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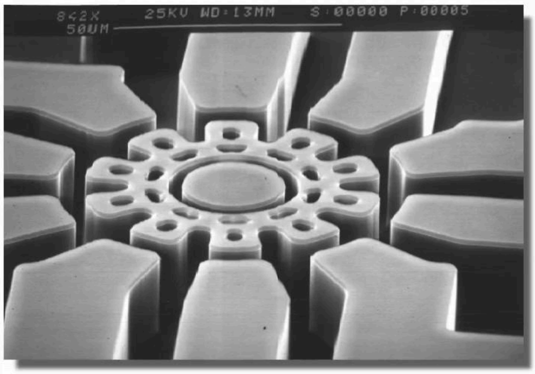
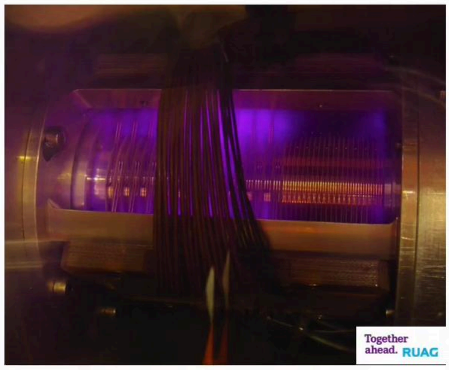


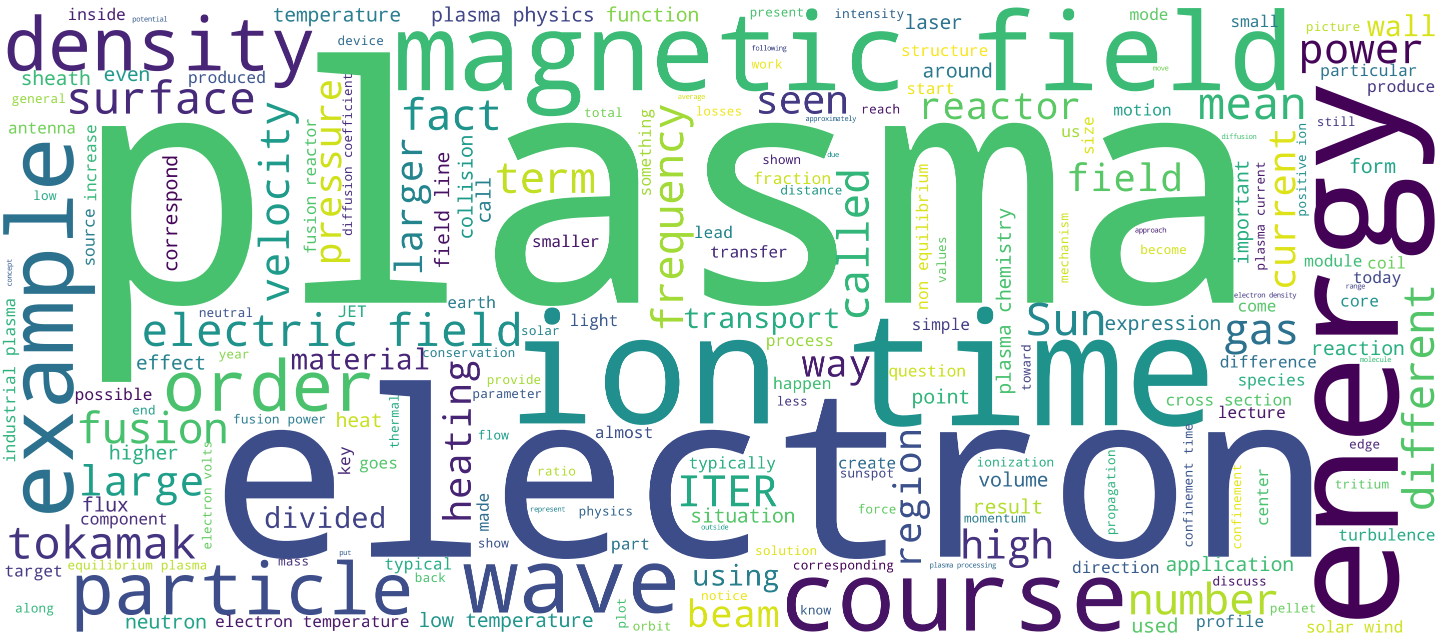


Survey of plasmas in industry and medicine

Plasma Physics and Application to Fusion Energy, Astrophysics and Industry

Lecture 5a

Alan Howling



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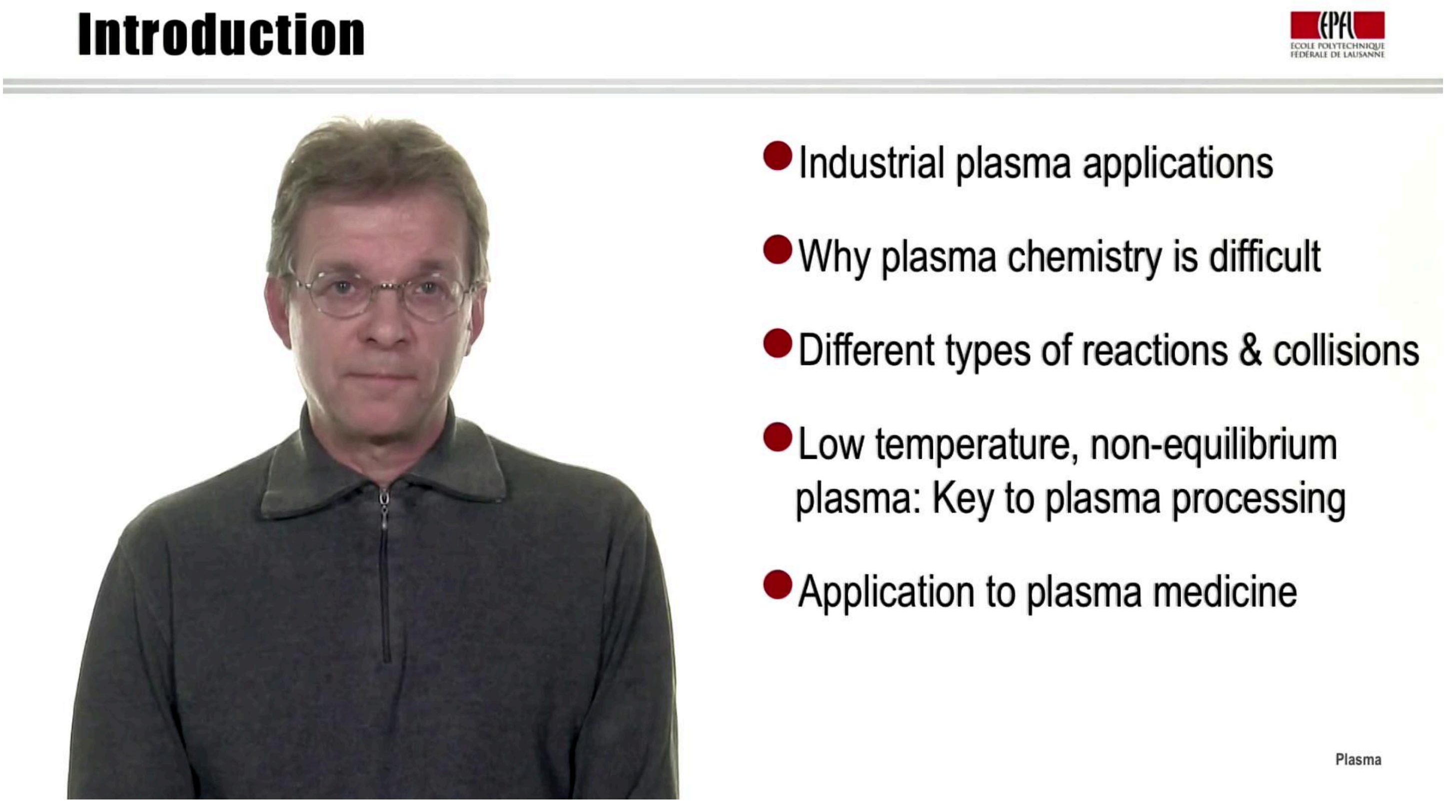

Welcome to the course on Plasma Physics and Applications. In this introductory module, we will discuss some industrial applications, we will see why plasma chemistry is a difficult subject, we will go through some different types of reactions and collisions, and then we come to the key to plasma processing, which is low temperature, non-equilibrium plasma. And then we will finish with a brief application to plasma medicine.

Notes

Summary

0m 05s

Industrial plasma applications

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- Microelectronics
- Photovoltaic solar cell panels
- Food packaging
- Refractory/Hard/Decorative coatings
- Electrical Discharge Machining
- Space Industry and aeronautics
- LED/GaN
- Re-writable DVD
- Powder/grain treatment
- Superconducting layers
- Architectural glass
- Combustion, waste treatment, auto...

Medical:

- Sterilization
- Wound treatment
- Dental treatment
- Cancer treatment...

Plasma

Industrial plasma applications can be found in all walks of life as you can see from this list on the left. In this course, I will speak, the next two modules about the space industry, and finally, on microelectronics which is important for all our computing and other electrical devices. Plasma physics is used more and more in the medical domain, for sterilization, wound, dental and cancer treatment.

Notes

Summary

0m 34s

Why plasma chemistry is difficult

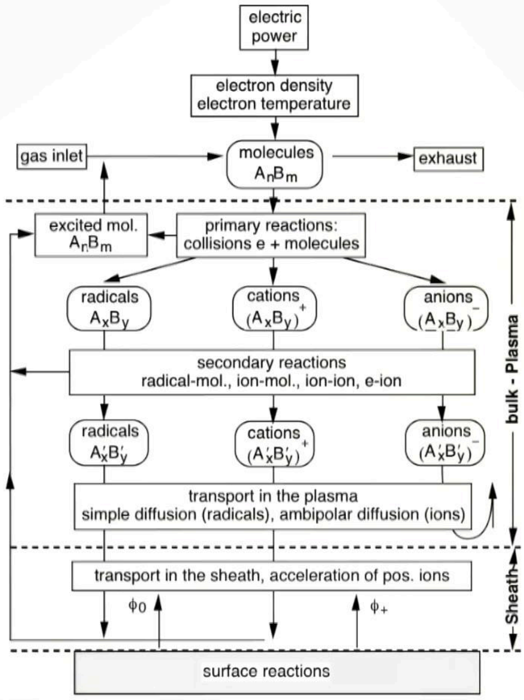
Compare with fusion:

What are the differences?

High pressure [mbar] of neutrals,
low degree of ionization $\sim 10^{-6} \rightarrow 10^{-3}$.

Collisional damping, "no waves"

Often no magnetic field, "no MHD"



Why is plasma chemistry a difficult subject? Let's compare it with fusion physics and see the differences. In industrial plasmas, we tend to have a high pressure of neutrals with a low degree of ionization -- that is, about only one particle in a million is ionized. Therefore we have collisional damping, that is 'no wave' physics, and we often have no magnetic field, that is, no magnetohydrodynamics. So what is the difficulty with plasma chemistry? We can see that in this diagram here, where we have a gas inlet of molecules, we have an electrical power source which creates a plasma with a certain electron density and electron temperature. These molecules are dissociated by the plasma -- by the electrons in the plasma -- to create neutral radicals, positive ions, and even negative ions by attachment. All these species can undergo secondary reactions between themselves which create a very complicated soup of plasma species. In this bulk plasma, the transport is determined by simple diffusion, for radicals and ambipolar diffusion for ions. There's also transport to the sheath, which will be the subject of the fourth and fifth module, where the positive ions are transported to the surface, and negative ions are trapped inside the plasma.

Notes

Summary

1m 04s

Why plasma chemistry is difficult

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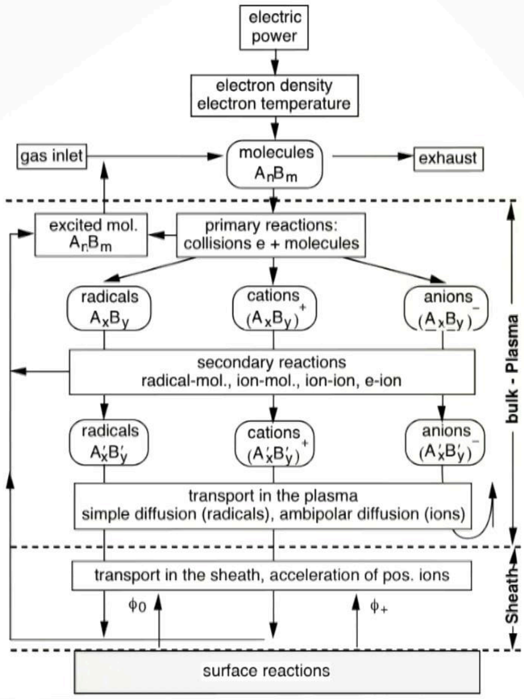


On the substrate itself, there are also surface reactions which change the composition of the plasma. The final saturated molecules are pumped out through to the exhaust. The complication of plasma chemistry comes from all of these different types of species.

Notes

Summary

2m 36s

Different types of reactions

Gas-phase volume reactions (homogeneous)

Ionization	$e + AB \rightarrow AB^+ + 2e$
Dissociation	$e + AB \rightarrow e + A + B$
Attachment	$e + AB \rightarrow A^- + B$

Gas/Surface reactions (heterogeneous)

Ion neutralization	$e + A^+ + srfc \rightarrow A + srfc$
Association	$H + H + srfc \rightarrow H_2 + srfc$
Secondary emission	$A^+ + srfc \rightarrow e + A + srfc$
Sputtering	$A^+ + srfc \rightarrow [B] + srfc$
Deposition	$A(g) + B(s) \rightarrow AB(s)$
Etching	$A(g) + B(s) \rightarrow AB(g)$

Transport of Species to Surfaces

Diffusion	Neutral flux	$= -D_A \nabla n_A$
Ion flux across sheath	Ion flux	$= n^+ u_{Bohm}$

Plasma

We have many different types of reactions, for example, gas phase reactions in the volume, which are called *homogeneous* because these are reactions between gas and gas. Type of reactions possible are electrons which ionize molecules, therefore giving two electrons. We'll see this in module 2 and 3. There's also dissociation of the neutrals into separate atoms or molecule groups. And even attachment to molecules which can give negative ions. There are also gas surface reactions which are called *heterogeneous* because this is between a gas phase and a solid phase. We see that ions are always neutralized with high efficiency on surfaces. Therefore electrons and ions are neutralized on surfaces. Hydrogen atoms associate on surfaces. These atoms cannot recombine in the volume because it's difficult to conserve momentum and energy in a volume process. Therefore hydrogen atoms, for example, recombine only on surfaces. Another surface reaction is where positive ions bombard the surface and release a secondary electron. Yet another is sputtering, where ions release a component of the surface itself.

Notes

Summary

2m 55s

Different types of reactions

Gas-phase volume reactions (homogeneous)

Ionization	$e + AB \longrightarrow AB^{+} + 2e$
Dissociation	$e + AB \longrightarrow e + A + B$
Attachment	$e + AB \longrightarrow A^{-} + B$

Gas/Surface reactions (heterogeneous)

Ion neutralization	$e + A^{+} + \text{srfc} \longrightarrow A + \text{srfc}$
Association	$H + H + \text{srfc} \longrightarrow H_2 + \text{srfc}$
Secondary emission	$A^{+} + \text{srfc} \longrightarrow e + A + \text{srfc}$
Sputtering	$A^{+} + \text{srfc} \longrightarrow [B] + \text{srfc}$
Deposition	$A(g) + B(s) \longrightarrow AB(s)$
Etching	$A(g) + B(s) \longrightarrow AB(g)$

Transport of Species to Surfaces

Diffusion	Neutral flux	$= -D_A \nabla n_A$
Ion flux across sheath	Ion flux	$= n^{+} u_{Bohm}$

Plasma

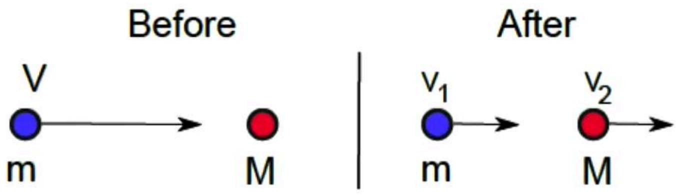
And finally, very useful applications are concerning deposition, where a gaseous atom 'A' reacts with a surface species 'B' and forms a solid surface deposition. The opposite process is etching, where a gaseous atom 'A' reacts with a surface atom 'B', and A and B both leave as a gas and are pumped away. The transport of species to surfaces is guaranteed by diffusion, by neutral flux, which is Fick's law or for ions, it's the Bohm criterion which we will show in modules 4 and 5.

Notes

Summary

4m 23s

Elastic collisions



Conclusion:

Electrons do not efficiently heat the gas.

Ions thermalize efficiently with the gas and the walls.

Plasma

Now we will consider elastic collisions. That means where only kinetic energy is exchanged. Consider this case of billiard ball collisions, where a ball of speed 'V' strikes a ball which is at rest, and afterwards they move off with their separate velocities. We consider conservation of momentum and conservation of energy, and simple Newtonian physics shows that the maximum fraction of energy transferred to Mass 'M' (big 'M') is this expression here. We can simplify this for the case of electrons. For an electron striking an atom, *m* is much smaller than *M*, and therefore this fraction of energy transferred is very much less than 1. In contrast to ions, where, for an ion striking an atom, the masses are almost exactly the same, and therefore the fraction of energy transferred is almost 1. This has important implications for plasma physics because it means electrons do not efficiently heat the gas, that is, the electrons do *not* transfer much of their energy to neutral atoms, whereas in contrast, ions thermalize efficiently with a gas and with collisions with a wall.

Notes

Summary

5m 07s

Power balance

Electrons gain energy from the electric field E and transfer it to the gas.

- The average power gain per electron = Electric force × electron drift speed

$$= Ee \cdot u = Ee \cdot \mu_e E = Ee \cdot \frac{e}{m_e \nu_m} E = \frac{e^2 E^2}{m_e \nu_m}.$$

For an electron temperature T_e and gas temperature T_{gas}
the average energy loss per electron collision = $\frac{3}{2}\delta e\left(T_e - T_{gas}\right)$.

- The average power loss per electron = $\frac{3}{2}\delta e\left(T_e - T_{gas}\right)\nu_m$.

- In steady state: $\left(T_e - T_{gas}\right) = \frac{2eE^2}{3\delta m_e \nu_m{}^2} \propto \left(\frac{E}{p}\right)^2 \propto \left(\frac{1}{\text{pressure}}\right)^2$

Plasma

Let's put this discussion on a more formal footing. In a plasma, the electrons gain energy from the electric field, and they transfer this energy to the gas, The average power gain per electron is the force on the electron times the electron drift speed, which is the electric field times the electron charge times the drift speed. Both of these are negative and cancel out to be a positive value. The electron drift speed is the electron mobility times the electric field. And the electron mobility is the electronic charge divided by electron mass times the collision frequency of electrons and neutrals. For an electron temperature Te and gas temperature Tgas, the average energy loss per electron collision is the energy difference, which is the electron charge times the temperatures in electron volts, times this delta which is the fraction of energy transfer we saw in the previous slides. Therefore the average power loss per electron is the average energy loss times the number of collisions per second. Therefore in steady state, we have a simple expression for the difference in gas electron temperature and gas temperature which defines as 1/pressure squared.

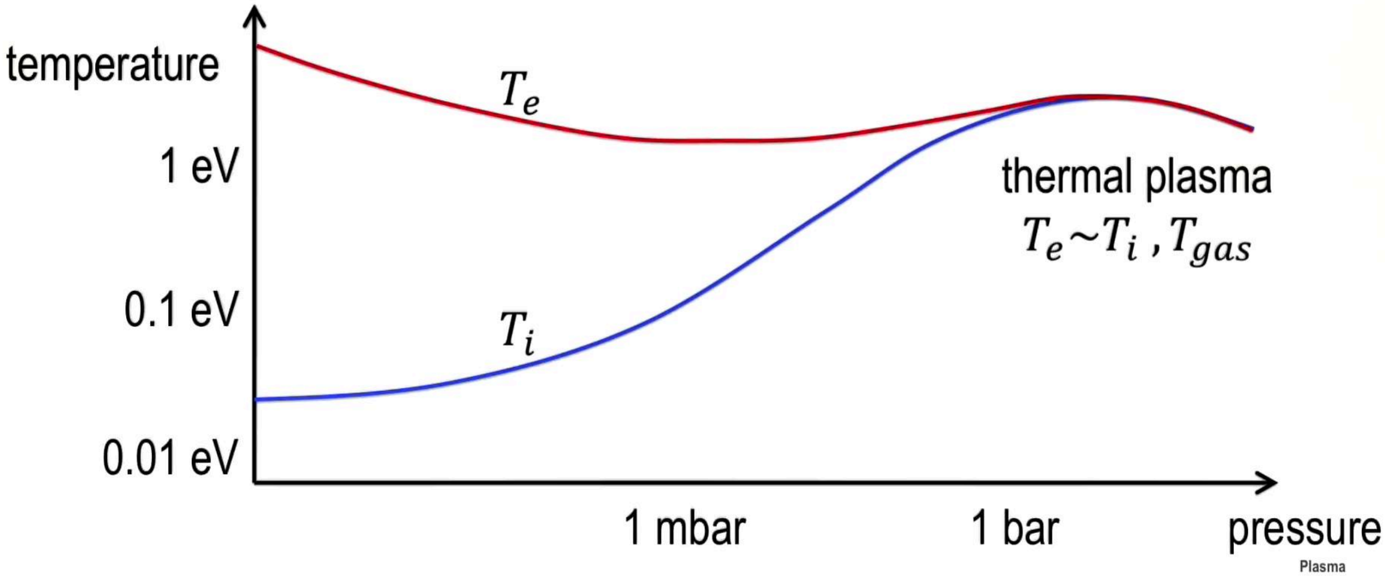
Notes

Summary

6m 31s

Low pressure, non-equilibrium plasma

- In steady state: $\left(T_e - T_{gas}\right) = \frac{2eE^2}{3\delta m_e \nu_m{}^2} \propto \left(\frac{E}{p}\right)^2 \propto \left(\frac{1}{\text{pressure}}\right)^2$



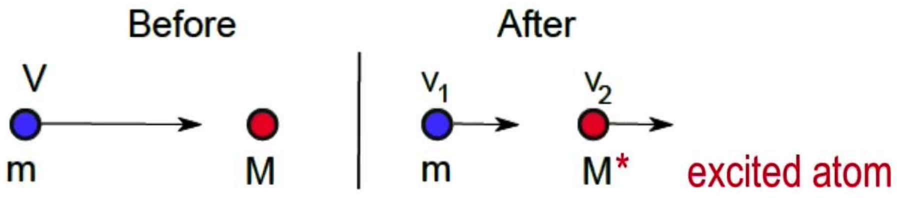
So this is a reminder of the previous expression. Now we find that in low pressures, the difference in temperatures can become very high. And therefore we have a non-equilibrium plasma, where the electron temperature can be much higher than the ion temperature at low pressures of the order of 1 millibar. At higher pressures and between conducting electrodes, this will lead to a thermal plasma where the temperatures are almost all equal. But at low pressures, the ion temperature is somewhere similar to the room temperature and the electrons have a few electron volts.

Notes

Summary

7m 58s

Inelastic collisions



Conservation of momentum & conservation of energy including internal energy of M :

The maximum fraction of internal energy transferred is $\frac{M}{m+M} \sim 100\%$ for electrons.

The simultaneous fraction of kinetic energy transferred is $\frac{mM}{(m+M)^2} \ll 1$ for electrons.

High energy electrons can modify chemical bonds without heating the gas

Plasma

Now you might ask the question, What are the use of electrons if they only transfer a small amount of their energy to the gas? Well let's consider a different situation where the electron billiard ball hits an atomic mass at rest, but afterwards this time, the atomic particle, or the molecule can be considered to be excited. That is, there is some internal energy gain by a target. We repeat conservation of momentum and conservation of energy, but this time, including the internal energy of the atom 'M', and now we find that the maximum fraction of internal energy transferred is almost 100% for electrons. That is, the electrons are capable of giving up almost all of their energy to the target molecule. At the same time, the electrons simultaneously give only a very small fraction of their kinetic energy to the gas. This means, in conclusion, that high energy electrons can modify chemical bonds in molecules without heating the gas.

Notes

Summary

8m 36s

Key to industrial plasma processing

In low temperature, non-equilibrium plasmas...
(2 eV ~ 23'000 K) $(T_e \gg T_{gas})$

High temperature plasma chemistry
on low temperature substrates

glass, plastics, people...

Plasma

This is then the key to industrial plasma processing. In low temperature, non-equilibrium plasmas -- and by the way, by 'low temperature,' I mean only a few electron volts, which is much colder than fusion plasmas -- but nevertheless, don't forget, that two electron volts is still 23,000 Kelvin. Non-equilibrium plasmas means the electron temperature is much higher than the gas temperature. And the key to industrial plasma processing is that we can do high temperature plasma chemistry on low temperature substrates. When I say 'low temperature substrates,' this can mean, for example, glass, plastics, or even people.

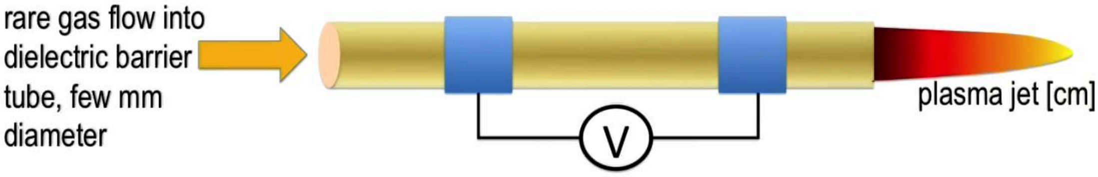
Notes

Summary

9m 54s

Plasmas in medicine

Example tool: Low temperature DBD plasma jet in air



Sterilization; treatment of skin, wounds, cancer, teeth, etc.

Plasma

Let's look at one example of an application in medicine. We will consider a low temperature dielectric barrier discharge jet in air, where we have a rare gas flowing into a dielectric tube, which could be glass. This glass separates the gas from the conducting electrodes which have an alternating voltage across them. This creates a plasma in the tube and a plasma jet emanating from the tube. This plasma jet could be used for sterilization, for example, for killing bacteria. It could also be used to treat skin, wounds, cancer, teeth, etc.

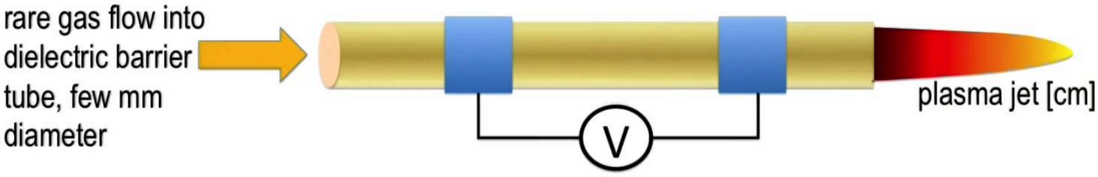
Notes

Summary

10m 42s

Plasmas in medicine

Example tool: Low temperature DBD plasma jet in air



Sterilization; treatment of skin, wounds, cancer, teeth, etc.

Plasma/medical mechanisms are not fully understood :
Chemical species (reactive oxygen and nitrogen radicals),
photons (UV), electric fields, electrical charges (electrons and ions) } synergies?

Plasma physics + biochemistry is complex, but rapid progress in research

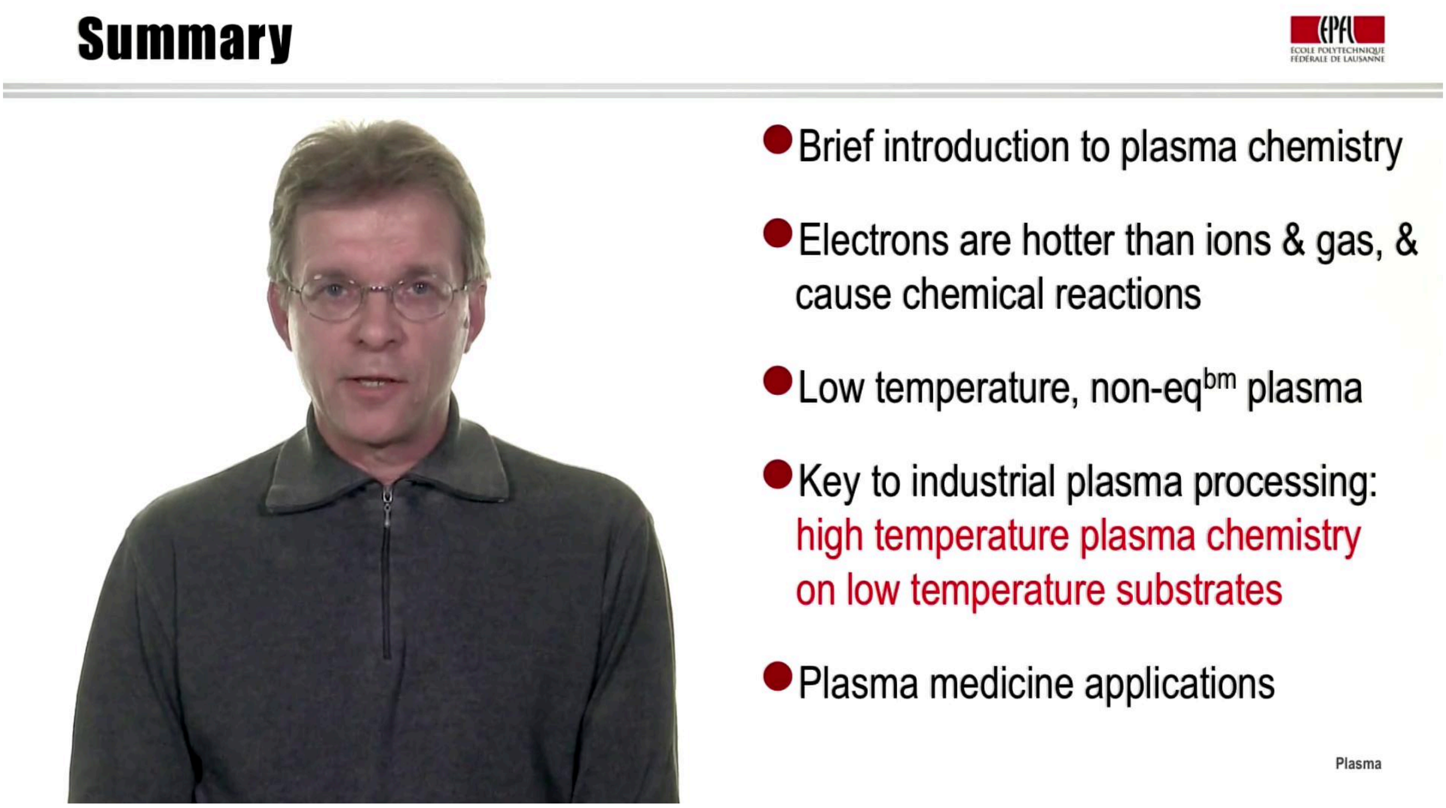
Plasma

Now the plasma medical mechanisms are not fully understood, but the plasma creates chemical species such as reactive oxygen and nitrogen radicals. The plasma also produces photons, for example ultraviolet photons. The plasma has electric fields, and it also has electrical charges in the form of electrons and ions. All of these four types of effects could play a role, and maybe even synergy between them. Now plasma physics and biochemistry is certainly a complex subject but there's been very rapid progress in the last decade.

Notes

Summary

11m 24s



To summarize this introductory module, we had a brief introduction to plasma chemistry, we saw that electrons are hotter than the ions and the gas. We saw that this gave a low temperature, non-equilibrium plasma, and the key to industrial plasma processing, which is that we have high temperature plasma chemistry on low temperature substrates. We finished with a brief application to plasma medicine.

Notes

Summary

12m 06s