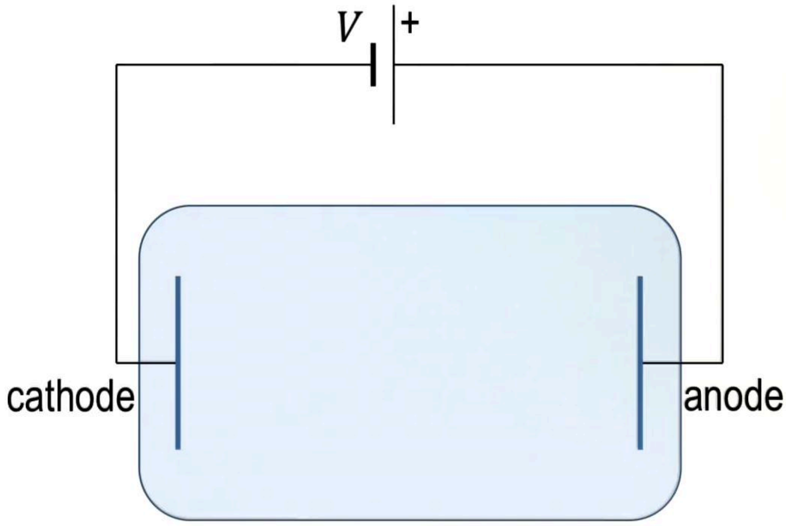
1m 09s

Background ionization

Apply a dc voltage between parallel electrodes

How does the plasma "start"?

Where does the first electron come from?



Plasma

That is, how does the plasma start or where does the first electron come from to start the plasma?

Notes

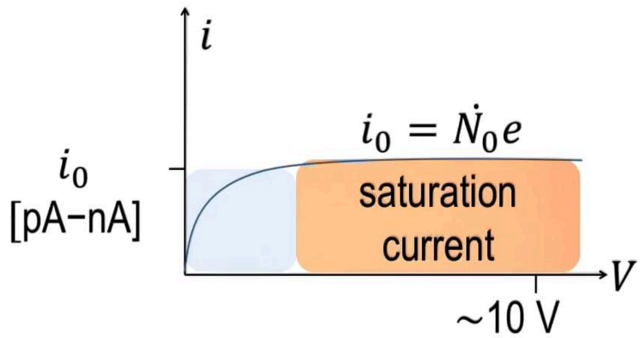
Summary

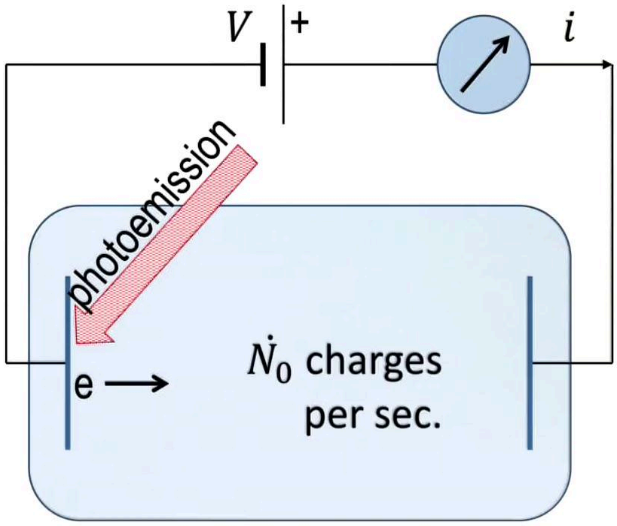
1m 32s

Background ionization

Saturation current :
all charges collected at the electrodes.

The discharge is too weak to be visible;
it depends on an external source
(*not* self-sustaining).





Plasma

The answer to this is that there is always background radiation on earth coming from cosmic rays or radioactivity in the environment. These rays or radioactivity can cause photoemission from the cathode or photoionization in the gas and these release electrons, which travel in the electric field from the cathode to the anode. Let's say that the photoemission creates N_0. charges per second and when all of these charges are collected at the anode then we have a saturation current, that is the saturation current is equal to the rate of production of all electrons times the electronic charge. This current is generally very small, of the order or picoamps, and this situation occurs for voltages up to, say, ten volts. Now this discharge is too weak to be visible. It depends only on an external source. This is not a self-sustaining plasma.

Notes

Summary

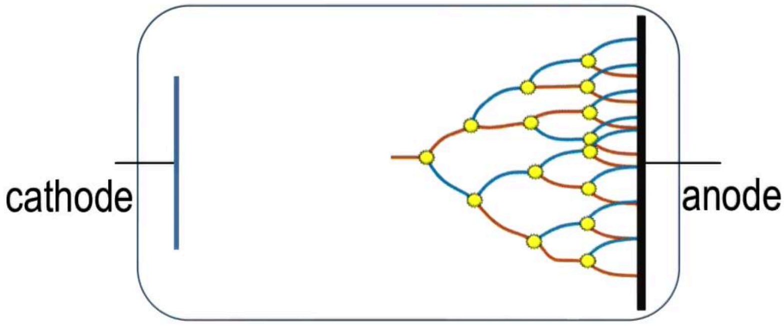
1m 41s

First Townsend coefficient

Increase the voltage further

- Ionization by electron impact creates more electrons: $e^- + Ar \rightarrow 2e^- + Ar^+$
- The discharge current now increases above the saturation current
- Each initial electron can create an avalanche of electron-ion pairs
- Introduce: *Townsend's first ionization coefficient*,

α = number of ionizing collisions per electron, per unit length along E



Now if we now increase the voltage still further, then the electron impact on atoms will eventually lead to ionization -- something considered in the previous module -- where each electron will therefore give rise to two electrons and the ion of the original atom. The discharge current will now increase strongly above the saturation current because each electron can create an avalanche of electron-ion pairs, as we see schematically in this diagram, where each electron arriving strikes an atom creating therefore two electrons, which are accelerated in the electric field. This repeats, causing an avalanche to the anode. This was considered by Townsend in the year 1900. Townsend introduced something called the "first ionization coefficient," which he defined as α = *the number of ionizing collisions per electron, per unit length along the electric field.* Now let's look at the number of electrons arriving at the anode due to the avalanche phenomenon of electrons coming from the cathode.

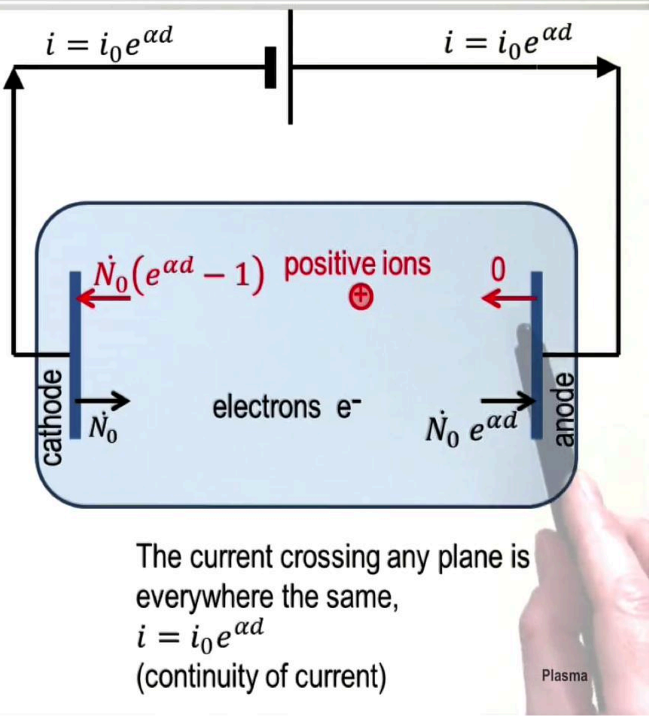
Notes

Summary

2m 46s

First Townsend coefficient

Townsend avalanche in a low pressure gas
- don't forget the ions created by ionization!



If *N.* is the rate of electrons arriving at position *x*, then by definition of *α*, the increase in the rate of electrons crossing *x* + *dx* is *N.* times *αdx*, which is the increase of the number of electrons due to ionization in the slice *dx*. We integrate this from the cathode to the plane at *x* and if *α* is independent of *x*, then we find that the rate of electrons crossing *x* increases with the exponential of *x* and therefore, the current leaving the anode -- since electrons have negative charge -- this current leaving the anode is the number of electrons leaving the cathode times the charge of the electrons times the exponential of *αd* and therefore the current is i_0e^{ad}, where i_0 is the saturation current from the previous slide. This strong increase in current is called the "avalanche effect." Don't forget that every electron ionizing event creates positive ions, which travel back in the opposite direction. Therefore, you can convince yourself that the current crossing any plane is everywhere the same by continuity of current. So the number of electrons arriving at the anode it $N_0.e^{ad}$.

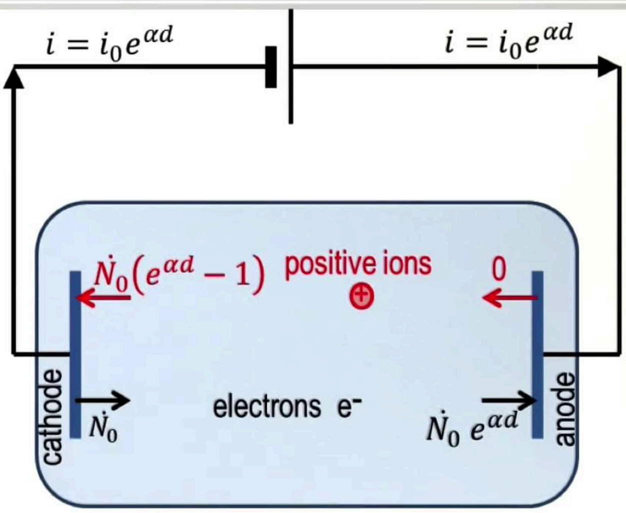
Notes

Summary

4m 04s

First Townsend coefficient

Townsend avalanche in a low pressure gas
• don't forget the ions created by ionization!



The current crossing any plane is everywhere the same,
$i = i_0 e^{\alpha d}$
(continuity of current)

Plasma

There are no positive ions leaving the anode, so this, the minus *e* times this is the current arriving here. The positive ions travel back and the sum total of current arriving at the [at] cathode is also $i_0 e^{\alpha d}$ and this current circulates also in the external circuit.

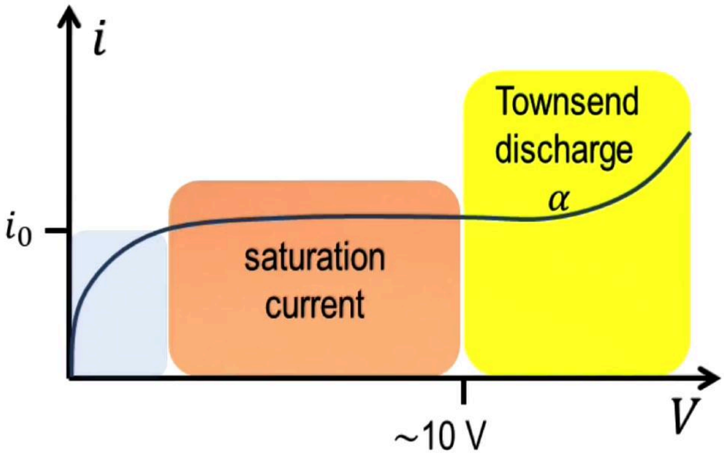
Notes

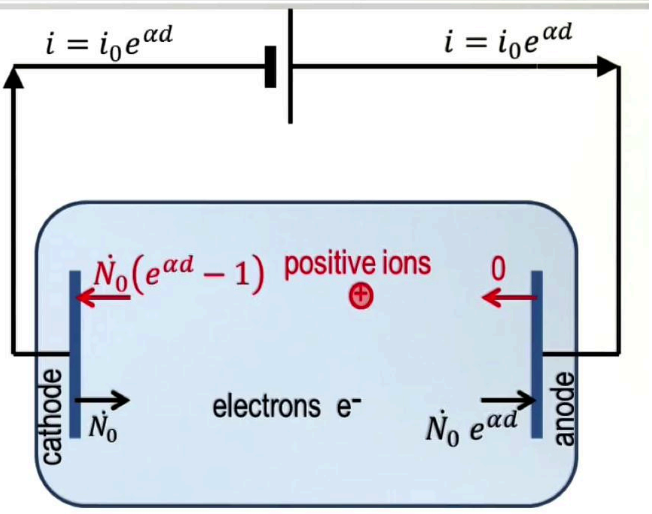
Summary

5m 37s

First Townsend coefficient

The current increases, but depends entirely on an external source (photoemission in this case).
It is not a self-sustaining discharge.





The current crossing any plane is everywhere the same,
$i = i_0 e^{\alpha d}$
(continuity of current)

Plasma

So if we go back to our current voltage graph, we find that beyond several volts, beyond the saturation current, we enter the Townsend discharge regime defined by α where the current is increasing exponentially with distance.

Notes

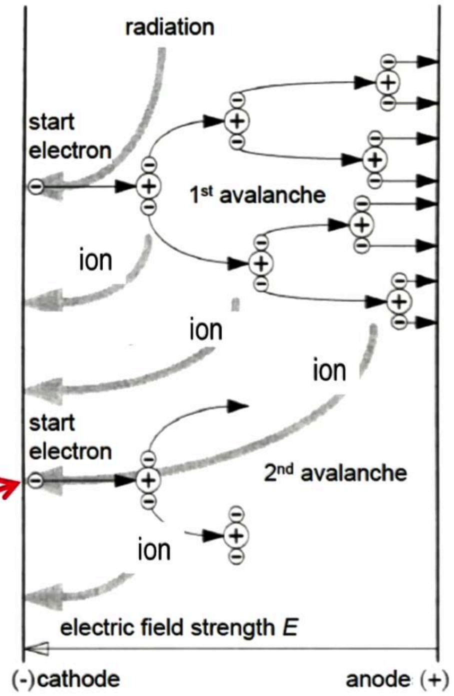
Summary

5m 57s

Second Townsend coefficient

All of the ions are accelerated towards the cathode where they are all neutralized, and some can also cause electron emission (Auger).

secondary emission event



Now if we look again at the cathode and the anode, we consider what happens when the ions themselves arrive back at the cathode. So we have the start electron. This causes an ionizing event, the ion goes back to the cathode, and the avalanche continues towards the anode. All the subsequent ions arrive back at the cathode. All the ions are neutralized there but some of them, when they strike the cathode, can cause secondary electron emission, for example, by the Auger effect, and these secondary electrons can create further avalanches. The secondary emission events are quite rare.

Notes

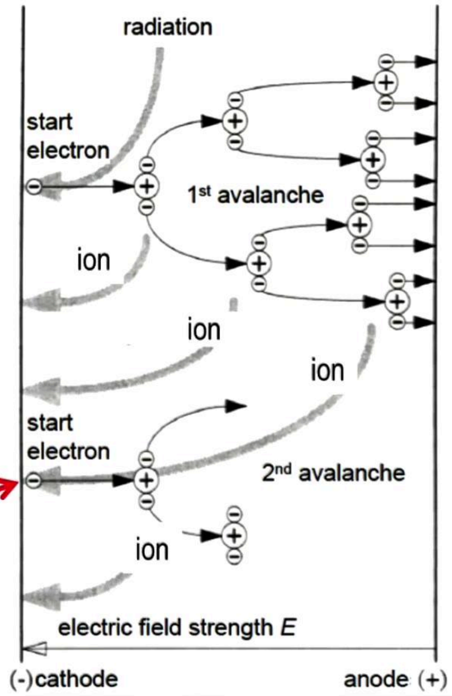
Summary

6m 16s

Second Townsend coefficient

Between electrodes, the current can increase even more strongly, due to secondary emission described by Townsend's second ionization coefficient, γ.
γ = number of electrons emitted per incident ion $\sim 10^{-2}$
depends on gas type and electrode material

secondary emission event

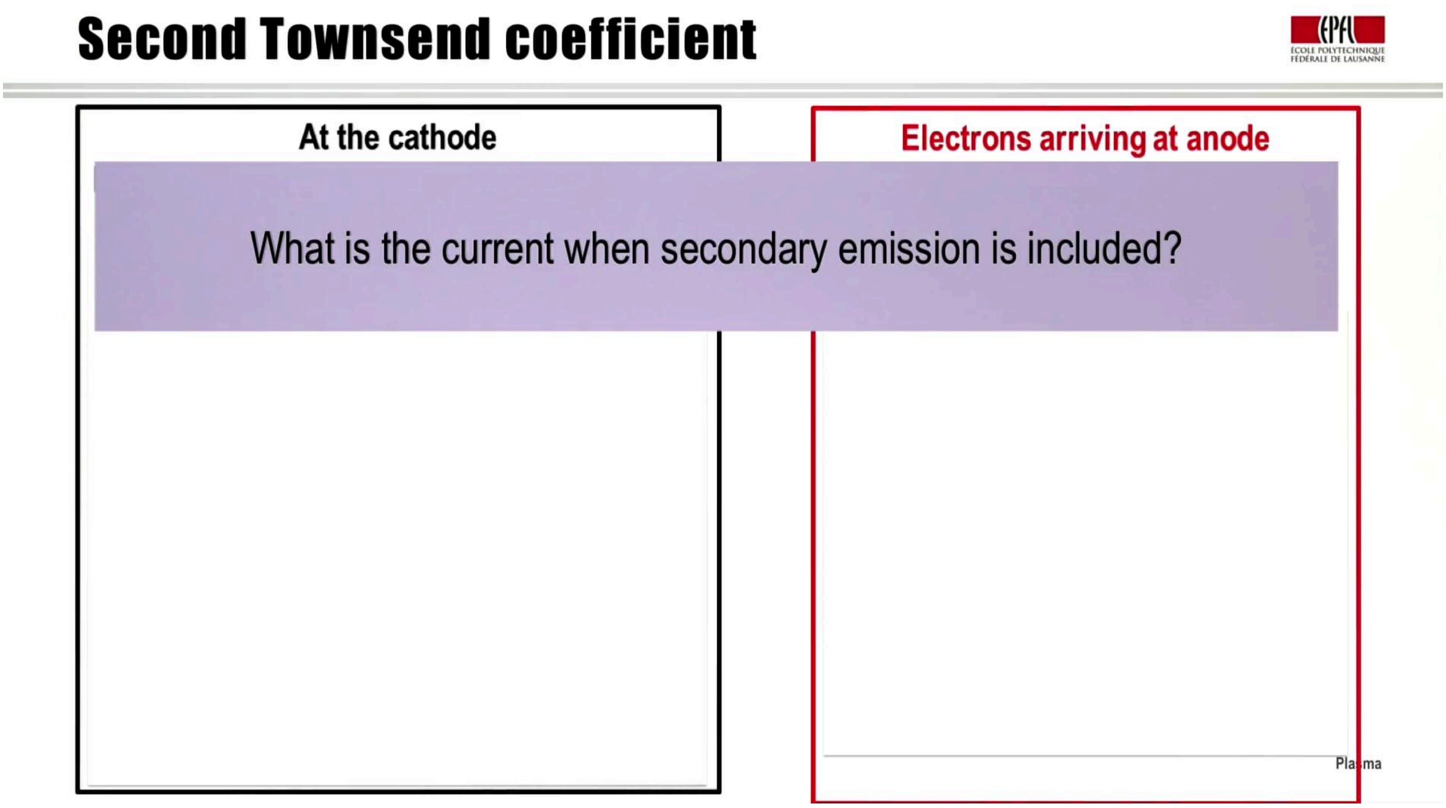


So now we want to consider what the current is in the presence of secondary emission. Between the electrodes, the current can increase even more strongly due to the secondary emission effect. The number of electrons emitted per incident ion is small, of the order of 10^{-2} and the probability, 10^{-2}, this probability depends on the type of gas -- that is the type of ion arriving on the cathode -- and the type of material that the cathode is made of.

Notes

Summary

6m 58s

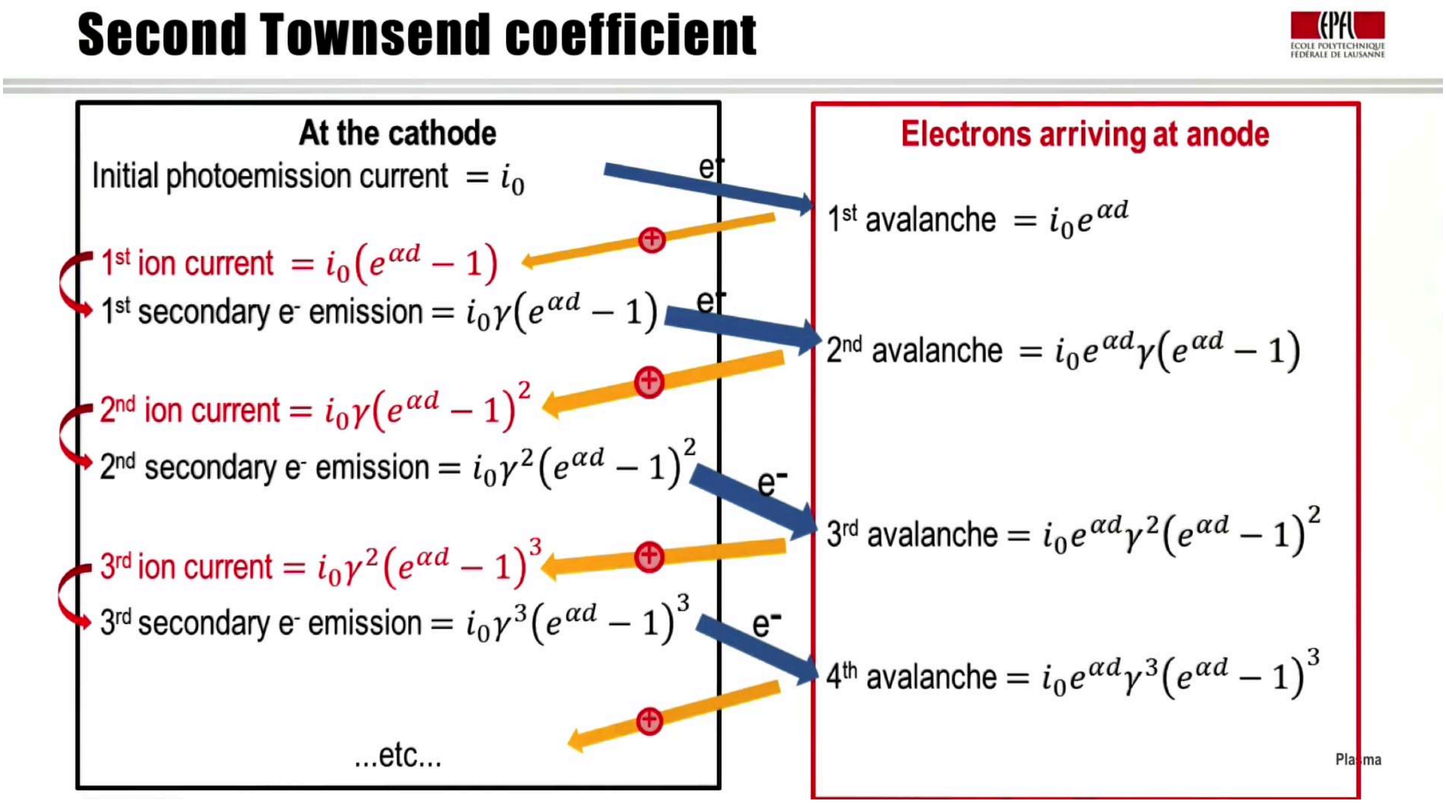


So the question is, what is the current when secondary emission is included?

Notes

Summary

7m 32s



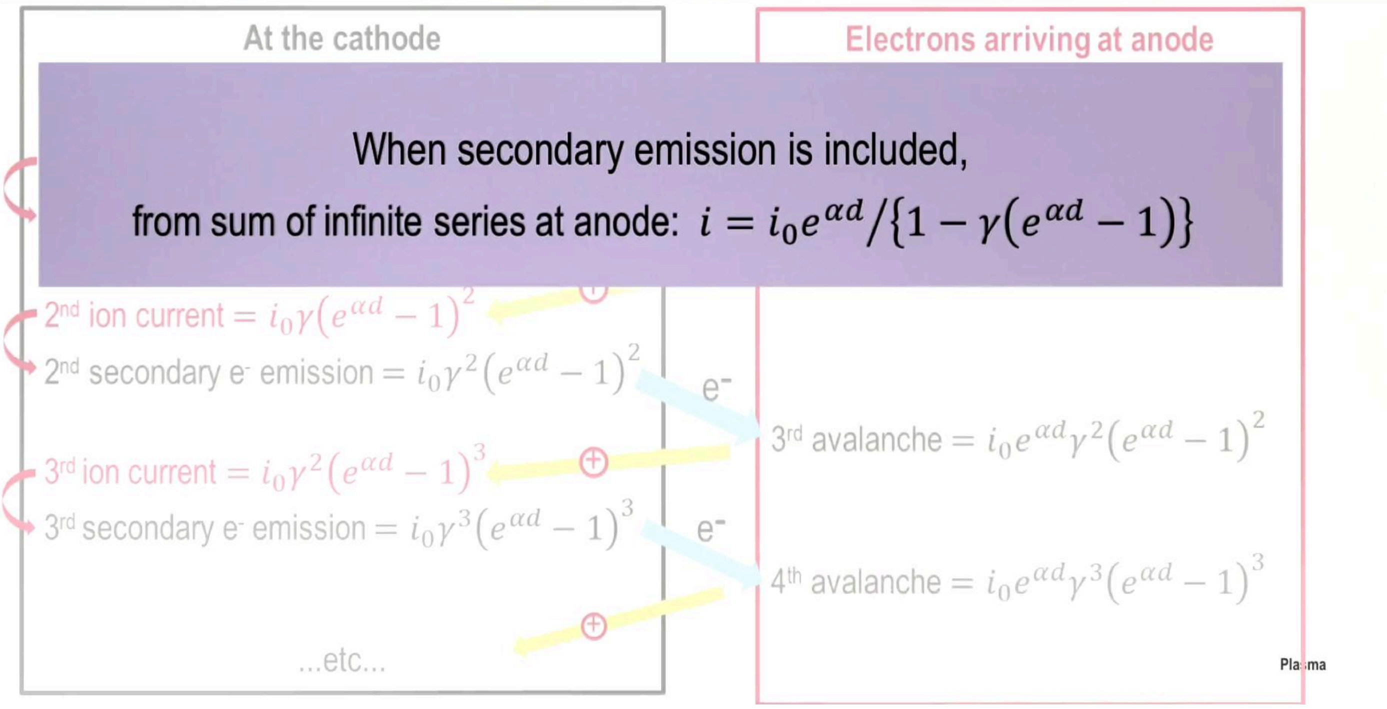
The initial photoemission current from the cathode undergoes avalanche as it arrives at the anode. All the ions created during the avalanche drift back to the cathode and a fraction γ of these ions creates secondary electrons, which themselves avalanche towards the anode giving you this number of electrons arriving at the anode, giving rise also to this number of ions, arriving back at the cathode, whose fraction γ gives another secondary emission source, which travels with avalanche to the anode, etcetera. So we can see that we have here a geometric series with a constant value of $i_0 e^{\alpha d}$ multiplied by a factor $\gamma(e^{\alpha d} - 1)$. This is the ratio between successive avalanches.

Notes

Summary

7m 38s

Second Townsend coefficient



The sum of a geometric series is the constant divided by one minus the ratio and therefore when secondary emission is included, we find that the sum of the infinite series of all the avalanches gives this current at the anode.

Notes

Summary

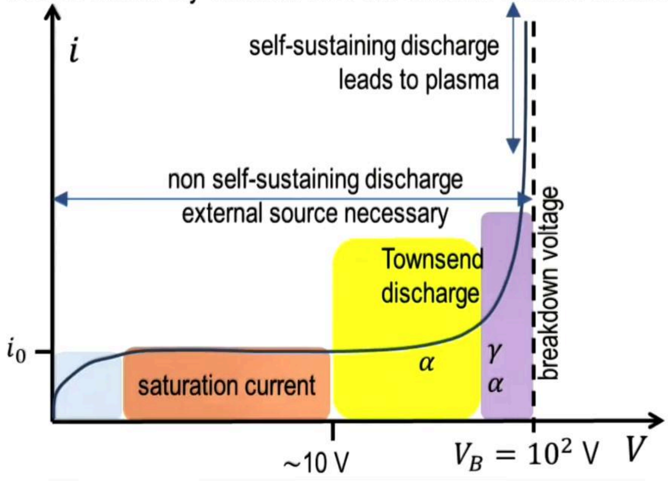
8m 41s

Breakdown criterion in gases

The Townsend criterion for breakdown: $1 - \gamma\left(e^{\alpha d} - 1\right) = 0$

- The gas "breaks down" and becomes a self-sustaining discharge,
  - independent of external source i_0, for $\gamma e^{\alpha d} = \gamma + 1 \approx 1$.

Physically, $\gamma e^{\alpha d}$ is the number of secondary electrons emitted per primary electron.
$\gamma e^{\alpha d} = 1$ means that every electron from the cathode creates another to replace it.



Plasma

So now we see the Townsend discharge current due to the first Townsend coefficient and the second Townsend coefficient increases the current even more strongly. This current still depends on the external source i_0. But note that the Townsend current will become theoretically infinite as the denominator here tends to zero. This, then, is the Townsend criterion for breakdown in gases between parallel electrodes -- that is that one minus the ratio equals zero. In this case, the gas breaks down and becomes a self-sustaining discharge. That is, that the discharge is independent of the external source for this condition $\gamma e^{\alpha d} = \gamma + 1$, which is approximately equal to one. Physically, this simply means that the number of secondary electrons created per primary electron is at least equal to one. That is, every electron from the cathode creates another to replace it. And now we have our full current voltage diagram, where the saturation current undergoes avalanche and secondary emission to become a self-sustaining plasma instead of a non self-sustaining discharge.

Notes

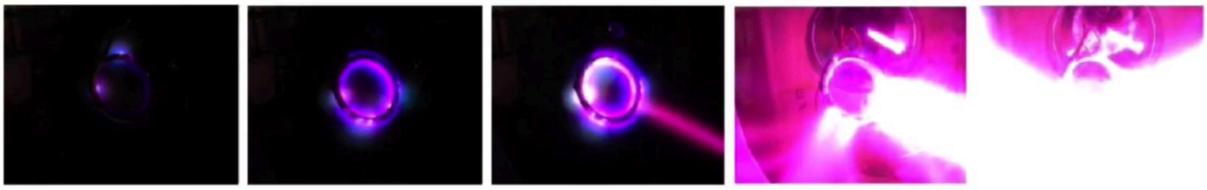
Summary

8m 59s

Breakdown criterion in gases

Breakdown can cause an arc whose current is limited only by the impedance of the external circuit

Current limit is increased →



Picture exposure time is reduced →

If the supply voltage is maintained (eg a solar panel), catastrophic arcing can occur with strong heating and melting of metal components etc.

NOT GOOD (especially when in orbit)

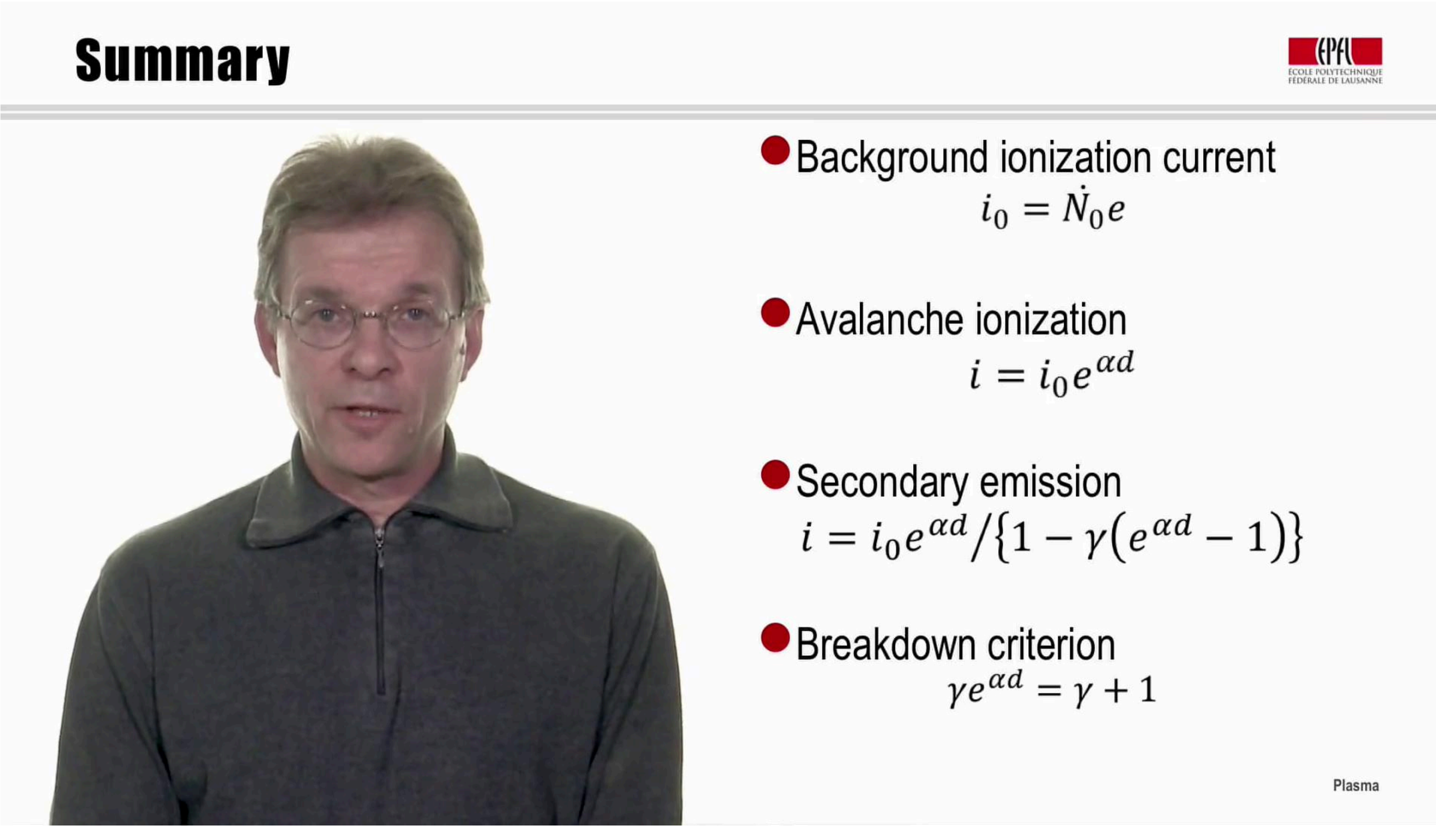
Plasma

When breakdown occurs between parallel conducting electrodes, this can cause an arc whose current is limited only by the impedance of the external circuit, as we can see in these photographs here, where the current limit in the external circuit was increased between each different experiment. So as the current limit becomes very high, we can get catastrophic melting of components and complete destruction of the electrodes. So if the supply is maintained, for example, by a solar panel, then catastrophic arcing could destroy a slip-ring in a satellite. This is not good, especially in orbit where the possibility of repair is very small.

Notes

Summary

10m 28s



So to summarize this module, we've considered the background ionization current. We've seen how ionization leads to an avalanche, which increases the current. We've seen that secondary emission increases the current still further and then we arrive at a point where we have breakdown; and the breakdown criterion is given by $\gamma e^{\alpha d} = \gamma + 1$

Notes

Summary

11m 16s