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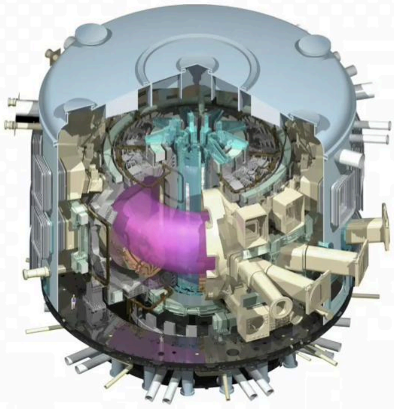
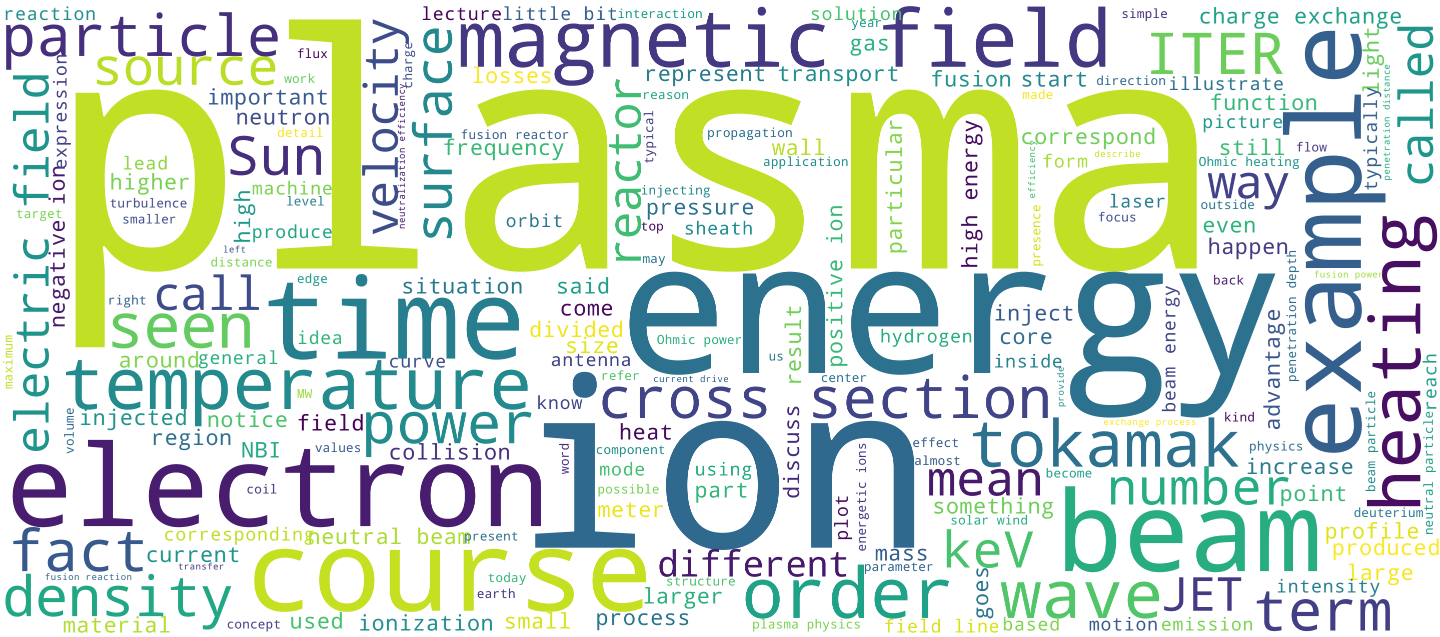


Plasma heating – ohmic and by neutral beams

Plasma Physics and Application to Fusion Energy, Astrophysics and Industry

Lecture 7f

Ambrogio Fasoli



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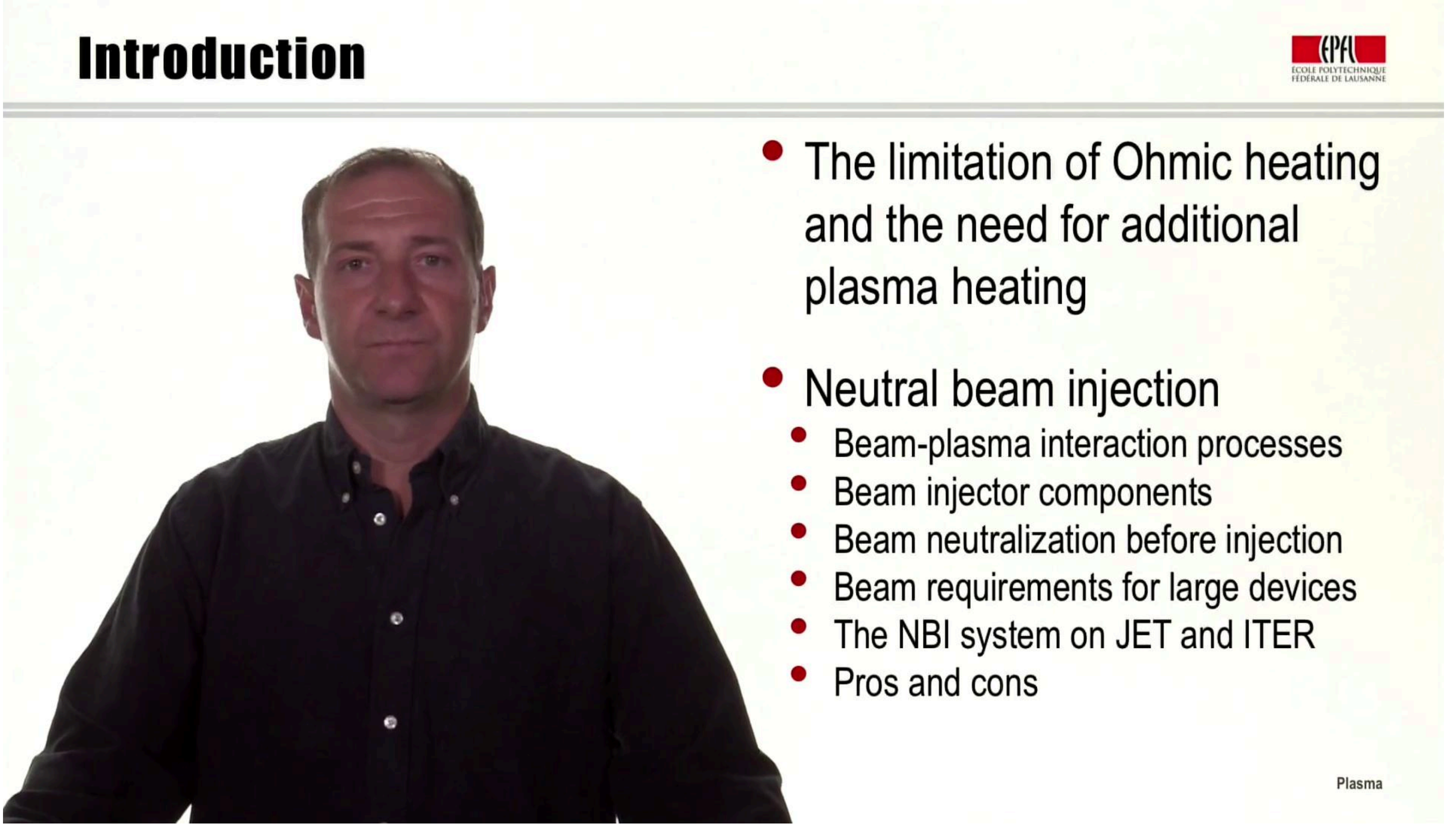
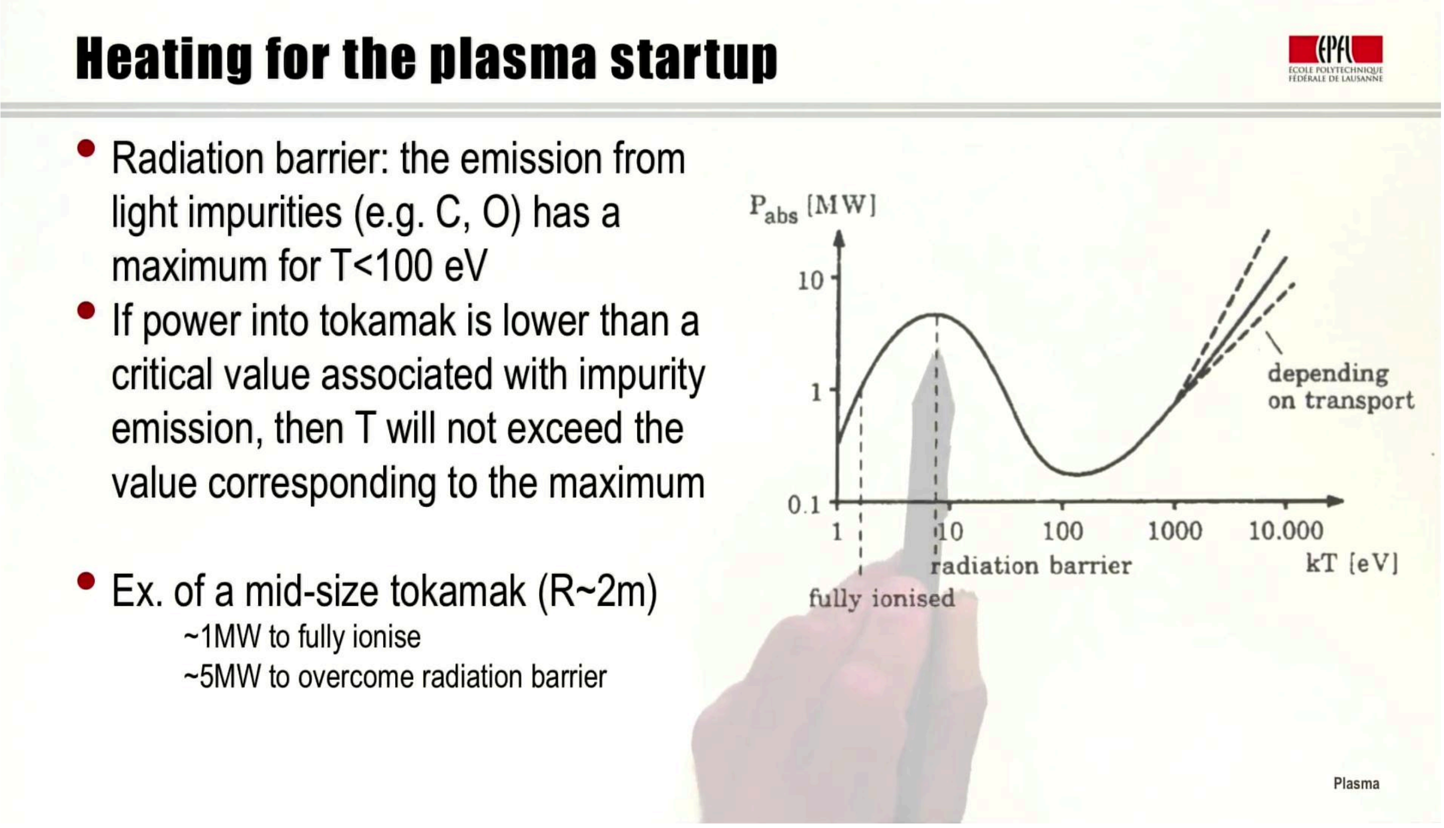


Welcome to the course on Plasma Physics and Applications. Today we will discuss the heating of the plasma to thermonuclear temperatures, that is temperatures that are needed for a fusion reactor to work. We will start by discussing Ohmic heating, that is the heating of the plasma by an electrical current, and the limitations of that method. Therefore we will illustrate the need for additional plasma heating, additional meaning in addition to the Ohmic heating method. We will then focus on the first of the systems that they will consider for a reactor: the neutral beam injection. We will explore the processes that take place as the beam is injected into the plasma, the components that are needed for the beam-injection system, the neutralization of the beam before its injection to the tokamak plasma, and the requirements that the beam needs to satisfy in order to be useable on large devices, for example on the ITER Tokamak. We will illustrate the example of the NBI system that is operational on JET, and we'll say a few words about the design of the NBI system for ITER. Finally, we'll discuss the advantages and disadvantages of the NBI heating method for a reactor in the future.

Notes

Summary

0m 05s



First I'd like to remind ourselves that we need power to initiate the plasma discharge, that is to ionize the gas that we inject into the tokamak. That's fairly intuitive. On the other hand, what may be a little bit less intuitive, is that we also need a certain power level to overcome what's called a *radiation barrier*. The radiation barrier comes about because the emission from light impurities that are present in our gas, and then in the plasma, has a maximum for temperatures that are typically of a few tens of eV, typically below 100 eV. And if the power that we inject into the tokamak is lower than a certain critical value that is associated with this impurity emission, then the temperature will never be able to exceed this value that corresponds to the maximum of the emission of the light by impurities. Typically, for a midsize tokamak, we have taken the example here of, say, a two-meter major radius tokamak, you need something like a megawatt to fully ionize your gas, to make the plasma, and you need more than that, something like 4-5 MW to overcome this radiation barrier.

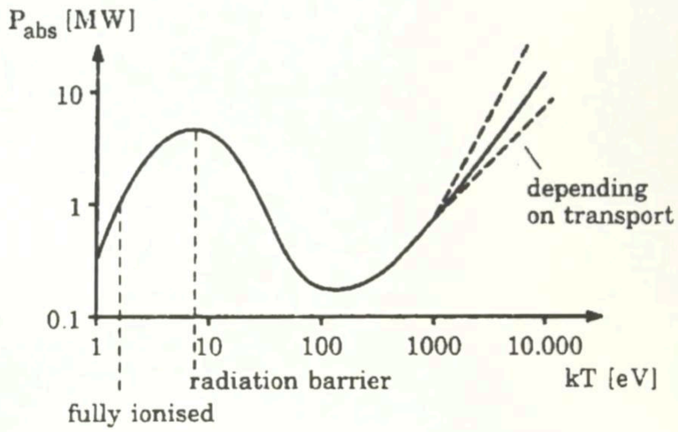
Notes

Summary

1m 24s

Heating for the plasma startup

- Radiation barrier: the emission from light impurities (e.g. C, O) has a maximum for T<100 eV
- If power into tokamak is lower than a critical value associated with impurity emission, then T will not exceed the value corresponding to the maximum
- Ex. of a mid-size tokamak (R~2m)
  ~1MW to fully ionise
  ~5MW to overcome radiation barrier



Plasma

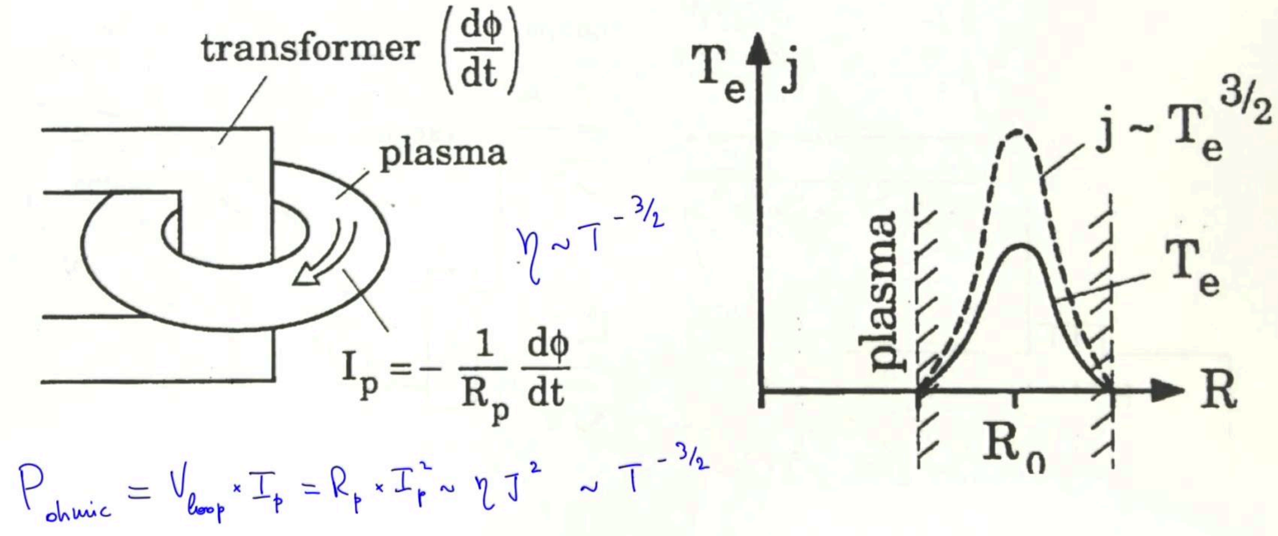
It's only after that level, once the radiation barrier is overcome, that we manage to keep increasing the temperature towards values that are of interest for thermonuclear reactions, and the efficiency and therefore the slope of the curve of the increase of temperature with the additional power injected into the plasma of course depends on the levels of transport the plasma has, and so on.

Notes

Summary

2m 44s

Ohmic heating



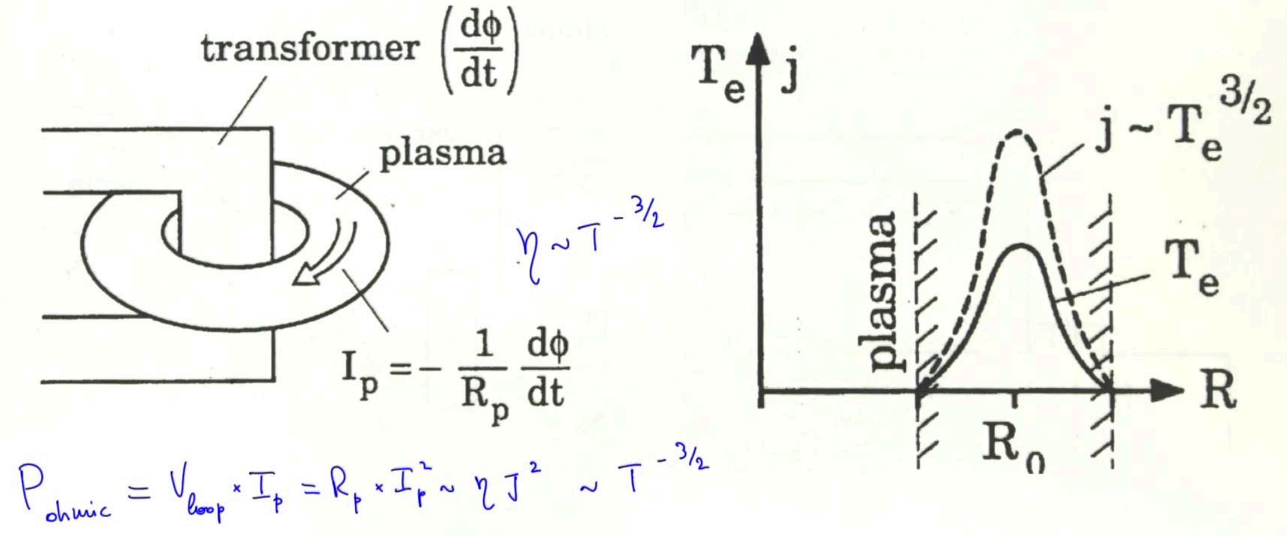
As you remember, the concept of tokamak is based not only on external fields that are produced by coils, mainly in the toroidal direction, but also by transformer action, that is by swinging the flux produced by the primary coil of the transformer, and therefore inducing an electromotive force in the plasma ring which therefore provides a drive for a current through the plasma. Now, as the resistivity, as we have learned in the first part of this course, is proportional to T^(-3/2), the profile of the current that will be driven into the plasma will be strictly related to the profile of the temperature of the plasma itself. So that's the first observation, but the second observation is even more important, and that is that the Ohmic power, let's call it Pohmic, that I can dissipate into the plasma, and in this case I'd like to heat the plasma by passing current through it. is obviously equal to the loop voltage that's generated by this transformer action, times the current that flows into the plasma, Ip. That's the resistance of the whole plasma, times the current, square, and that is proportional to the resistivity [η] times the current density square, so we will have a direct dependence on the resistivity, therefore it will have a dependence upon T^(-3/2).

Notes

Summary

3m 14s

Ohmic heating



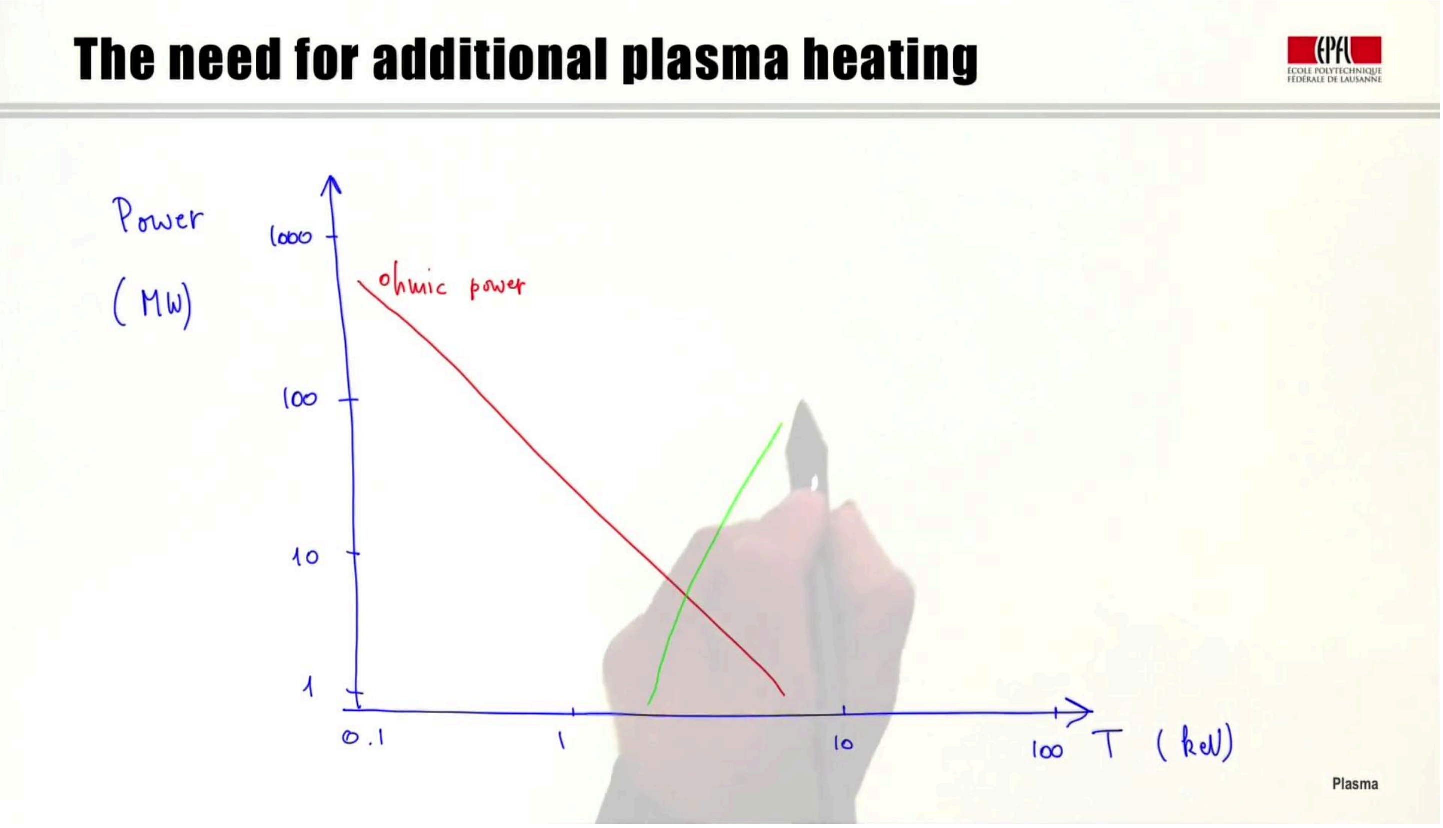
Plasma

So if on one hand this current is efficient in producing the poloidal field and needs to complete the magnetic field structure for trapping the plasma into the tokamak, this current is progressively more and more inefficient at heating the plasma as we increase its temperature.

Notes

Summary

4m 56s



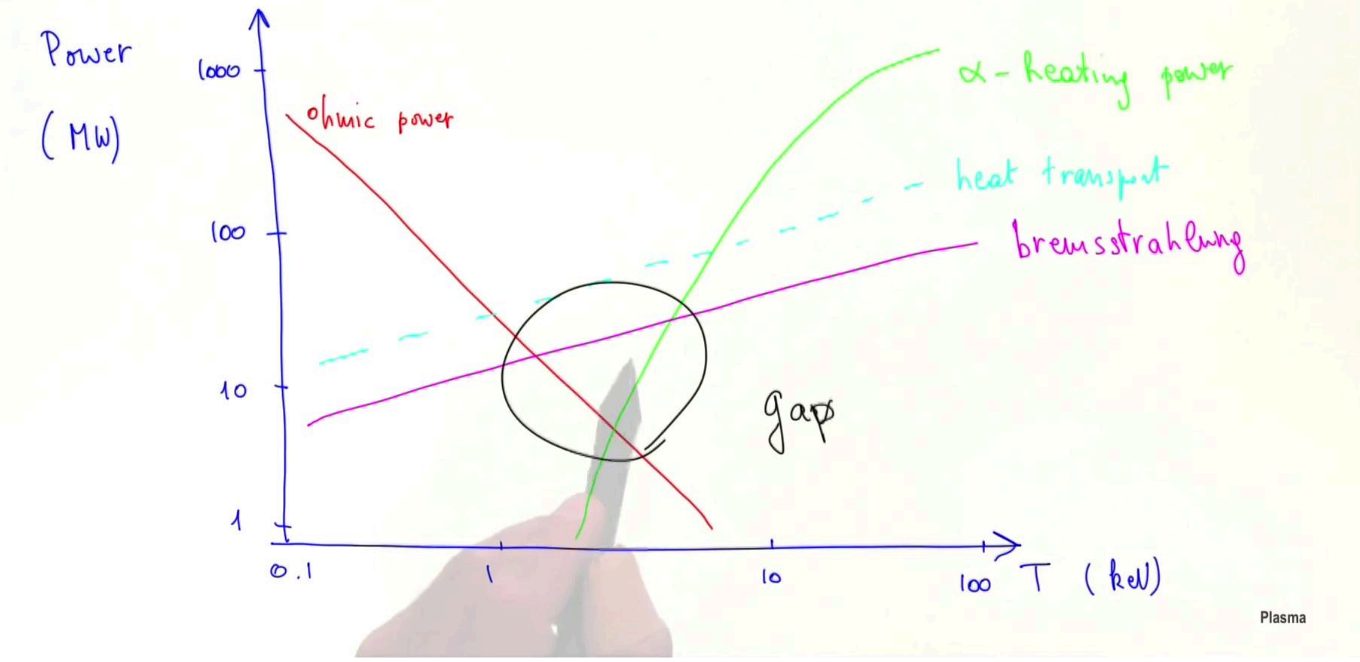
We can therefore discuss why we need, specifically, additional plasma heating. I like to illustrate that in a semi-quantitative way, in a plot in which I represent vertically the power corresponding to different channels in the plasma, say in MW. Say we take a logarithmic scale, say 1, 10, 100 and 1,000 MW, and I represent that as a function of the temperature, say in keV, of the plasma. So we have just learned that the Ohmic heating will go down with the power of temperature to the 3/2, so say it will take a curve of this kind. I can also represent the horizontal axis with a logarithmic scale. This is 10 keV, and then say all the way to the right we have 100 keV. So the Ohmic heating power goes down to a very low level before the plasma can reach the temperature of the order of 10keV. The example taken here, semiquantitatively, is an example of a -say- 1 meter major radius tokamak. So this is the Ohmic power, going down with the power of T, temperature. Now, in a reactor we will count at some point on the power provided by the heating due to the alpha particles that are issued by fusion reactions themselves, and that will be coming about when the plasma temperature will be larger than a few keV's so say it will be something like that.

Notes

Summary

5m 18s

The need for additional plasma heating



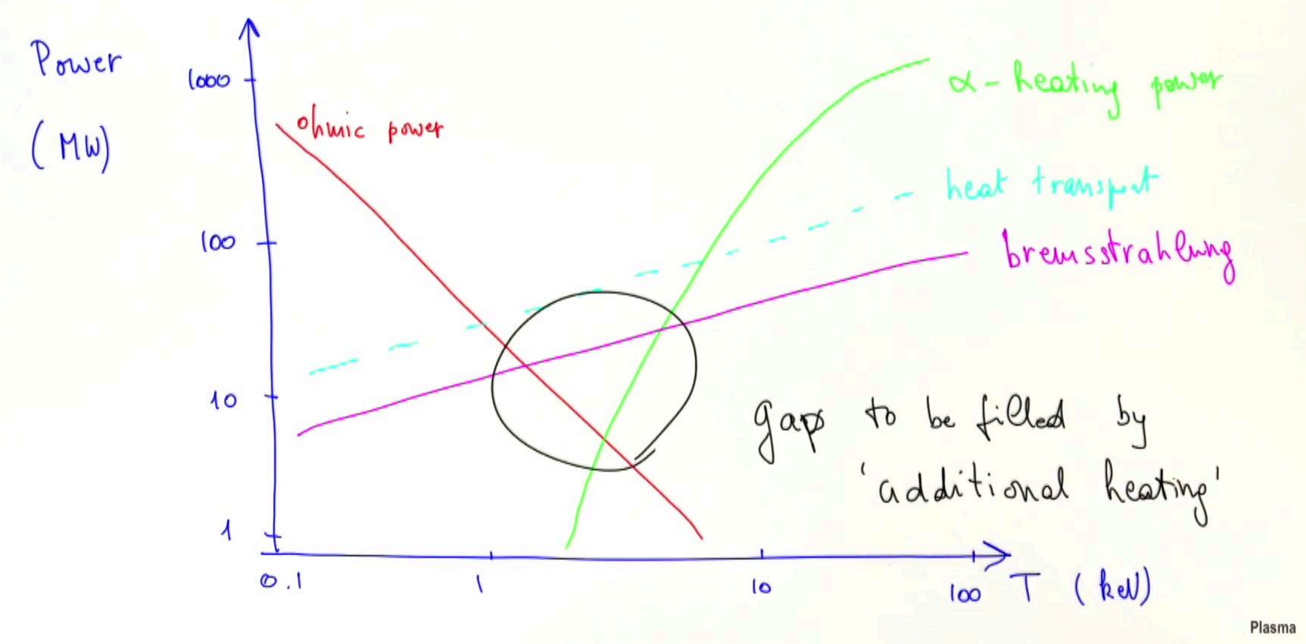
So this is the alpha heating power. And if we had no losses it would be no problem, because we would use the Ohmic power all the way to the point, which would be around a few KeV, where the alpha particle heating would take over. But, we of course do have losses. We have losses in the form of radiation, like bremsstrahlung, but also losses in the form of a convective and conduction transport of ion and electron heat, in particular, of ion heat. So let's put even the lowest possible loss power that we can have, that of bremsstrahlung, and in all the circumstances we can think about in practice, this bremsstrahlung level will be higher than the level at which the curve of Ohmic power crosses that of the alpha heating power. So even without invoking any transport from conduction and convection, which we actually know would dominate the bremsstrahlung, so I can even perhaps just trace it, something like that, just call it *heat transport*. Even if we reduce that to a minimum level, below bremsstrahlung level, which would be, in practice, very, very difficult to do, we will have a gap, here, that is a region where we will not be able to connect the Ohmic power to the alpha heating power.

Notes

Summary

7m 12s

The need for additional plasma heating



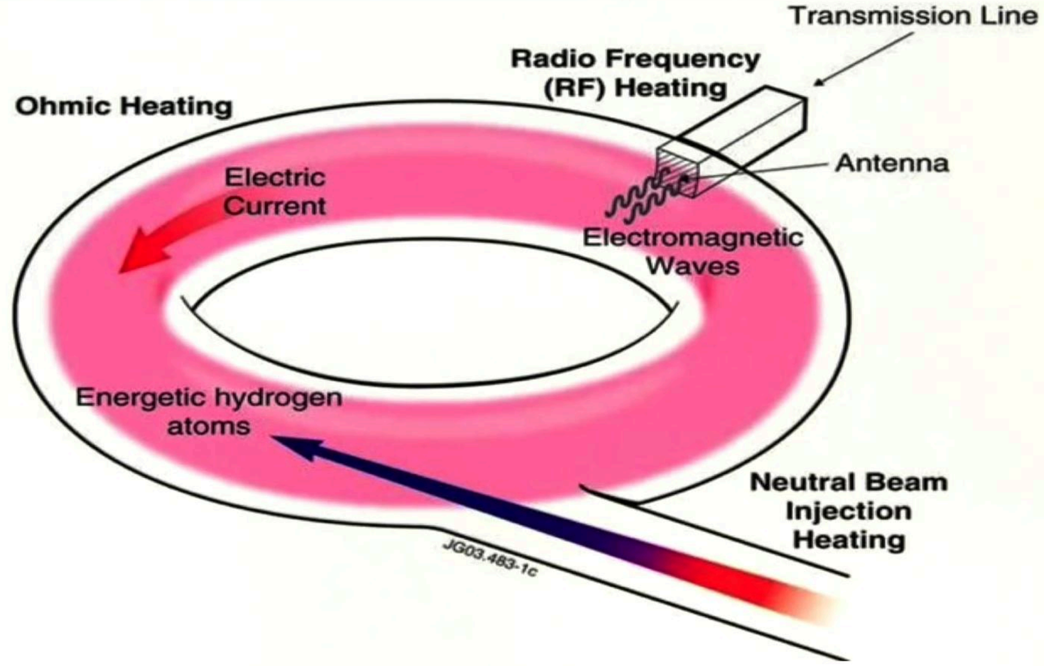
In other words, we have a shortfall of power in this region, which is in the region of a few keV of temperature where we need to do something, and do something means heating the plasma by other means than Ohmic power. So this gap needs to be filled by what we call *additional heating*.

Notes

Summary

8m 53s

Additional plasma heating

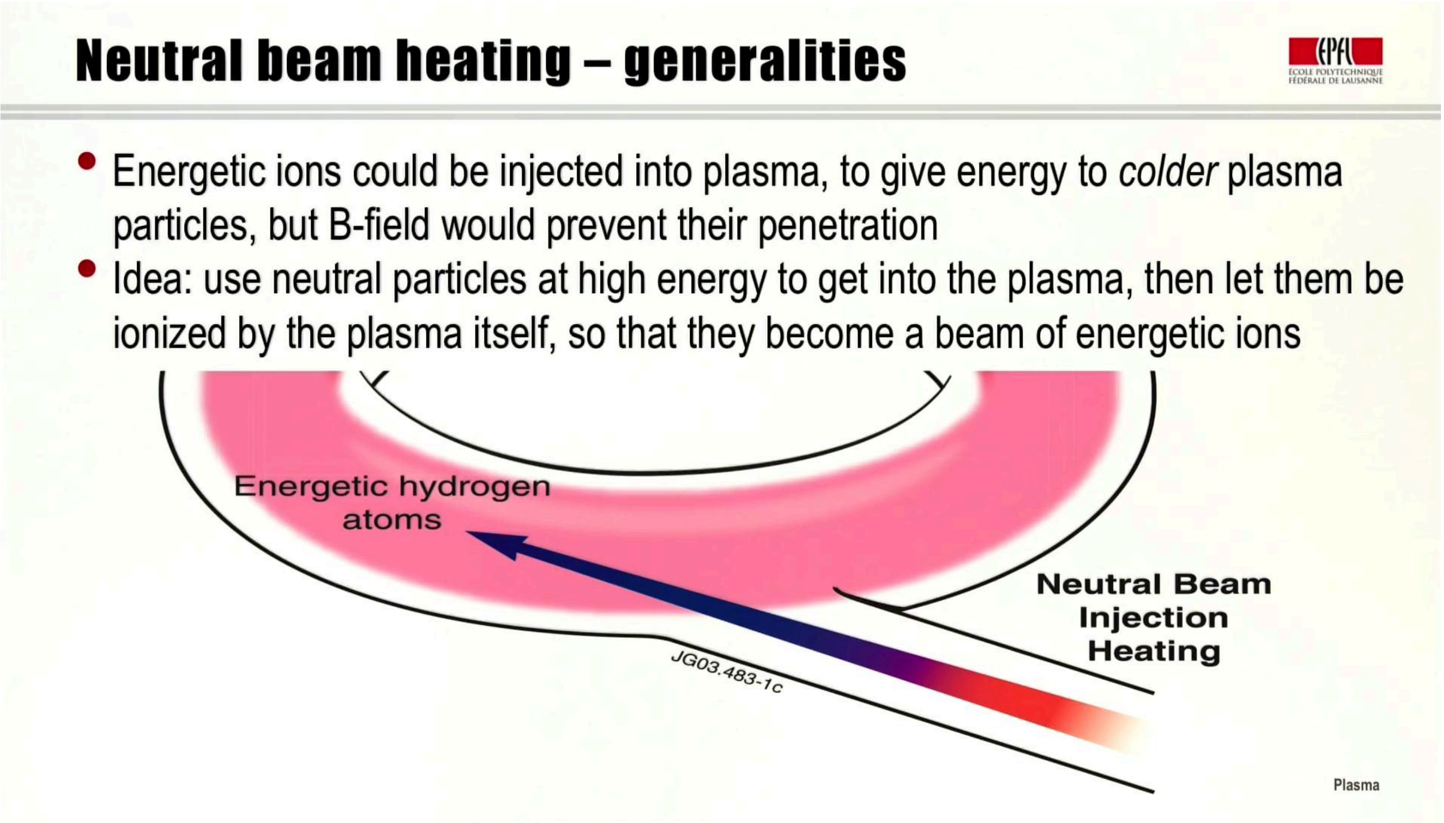


So let's briefly review what options do we have for heating the plasma, in addition to passing electric current through it, which is what we refer to as *Ohmic heating*. We may heat the plasma by injecting a beam, of very energetic neutral particles that will become ions, once they are entering the plasma. And these particles will transfer their energy and momentum by collisions to the plasma particles, and therefore will heat the plasma, or we can inject waves into the plasma. We have seen, in previous parts of this course that there are several possibilities for waves to exist in plasma, at different frequency ranges. We can inject waves that resonate, for example the electron species, that would be high frequency, or we can inject waves that resonate with the ion species, that would be lower frequency. And in both cases, we can transfer power from these waves, that we can inject using transmission lines and antennas that are close to the plasma to the plasma, therefore heating it to thermonuclear temperatures.

Notes

Summary

9m 17s

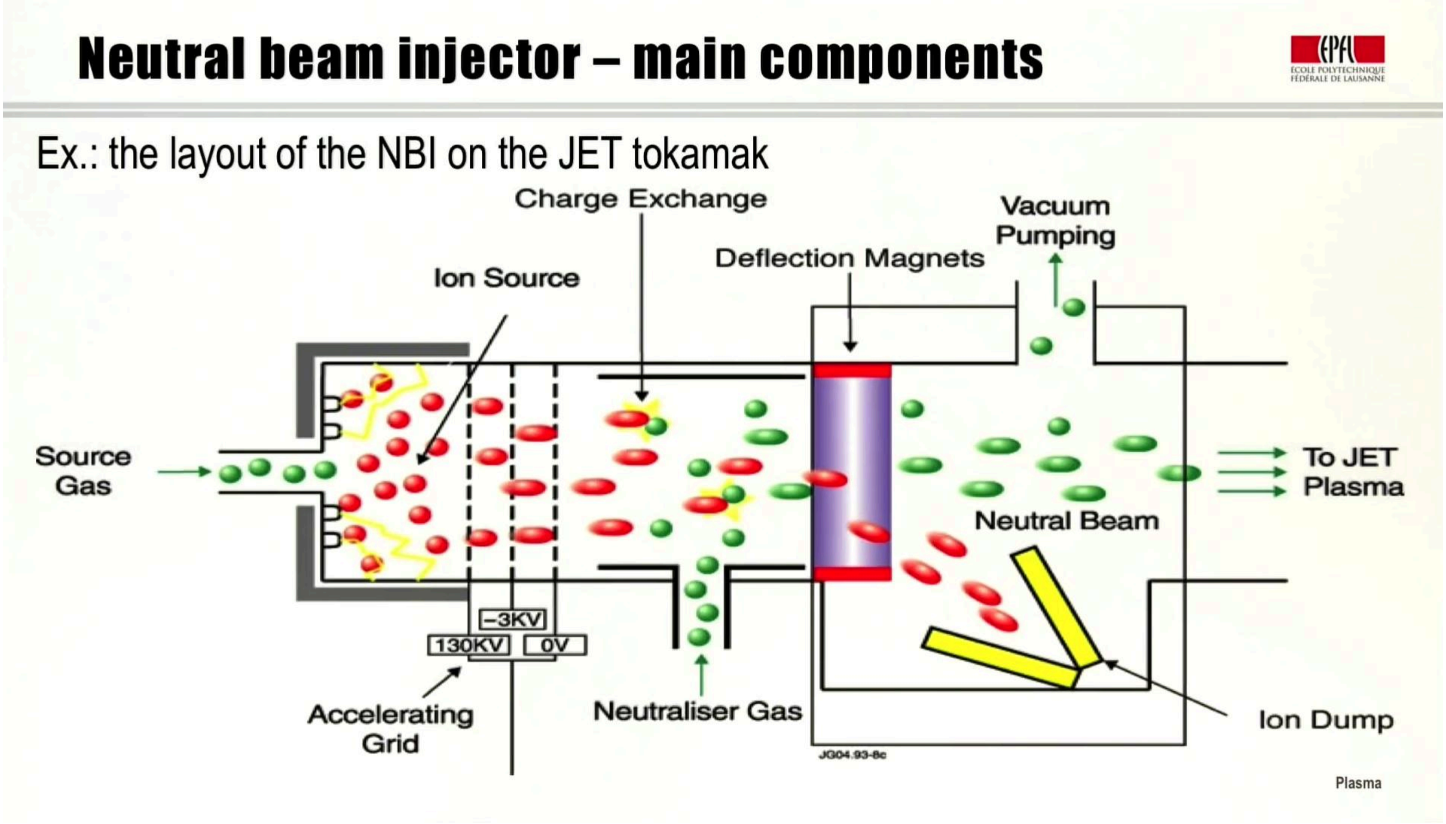


Today, as we said, we will focus on the first of these methods, that is the neutral beam heating. So the idea here is to inject, somehow, energetic ions into the plasma, that would give the energy to colder plasma particles. By energetic ions, we mean ions that don't belong to the thermal distribution of the plasma itself, so there should be much more energetic than the energy corresponding to the plasma temperature. But how can we inject a beam of ions into a very complicated magnetic field that we had actually prepared, and set up, in order to avoid the leaking of plasma out from our confinement volume. Such field will of course prevent the penetration of ions from outside as it prevents the escape of ions from inside. So here's the idea: we can use neutral particles at high energy to get into the plasma, because neutral particles of course don't feel the influence of the magnetic field that provides confinement. And then let them be ionized by the plasma itself. So once they are in the plasma, they progressively become a beam of energetic ions, which then, in turn, can transfer, by Coulomb collisions, their energy to the plasma, ions and electrons.

Notes

Summary

10m 26s



That's the idea of the neutral beam. What are the main components in a neutral beam? In order to illustrate them I've taken a very simplified, of course, layout of the neutral beam injector that we use on the JET tokamak. Let's run through the different elements here. We have, of course, a source of gas that's injected into the source of ions for the beam, in this example, and in the injector in the JET, the ions are positive ions that are created by an arc discharge. There are other options, in fact. For example, one can use rf waves to create the plasma from which we extract the ions for the injector. We'll discuss that option a little bit later. Then once we have a source of ions, we need to extract the ions and accelerate them. But it's actually relatively easy to accelerate ions, or charged particles in general, because they can be accelerated by a set of electrostatic grids that provide them with the energy corresponding to the potential difference that we apply to the grids. So now we have a beam of ions that are highly energetic. What we need to do is to neutralize them before they are injected into the tokamak system.

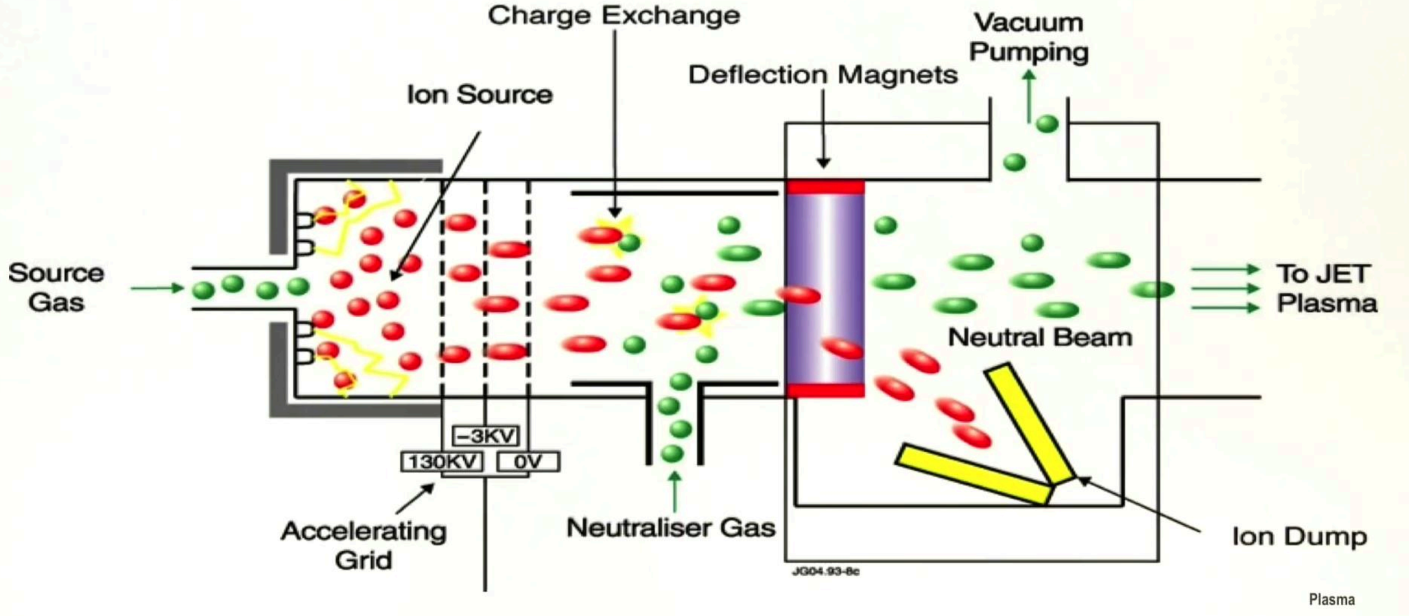
Notes

Summary

11m 47s

Neutral beam injector – main components

Ex.: the layout of the NBI on the JET tokamak



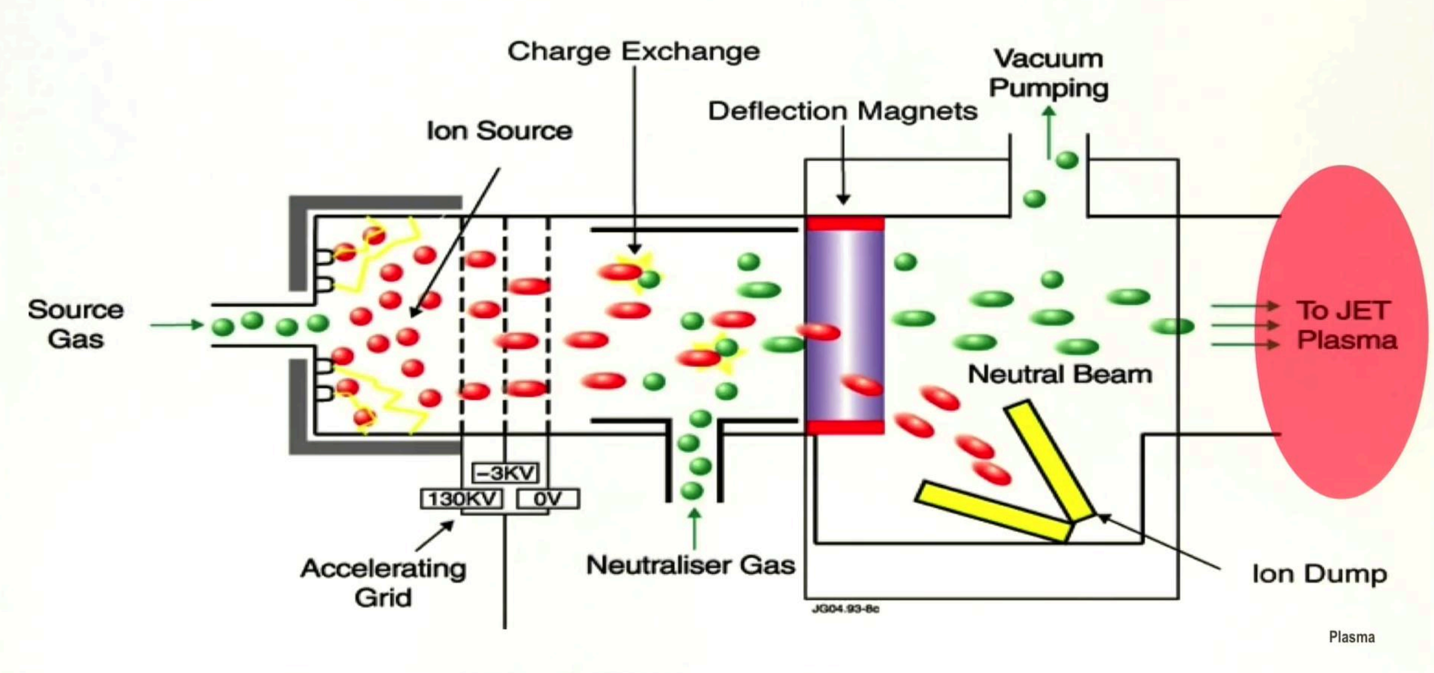
As we said, the ions will not be able to penetrate into the tokamak volume if they are still ions, that is if they are still charged. So we need a chamber that neutralizes them. We can inject a gas to do that, and attach an electron onto the ions, in this case, because we were starting with positive ions. Of course this process will not be 100% efficient, so what we need to do is to get rid of the ions that remain ions, by deflecting them using a magnet and by collecting them on an ion dump, which will need to be, of course, actively cooled, and then in the presence of a very high vacuum, pass this beam of particles that are still energetic, because they were accelerated once they were ions, but they are now neutral, to, finally, the plasma.

Notes

Summary

13m 12s

Processes occurring as beam penetrates in plasma

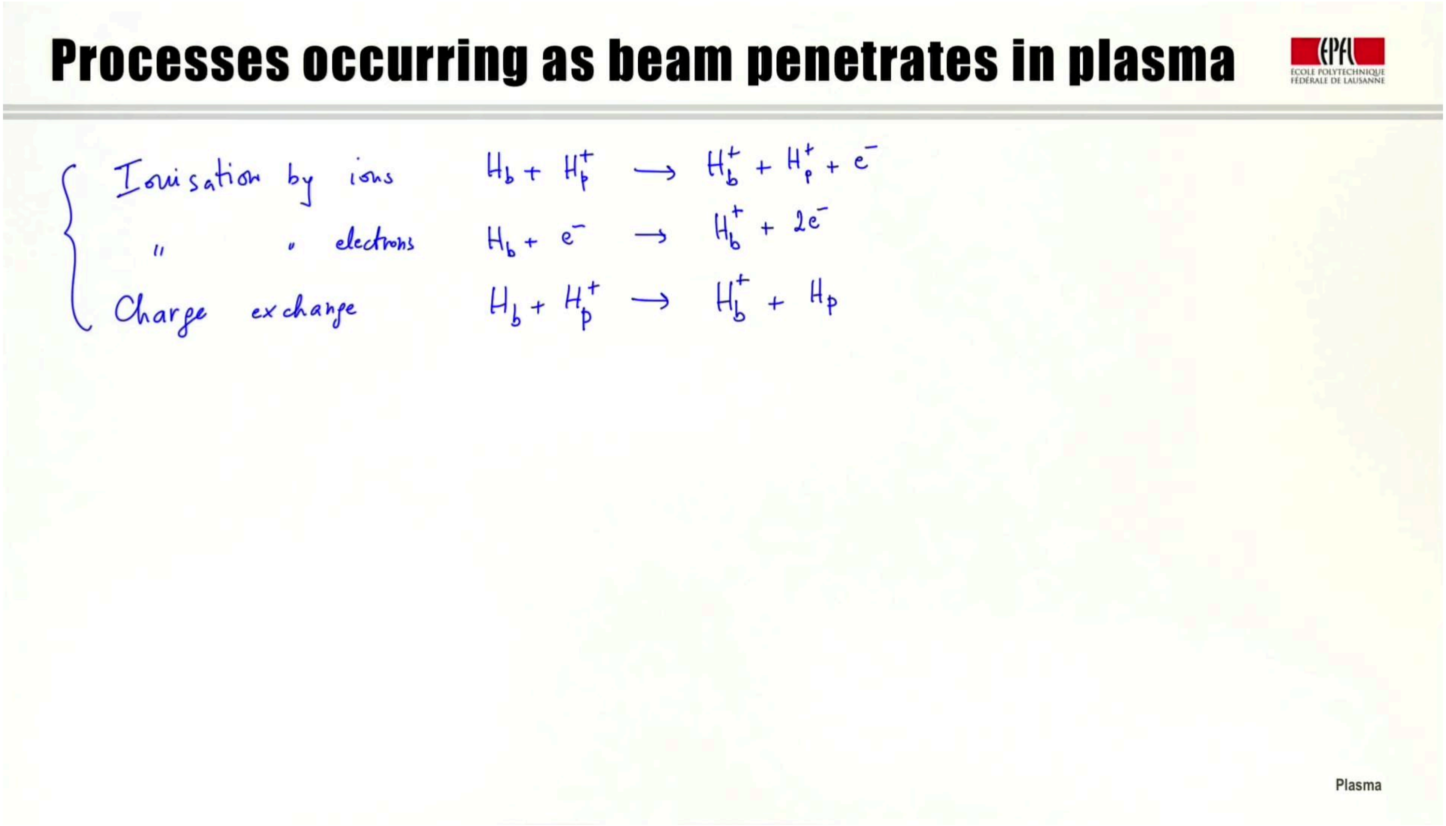


We focus now on what happens in the plasma once the neutral particles at high energy are injected into it.

Notes

Summary

14m 03s

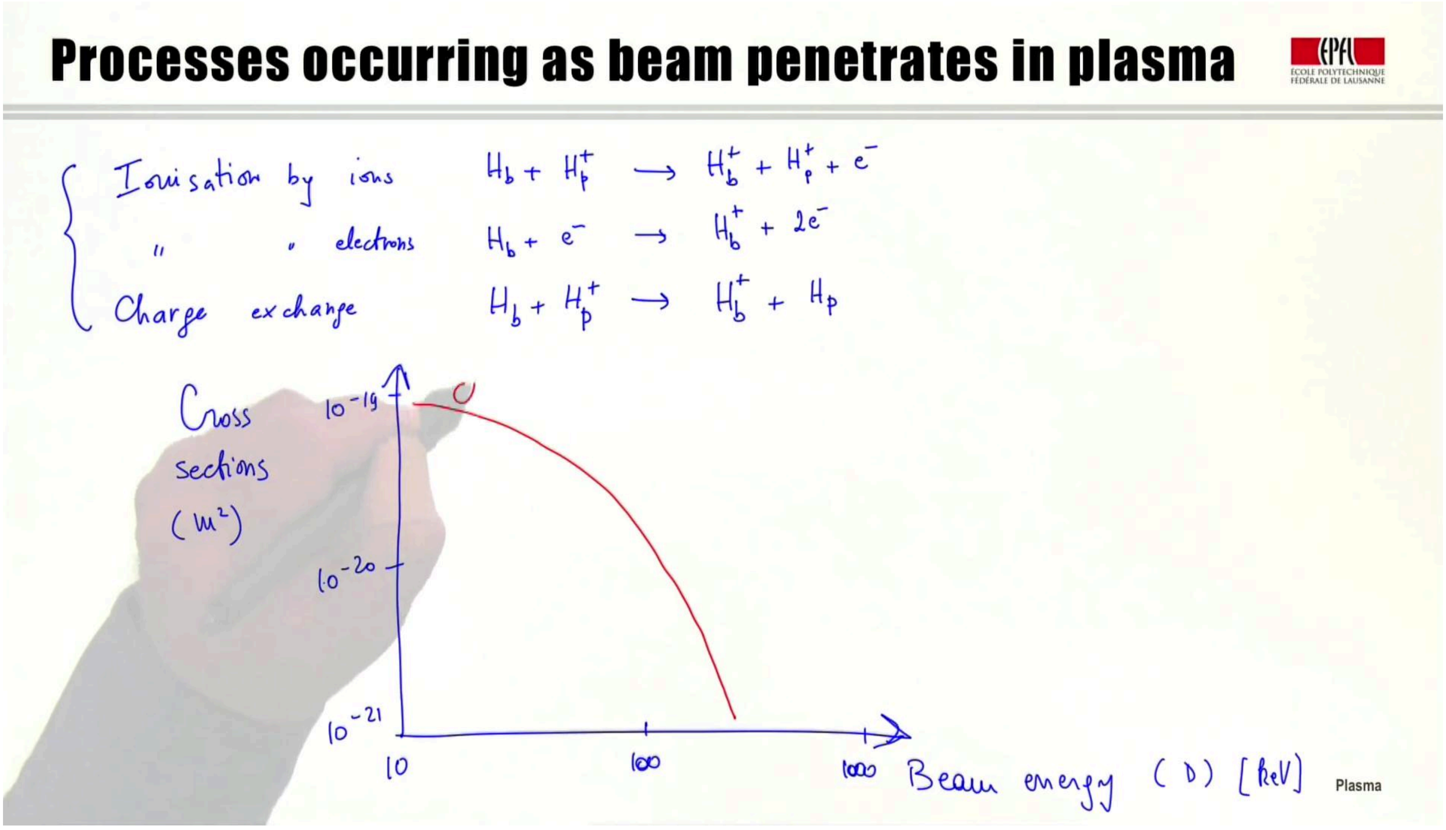


So we focus on the processes that occur as the beam arrives into the plasma. We have, essentially, three possible processes. First, we can have ionization by ions. I take the example of a hydrogen beam, so the notation is a little simpler. So I have the beam, hydrogen particle, that's a neutral, which encounters an ion, a positive ion in the plasma, and gets ionized. So of course there will be the creation of a positive ion in the beam, and of a free electron. We can also have ionization by electrons. I still have my beam particle, which in this case encounters an electron, and gets ionized by it, with, of course, the release of an additional electron, so we have two electrons plus an ionized beam particle. Or we can have a third process, which we call a *charge exchange*. So here there is no direct ionization, but there is an exchange of charge between the neutral beam particle and the plasma ion, so that I have now an ionized neutral beam particle, and a neutral particle that was that was an ion in the plasma. So of course these are binary processes that we can treat as collisional processes, that is, represent them in terms of their effective cross section.

Notes

Summary

14m 13s

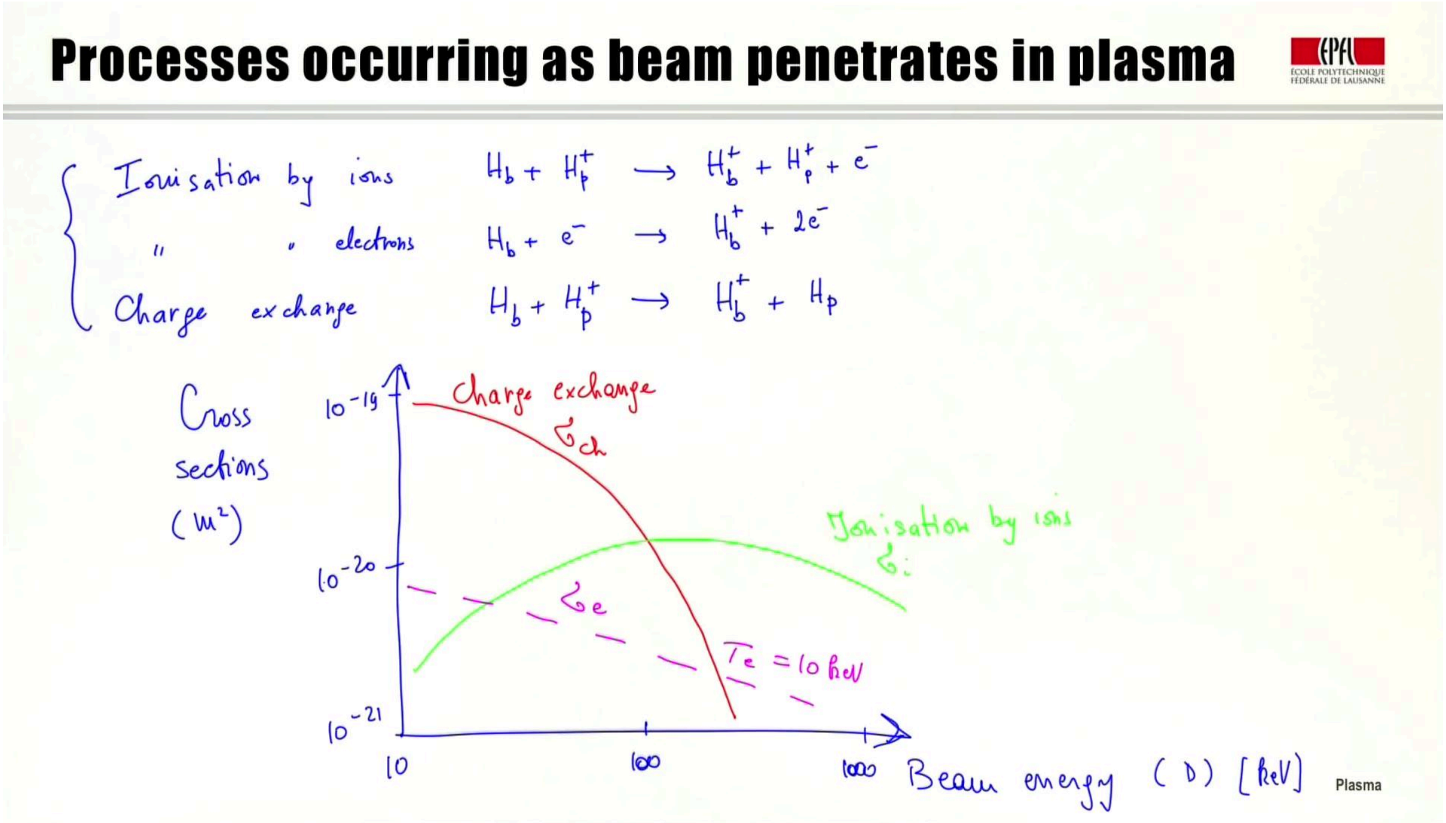


And the effective cross section will tell us which process is the most likely to occur, depending on the parameters, for example, depending on the energy of the beam. I noticed that the charge exchange process will also lead to the emission of light, and the emission of light will contain the signatures of the properties of the ion motion in the plasma, namely: ordered flows, in terms of the Doppler shift of the line emission, or the thermal motion, in terms of the Doppler broadening of the line emission. So the charge exchange process is used also to diagnose both ion velocities and ion temperatures. Let's represent qualitatively the cross sections for the different processes. And I do that as a function of the beam energy, and let's just take as a reference a deuterium beam. I consider a scale in keV, say 10, 100 and 1,000. That is one MeV in a logarithmic scale, and on the vertical scale I considered the cross section in square meters. Again, on the log scale, 10^{-21}, 10^{-20} half way, and 10^{-19} at the top. So let's start with the process that has the largest cross section at low energy, and that is the charge exchange process. And qualitatively it has a cross section that goes down with energy in this way.

Notes

Summary

15m 54s

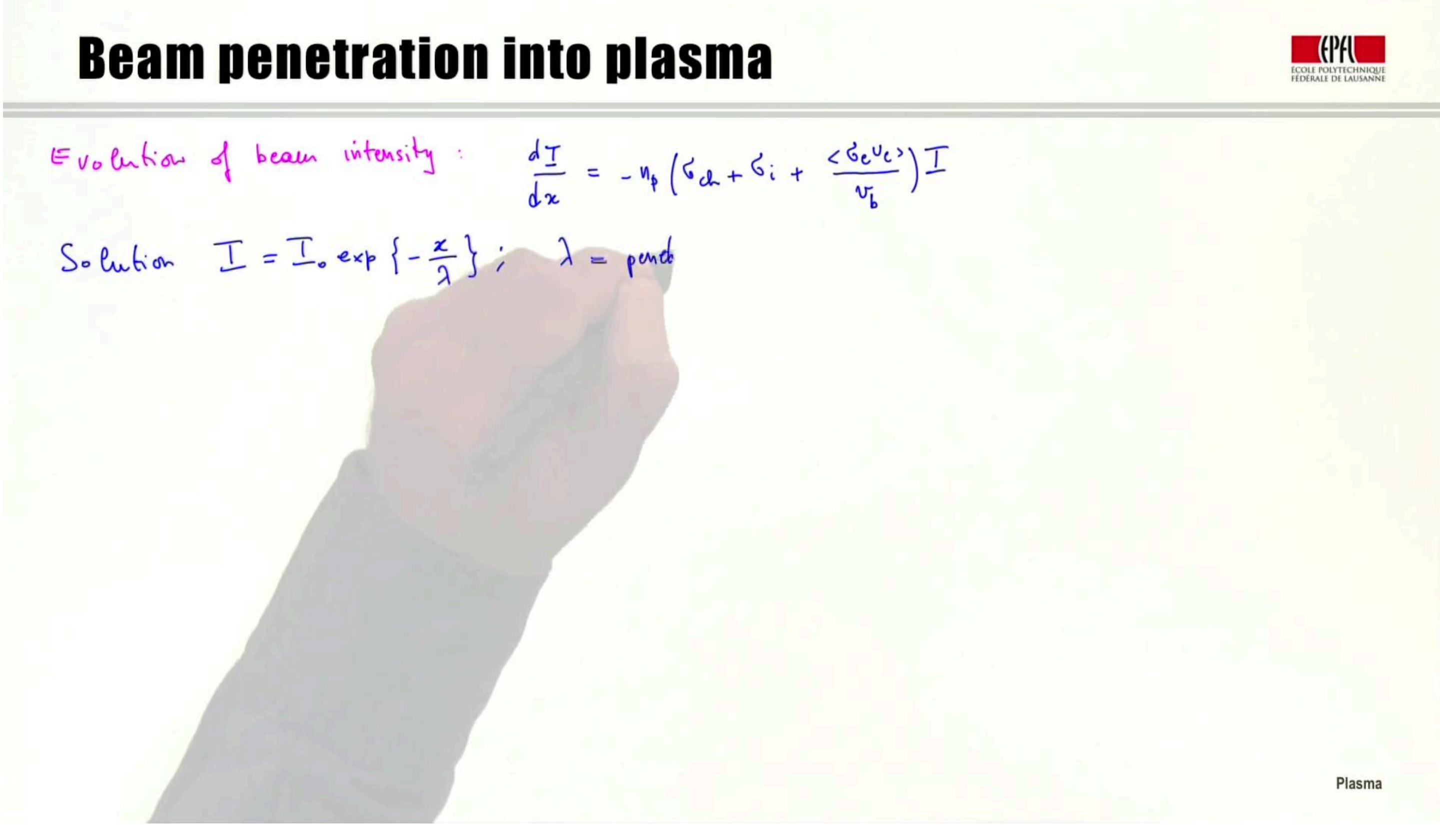


So this is a charge exchange process that we represent with a cross section called σch (sigma_ch). At high energy, we have the ionization by ions that dominate. And again, in a qualitative way, I draw the cross section for that, in green. Let's call that σi. What about the ionization by electrons? That, in general, is actually smaller, or has a smaller cross section than the other two. And of course its value will depend on the electron temperature. For example, for the case of 10 keV, say I take the temperature for the electron of 10 keV, and this is the cross section for electron ionization, or better, for ionization of the beam by electrons. So we see that at low energies the process is dominated by charge exchange, whereas at high energy, the dominant process is ionization by ions.

Notes

Summary

17m 43s

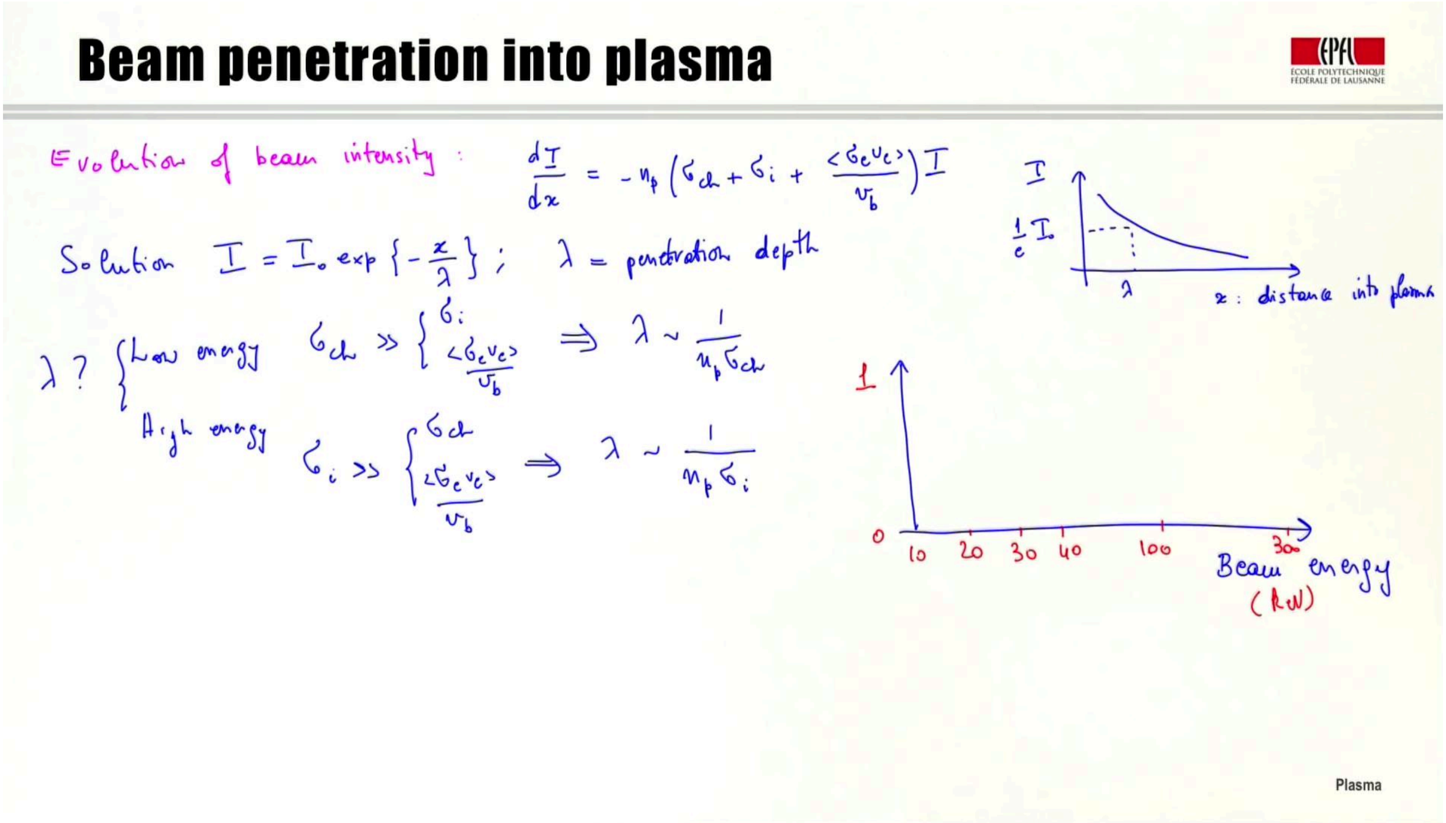


Now we are ready to represent what happens as the beam penetrates into the plasma. We know what processes are happening. We even know which ones are dominating, depending on the energy. So what's the evolution of the beam intensity? I can write the equation that describes that as the variation of the intensity of the beam with distance -- and I write that in a one-dimensional way, to keep things simple-- is equal to minus the density of the targets, that is the density of the plasma times the cross section for charge exchange, [plus] cross section for ionization by ions, and the term that corresponds to the ionization by electrons. Let's write that, that's <σe ve>, integrated over the plasma distribution divided by the beam velocity, of course, times the intensity. I just notice that for the third term it's different, because the dominant velocity in the collisional process is between the beam ions and the electrons is actually that of the electrons. What is the solution to this kind of equation is, of course, an exponential. So let's say I_0 is the initial intensity, and the exponential is a function of the penetration distance into the plasma, and is parameterized by a parameter λ, that we can call the *penetration depth*.

Notes

Summary

19m 01s

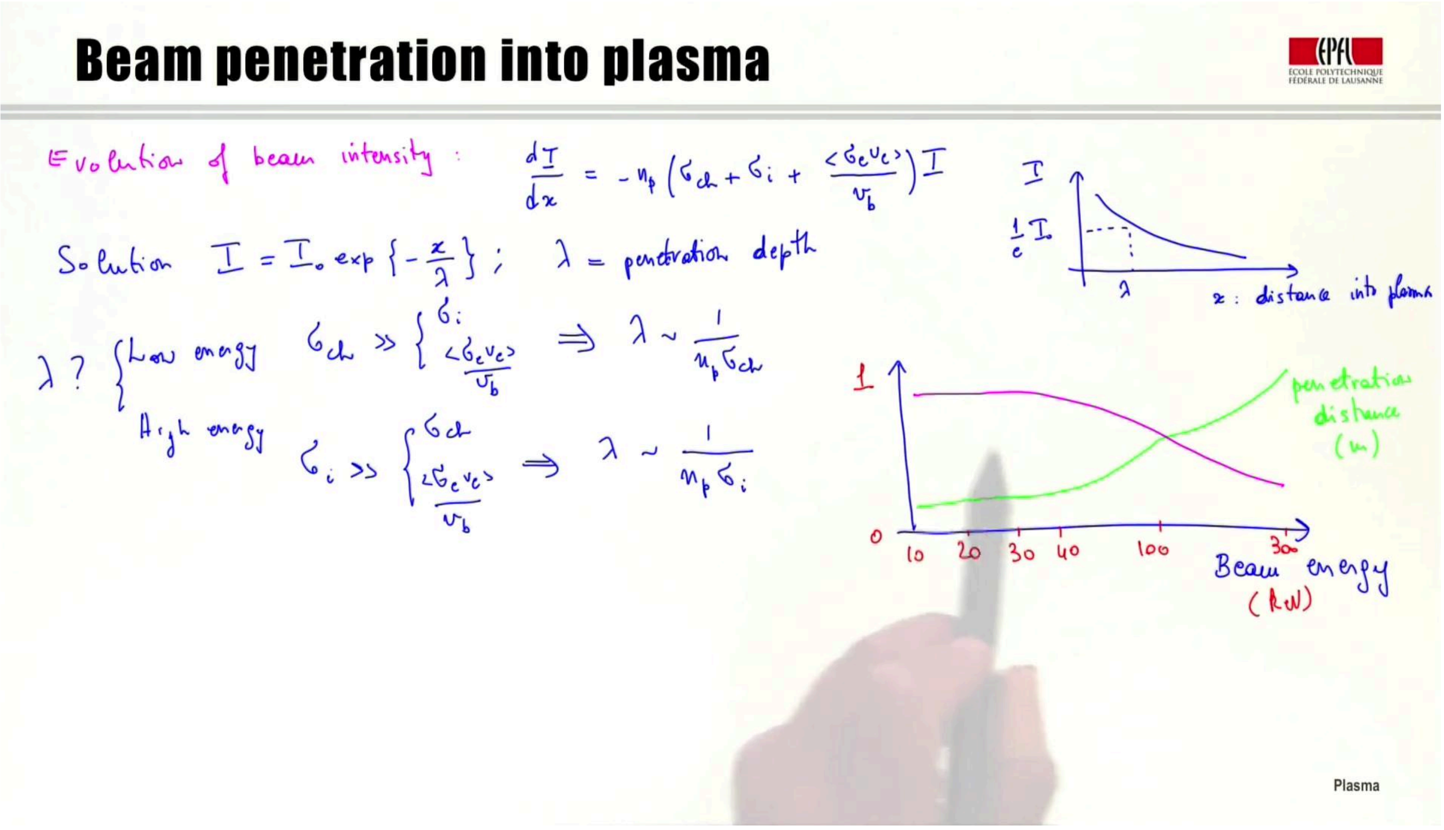


So what we have is something like that. As we say, x is the distance into the plasma, the intensity will go down exponentially as we go into the plasma. There's a point at which the density is 1/e times the initial intensity, corresponds to our penetration depth. So what is λ determined by? We said that at low energy, charge exchange dominates, so the cross section for charge exchange is much larger both than σi and then the equivalent term for the interaction with electrons. [<σe ve> / vb] Therefore the penetration depth in this case will be 1 over the density of the plasma, times the charge exchange cross section. [λ ∼ 1/(np σch)] At high energy, we have a situation in which it is the ionization cross section for ions, to ionize the beam, that dominates, therefore the penetration depth will be given by 1 over the plasma density the ionization cross section for the ions onto the beam particles. [λ ∼ 1/(np σi)] I can now represent, in a plot, as a function of the beam energy, the penetration distance and diffraction of the beam that remains neutral. Say if we go from zero to one, and we have something like 10, 20, 30, 40, say 100 and 300 keV of energy for the beam.

Notes

Summary

20m 40s

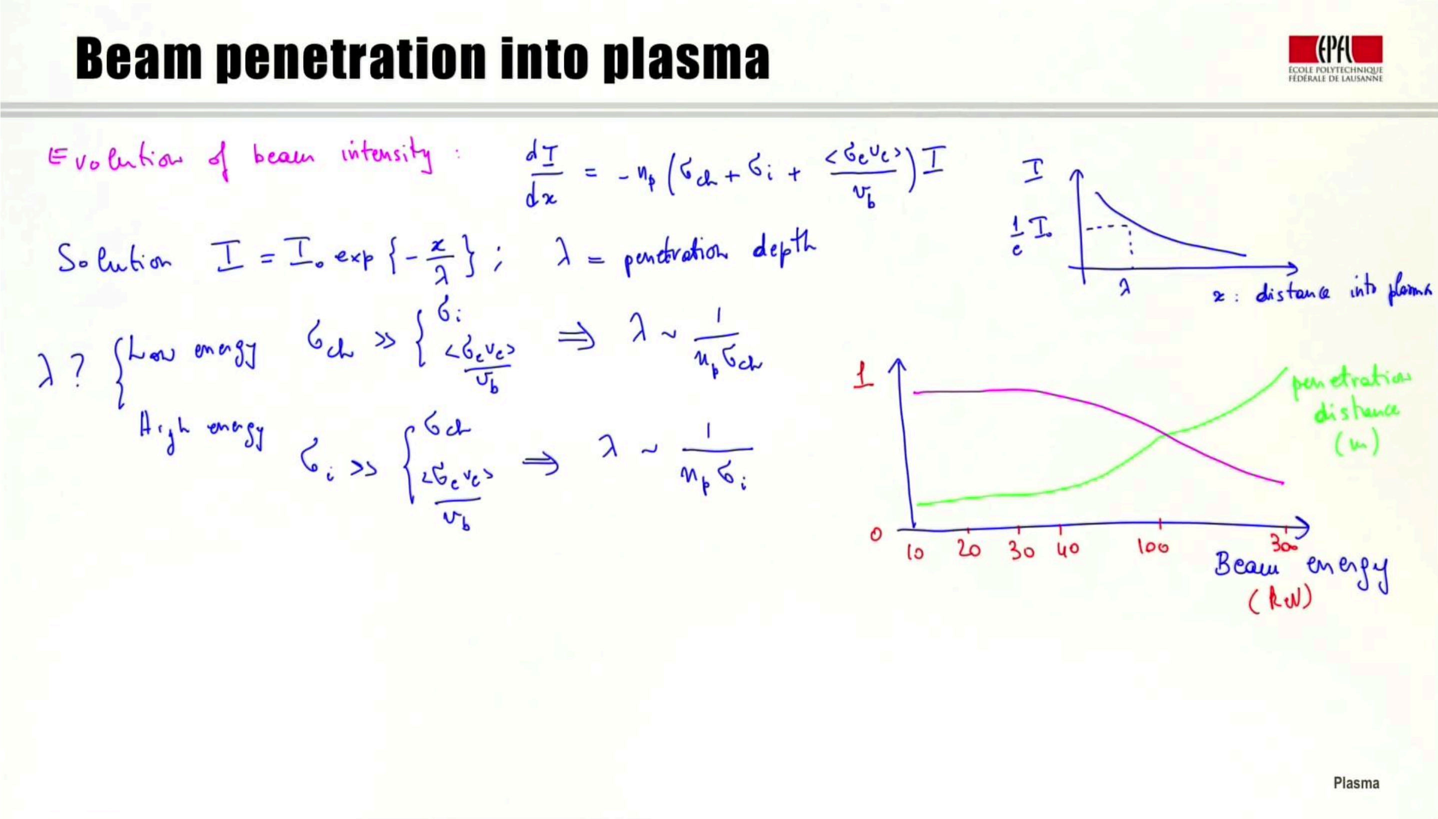


So my penetration distance will go higher and higher as I will increase the beam energy. I represent this in meters, so it will go to macroscopic distances such as meter or a few meters, as I increase the energy of the beam above a few hundred keV. I have a qualitatively represented this curve with a knee, and that knee corresponds to the energy at which I have a transition between a process that's dominated by charge exchange, and a process that's dominated by ionization by ions. In this example, I consider qualitatively a deuterium beam in a deuterium plasma. Together with a penetration distance increasing with the beam energy of course we have the opposite effect for the neutral fraction, that is the fraction of the beam that remains neutral, that will go from almost 100% to almost 0% as we go higher and higher in energy. So one key point here is that for plasmas that are large, so we need to go to a meter or more into the plasma with our beam, we need to go to hundreds of keV or more for the energy of the beam. So for large plasma we need large beam energies. The other point that we need to be careful about is that on the opposite, for small plasmas, we need, and we must use, low beam energies.

Notes

Summary

22m 37s



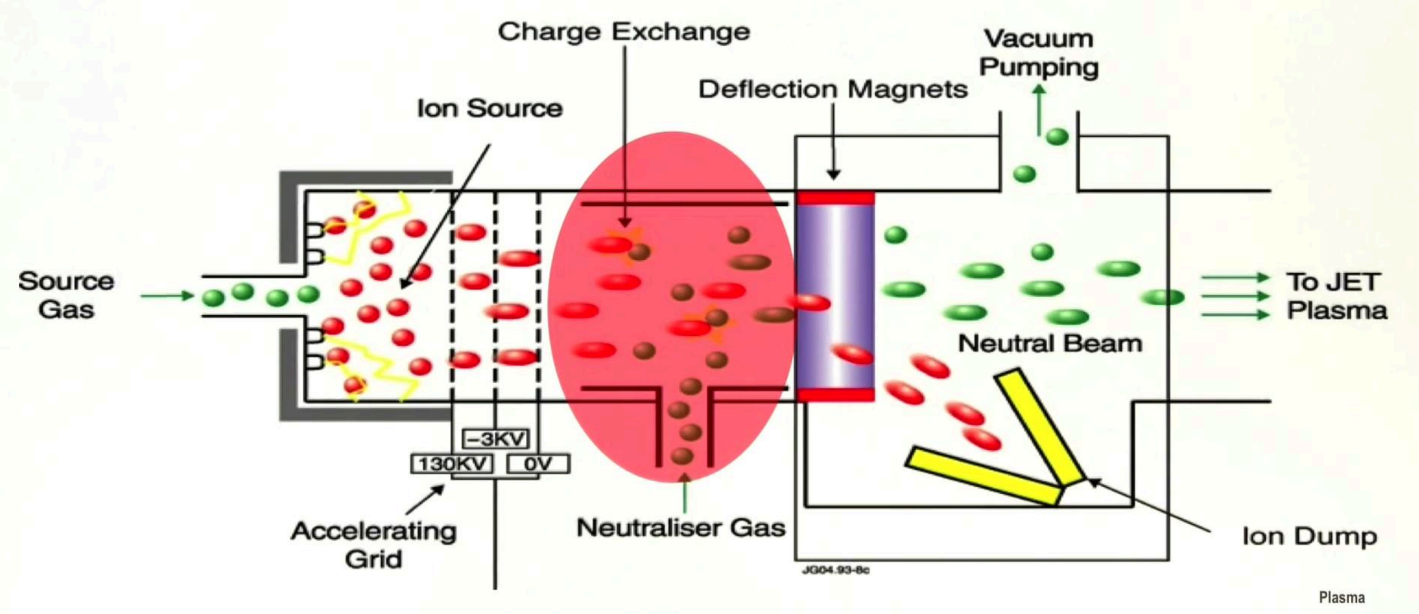
Otherwise the beam will not be absorbed by the plasma at all, and will pass through the plasma, and impinge on the walls on the other side of the injection port, and therefore potentially damage the machine, so that's so-called *shine-through*, and the shine-through determines the minimum plasma density at which we can operate a beam.

Notes

Summary

24m 26s

Beam neutralisation before injection



Having established what we need for the beam, let's go back a little bit to a key point in the beam system, that is the neutralization of the beam before it's actually injected into the machine, into the tokamak.

Notes

Summary

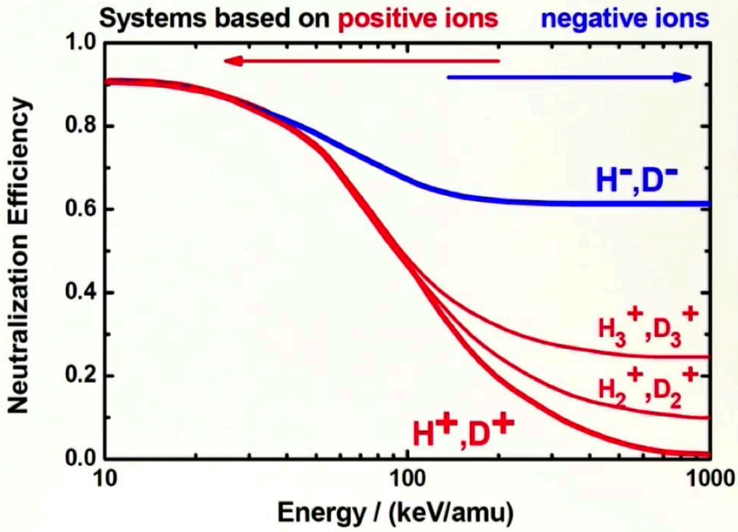
24m 49s

Beam neutralisation before injection

- Neutralisation efficiency for positive ions goes down for high energies
- Negative ion neutralisation easier due to low affinity (0.75eV) of additional electron

$$H^- + H_2 = H + H_2 + e^-$$

- For large, dense plasmas high energies are needed, therefore negative ion beams must be used



Plasma

And if we represent the efficiency with which we neutralize the beam as a function of the beam energy, here it's in terms of keV per atomic mass unit, we notice that this efficiency, which is decent at low energy, say energy of the order of 10, or 20, or 30 keV, for hydrogen, for example, it goes down very significantly as we go towards energies that are of the order of 100 keV. It goes down for the case of positive ions. That's the case we have illustrated in the example taken from JET, and this is the same, or similar, for the different species that we have in the beam. So there's no way we can have a beam of several 100s of keV, hydrogen or deuterium, with positive ions, the reason being that the neutralization efficiency will be very, very, very small. What can we do then? Well, we can look at the blue curve, which corresponds to the neutralization efficiency for beams made with negative ions, and notice that although that does go down some, it remains at levels that are still tolerable and compatible with the operation of reactors, say at least 60%, all the way up to say an MeV for hydrogen here, so all the way up to the energy that we need in order for our beam to reach a penetration distance of the order of a few meters, that is the size of ITER and the future reactors that we are foreseeing to have.

Notes

Summary

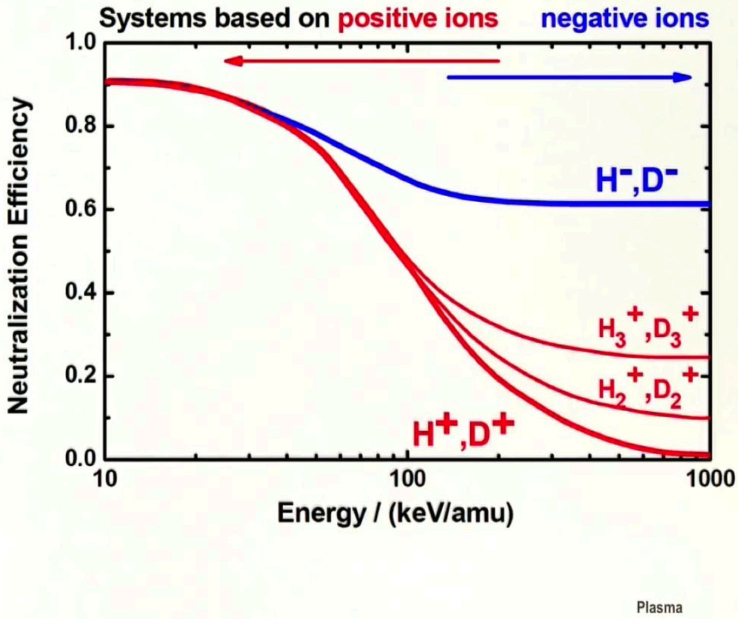
25m 04s

Beam neutralisation before injection

- Neutralisation efficiency for positive ions goes down for high energies
- Negative ion neutralisation easier due to low affinity (0.75eV) of additional electron

  $$H^- + H_2 = H + H_2 + e^-$$

- For large, dense plasmas high energies are needed, therefore negative ion beams must be used

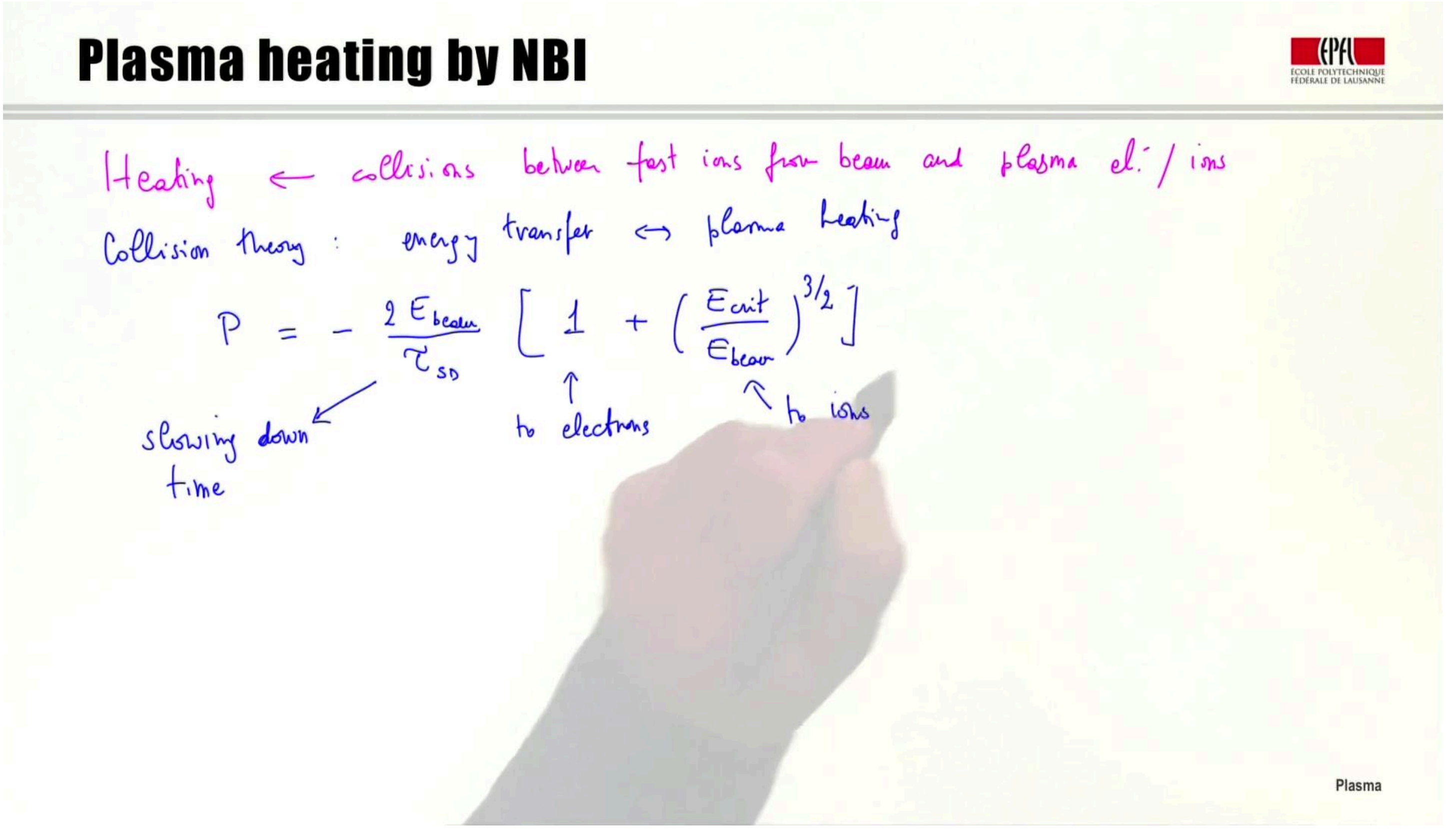


The reason for that is that the neutralization for the negative ions is much easier because of the low affinities, less than an eV, typically 0.75eV, of the additional electron that's attached to the hydrogen. So because we need large penetration depth, and that implies large energy, for large and dense plasmas we therefore need and *must* use negative ion beams.

Notes

Summary

26m 51s

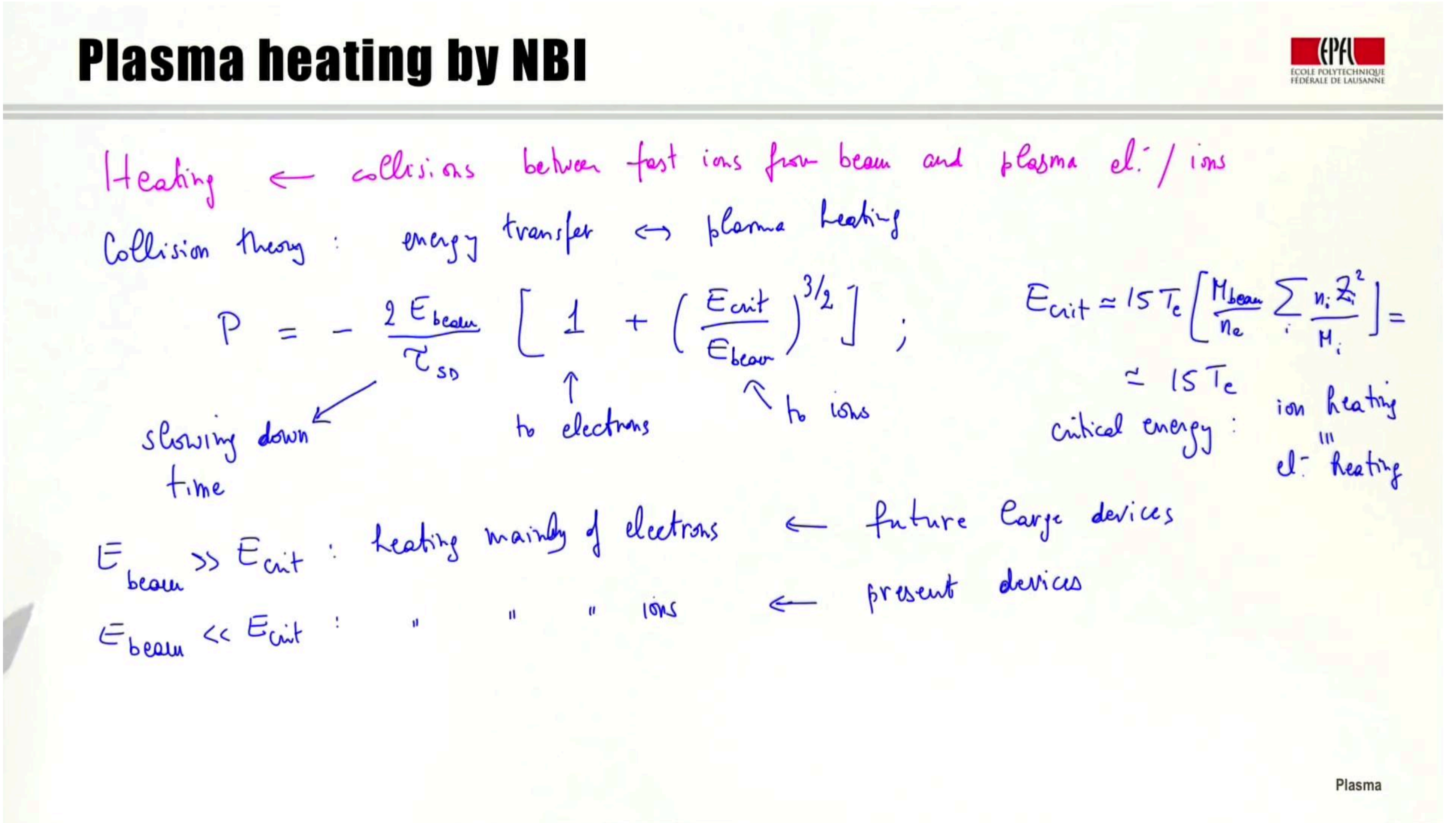


So what happens in the plasma once we manage to get the beam into it? Well, the plasma, and that's of course the reason why we do it, will be heated. Let's look at that a little bit more into the details. So, where is the heating from? The heating comes from the collisions between fast ions from the beam, and plasma electrons or ions. You have seen, in the first part of the course, how one treats collisions, in particular Coulomb collisions, these are the ones we're considering now, so the energy transfer is of course what we want, because that's corresponding to plasma heating. So how does that work? We can represent this heating in terms of power, and that will be equal to minus the energy deposited by the beam, divided by a typical time over which the particles will be slowing down-- these are the suprathermal particles injected by the beam, we call that the *slowing down time*, -- times two therms, one corresponding to the heating of the electrons, and the second one corresponding to the heating of the ions, so this is the part going to the ions.

Notes

Summary

27m 23s



The critical energy, which we refer to as Ecrit in this formula, is given by about 15 times the electron temperature, times the mass of the beam divided by the electron density, times the sum of a different species of the density Zi² divided by the mass of the species, and in most cases this is not that different from taking something like 15 times Te, and that critical energy, this critical energy is the energy at which the heating of the electrons is equivalent to that of the ions. So we can have say two situations, if the beam energy is much larger than the critical energy, the heating will be mainly on electrons. Whereas if we have the opposite situation the heating will be mainly of the ions. Now this will be the case of future large devices, whereas this is the case of present devices.

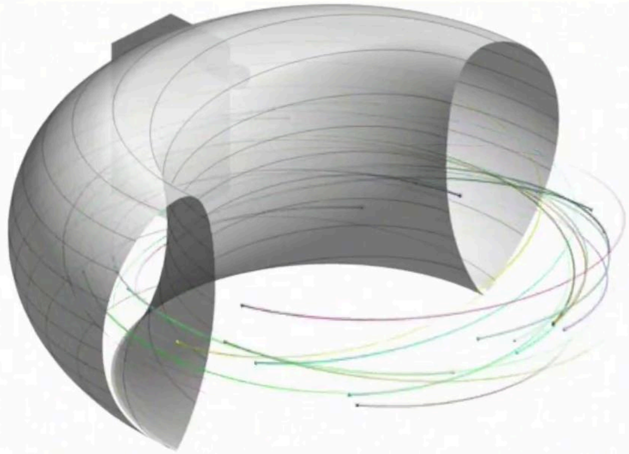
Notes

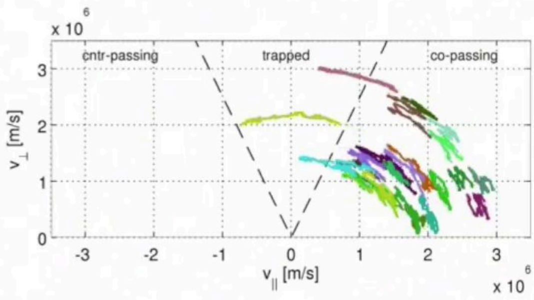
Summary

28m 50s

Energetic ions from NBI

- Ions at ~100keV in present devices, ~1MeV in ITER
- Injection geometry determines initial orbits
  - If tangential, mostly passing orbits, collisions scatter into trapped





Mattia Albergante

So we have seen that the heating of the plasma comes about because we inject neutrals at high energy that become energetic ions, typically at present we inject energies of the order 100 keV, in ITER we will inject energies of the order of 1MeV. The injection geometry is also an important parameter because that determines the character of the orbits of these energetic ions. If the injection is tangential, that is as parallel as possible to the toroidal direction, we will start with mostly passing orbits, that is orbits, as you can see in this movie, that are circulating around the tokamak, but of course there will be some collisions, and the collisions scatter the circulating particles into trapped orbits, as you can see, not only from the representation in real space on the left, but also from the representation in the velocity speeds on the right, where the ions are going from passing, to being trapped by collisional effects, this is a simulation in a realistic tokamak environment. So these are the characters of the orbits that we have for the fast, or energetic ions that are injected from NBI. That's important not only for the heating and the possibility of driving a non-inductive current in the plasma with these energetic particles, but also for the potential interaction that these particles can have with plasma instabilities as we will see in a lecture in the future.

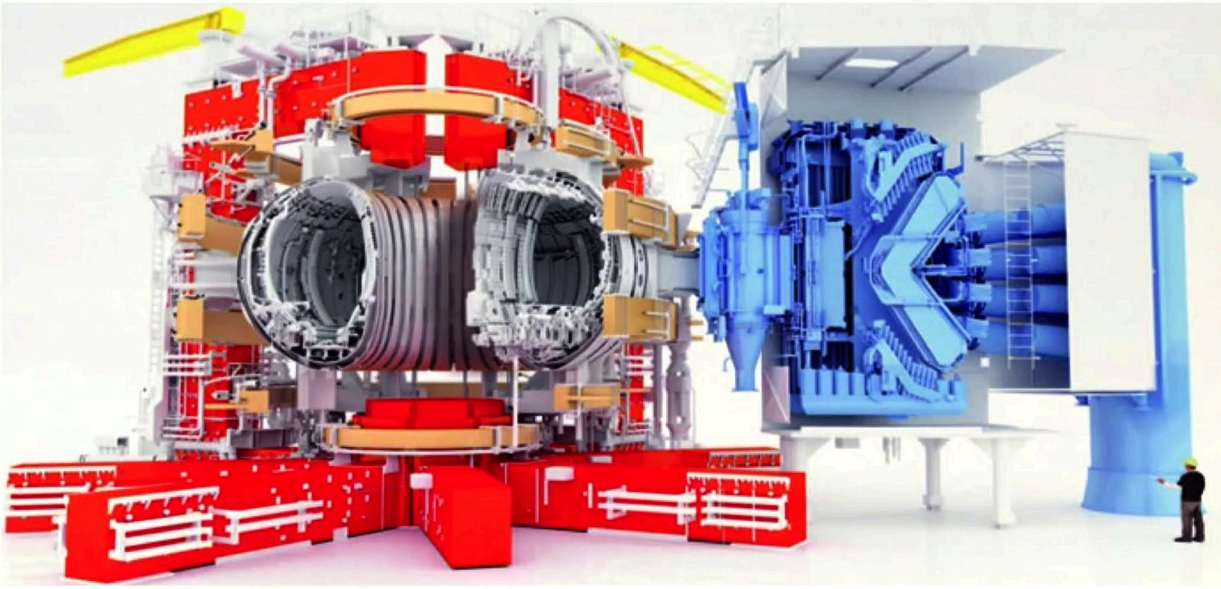
Notes

Summary

30m 18s

Example of present NBI system: JET

Radial and tangential injection; 2x8 injectors 80keV (H^+), 130keV (D^+) – up to 34MW



Plasma

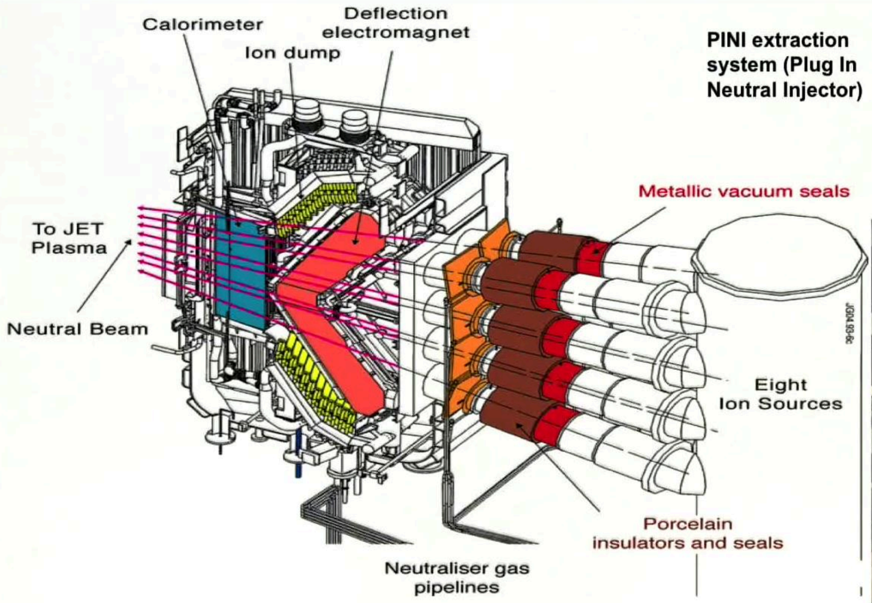
I would like now to discuss briefly some concrete examples of NBI system. First of all a system that exists, and in fact has been operational for a number of years, that of JET. JET has different injectors, 2x8, both for radial and tangential injection, at either 80keV or 130keV of energy. This is sufficient for the beam to go into the core of the JET plasma, and these energies, as we said before, don't require negative ion technology because the neutralization of positive ions is sufficiently efficient. The JET system has up to 34MW of total power in its recent upgrades. You can see the size of the system here, which is almost the same as that of the entire tokamak.

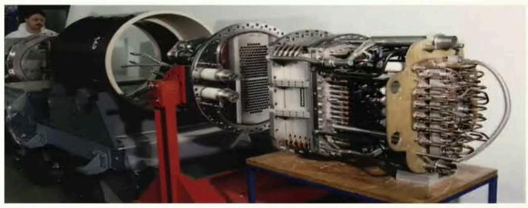
Notes

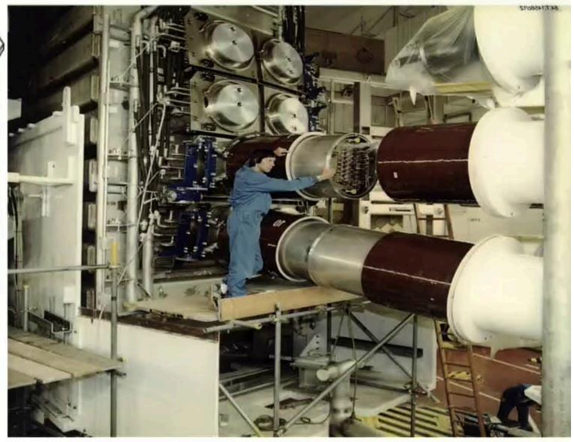
Summary

32m 02s

Example of present NBI system: JET







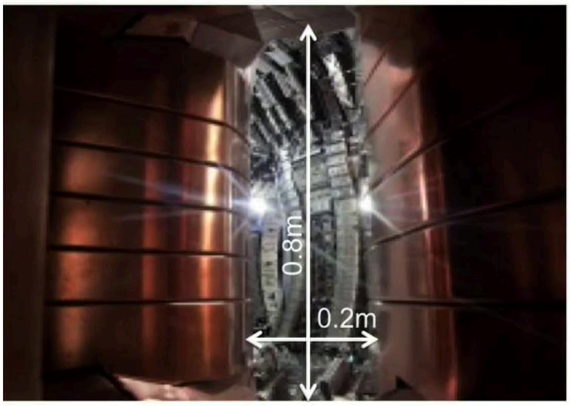
We can look at some of the details. Here is the layout of the system, with the one injector with eight ion sources, with insulators and seals that you can see in the layout here, and you can see in the actual picture when the system was installed, on the right. Each of these tubes has a so-called *PINI extraction system*, that's a Plug-in Neutral Injector. This particular technology was developed for JET. We can notice the electromagnet to deflect the non-neutralized ions, the dump for those that in fact need to be evacuated because they're not neutral. And the calorimeter that measures how much power we are actually injecting. On this side there would be a port that would lead us to the JET plasma.

Notes

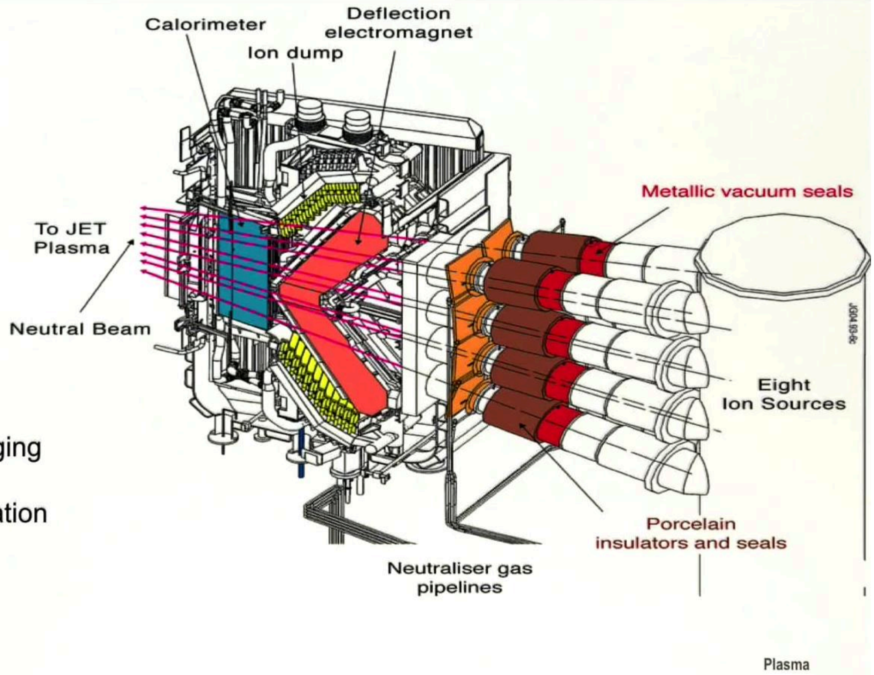
Summary

33m 00s

Example of present NBI system: JET



Beam divergence must be low to avoid damaging beam duct and outgassing from beam-wall interactions, which would block beam propagation



So this is the same picture as before, but now we are looking at that port that leads into the JET plasma, the port is about 20 cm of width, for a height of about 80 cm. I just put the picture because I'd like to stress the point that the divergence of the beam is an important parameter. We can't impinge with the beam on the walls of the duct that takes us to the machine, both because we would damage the beam duct, but also because as soon as we deposit some power here there will be significant outgassing from the beam wall interactions, and this outgassing would block the propagation of the beam, which would therefore never even reach the plasma volume.

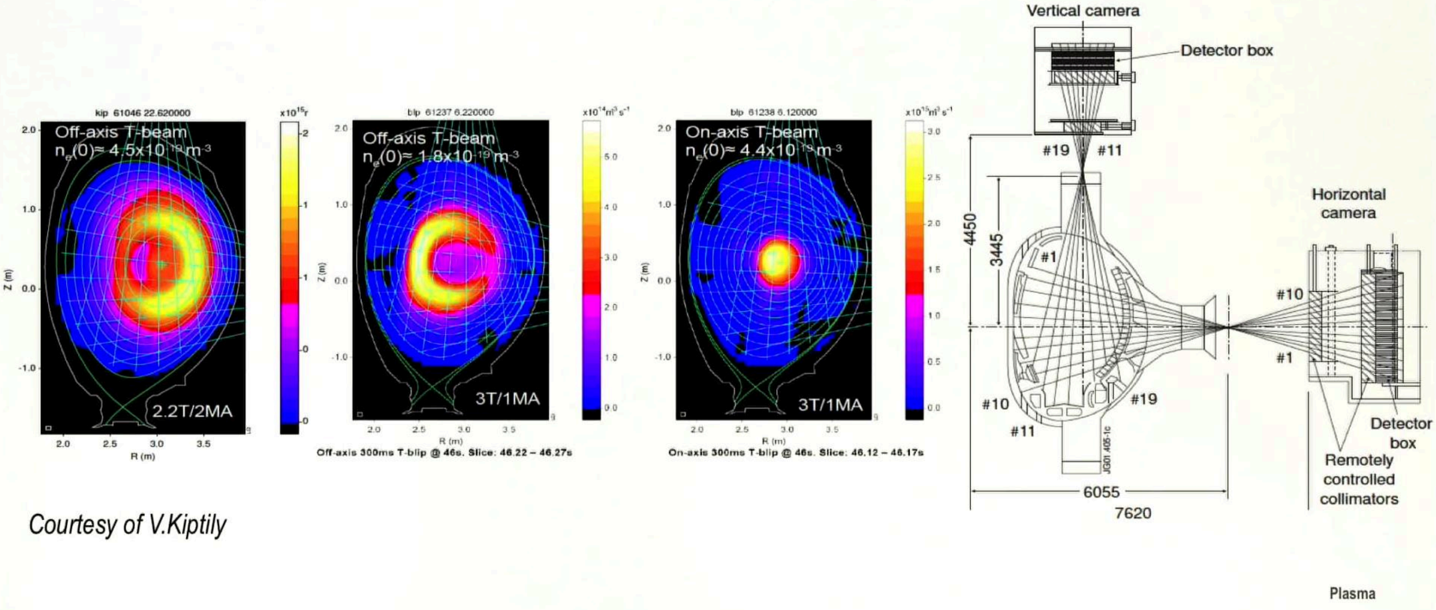
Notes

Summary

33m 58s

Evidence for NBI-generated fast ions in JET

- Emission profiles of 14MeV neutrons in trace-T experiments with T-NBI *blips*



Courtesy of V.Kiptily

So we said that the beam works by generating fast neutrals that become fast ions. Let's look at the evidence for the presence of these fast ions in a JET tokamak in a few examples. In this case we were actually injecting some tritium into the plasma, using what we call tritium NBI *blips*, so small amounts of tritium injected in the NBI system. And what we can do in this case, is to measure the profiles of emission of the 14MeV neutrons that issued from the D-T reactions in the plasma. And by looking at the different lines of sight, both vertical and horizontal, we can tomographically reconstruct such emission profiles, and these are examples of that in slightly different situations, so we won't go into any details, but they indicate essentially where the fast ions are, that were injected with the NBI. And depending on the values of the current and the field in the plasma, which are varied, here, and depending on the injection geometry in the first two cases on the left: off-axis, and in the third case: on-axis, we can have slightly different profiles, or in fact significantly different profiles for the fast ions. So this confirms that we are actually injecting the fast ions into the plasma where we think they are going, [and in this case] Let me now just say a few words about the NBI system that's being designed and constructed for ITER.

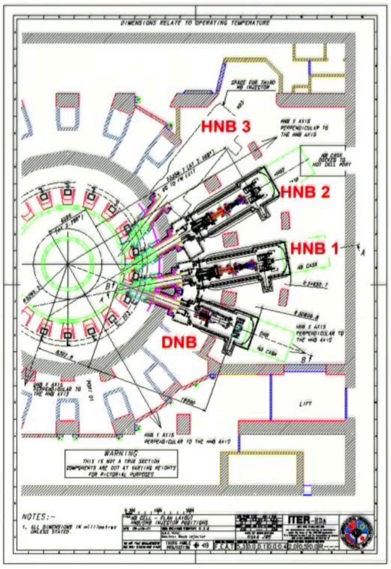
Notes

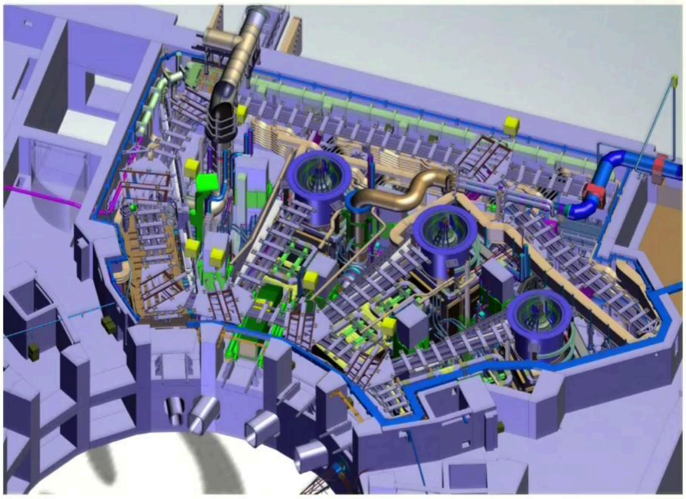
Summary

34m 46s

The NBI system for ITER

For heating and current drive: 2 tangential D^- beams (1MeV, 33MW, 3600s)
For charge exchange diagnostics: 1 radial H^- beam (100keV, 3MW, 400s)





Courtesy of ITER Organisation

Plasma

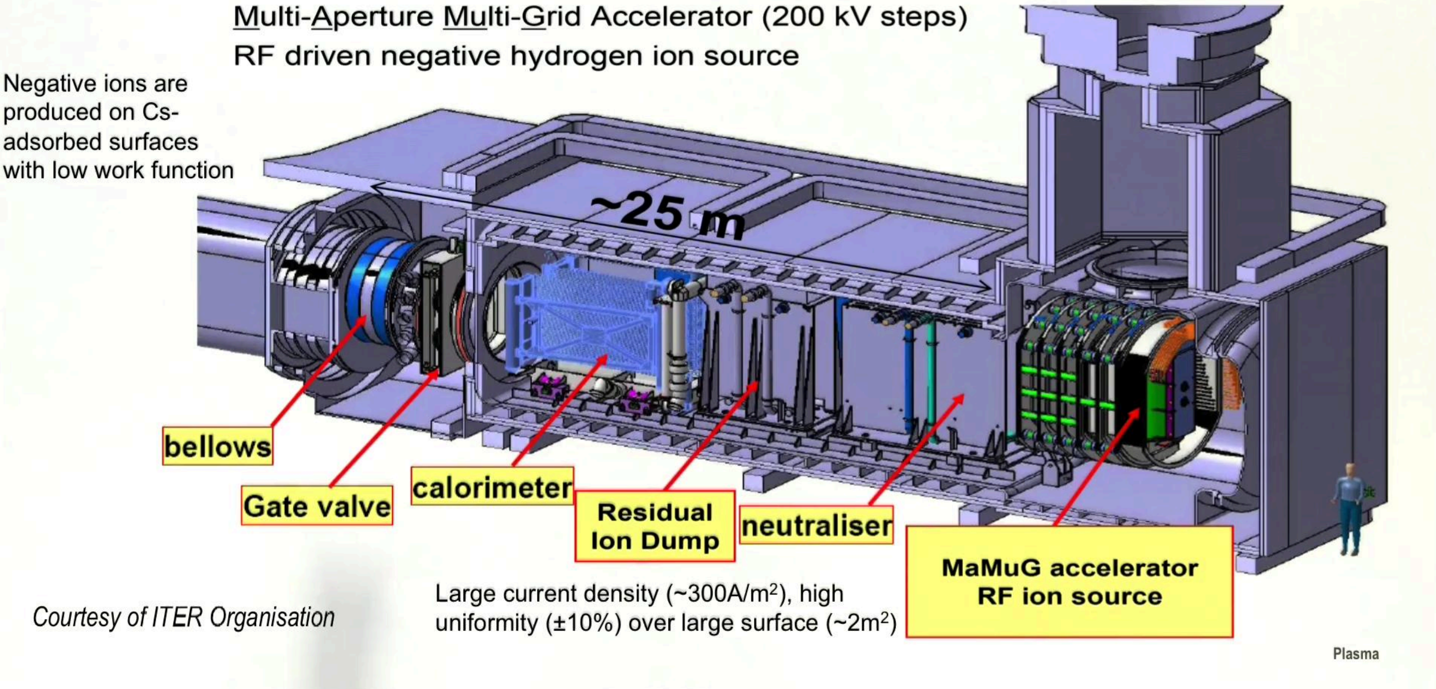
For heating and current drive, we will have two, at least initially, two tangential beams of negative ions, deuterium. Because of the size of ITER, these would be in the MeV range for the energy, in fact would be about 1MeV, a power of 33MW, similar to that of JET, but for much longer duration of a pulse, 3,600 seconds. There will also be a third beam, for diagnostic purposes. As we mentioned, the charge exchange process provides light, that carries information about the ion temperature and about the ion ordered velocity, as well. Now in order for that process to dominate, remember that we need to have low energies, and therefore we inject in the beam, we will be injecting in the beam in ITER at an energy of about 100keV for diagnostic purposes, a beam that won't have, of course, much of a power, of the order of 3MW. So here you see a layout of the geometry of injection into the ITER tokamak, seen from the top. And you see a CAD drawing of the three systems, the two heating and current drive systems and the diagnostic beam, into the ITER system.

Notes

Summary

36m 23s

The NBI heating and current drive system for ITER

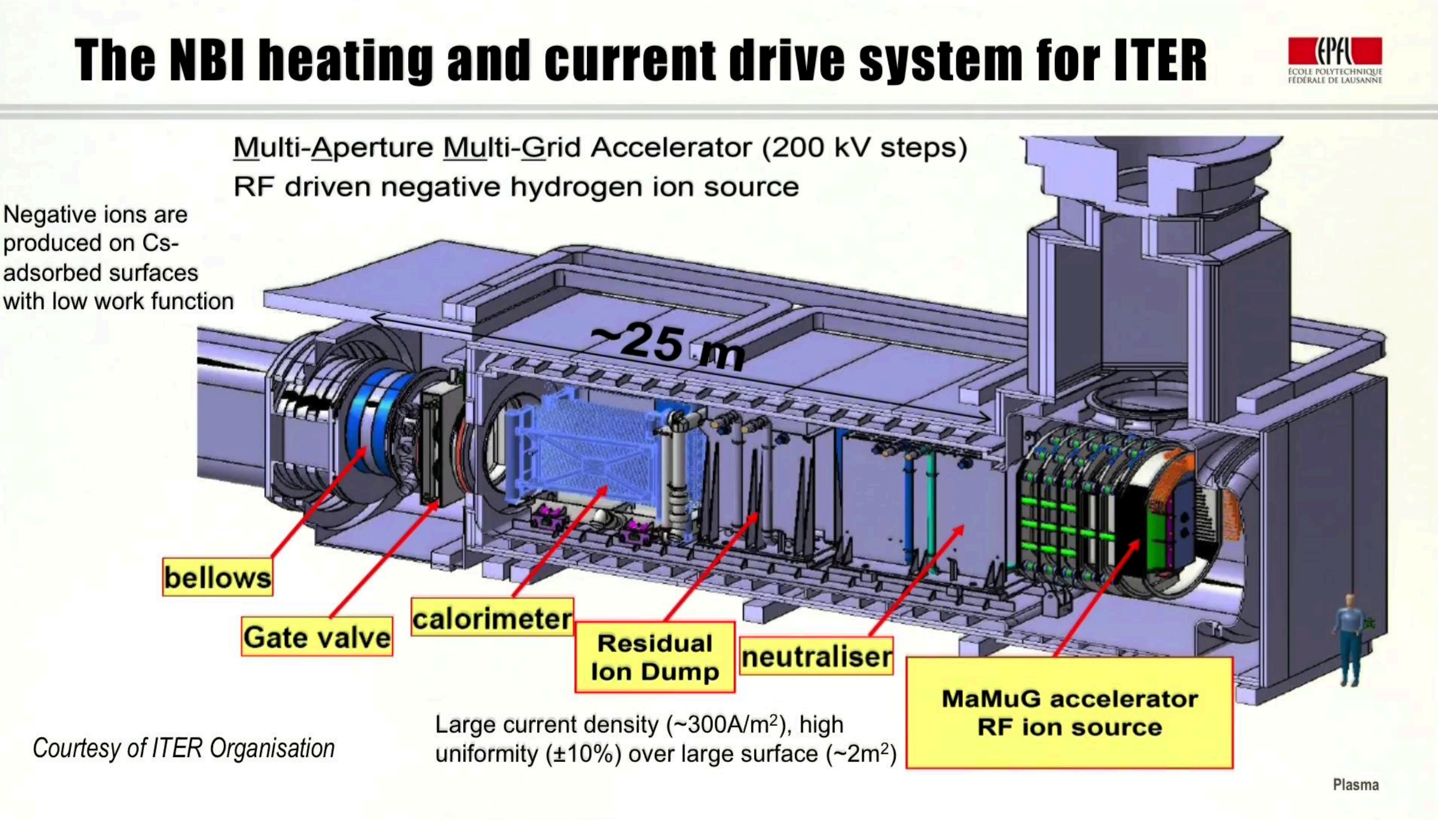


Now the source itself, and the whole beam accelerating system and the neutralization for ITER is a challenge, and that's why it's still the subject of significant R&D. There will be a very large surface source, with a couple of square meters of surface which needs to produce a very large current density, something like 300A/m², with a high degree of uniformity across the surface. The concept used is so-called MaMuG, that extracts and accelerates the ions produced from this source. Multi-Aperture Multi-Grid Accelerator System, each step is 200 kV. For the source itself, the technology, based on the radio frequency production of a plasma is used, as opposed to arc discharges. The choice was based on the reliability tests having been made in different devices, and also on the need of having very low maintenance requirements for the system, once it's operational. I'll just highlight the fact that the negative ions are produced on surfaces that are covered with cesium, it has been deposited on them, so low work function surfaces, and this is a surface production of a plasma. We're talking about, of course, the source for the neutral beam, as opposed to the volume production we have seen in, for example, the JET system, which is based on arc discharges.

Notes

Summary

37m 51s

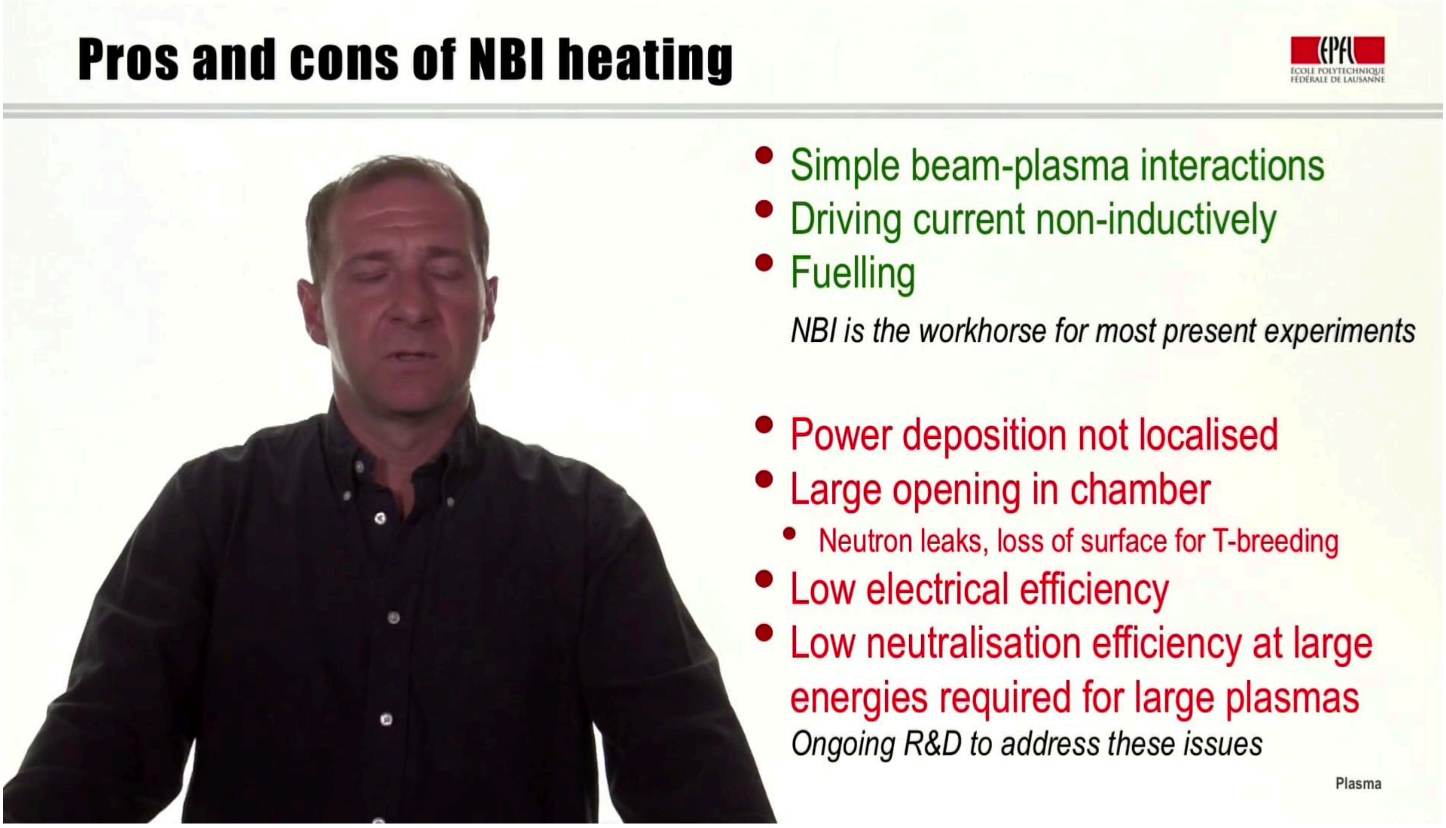


So this is the source, that's the acceleration stage, the neutralizer has quite a large volume, the Residual Ion Dump, the calorimeter, so all the elements we have seen for JET, and of course there will be a valve and a set of bellows to connect the whole system to the tokamak.

Notes

Summary

39m 44s

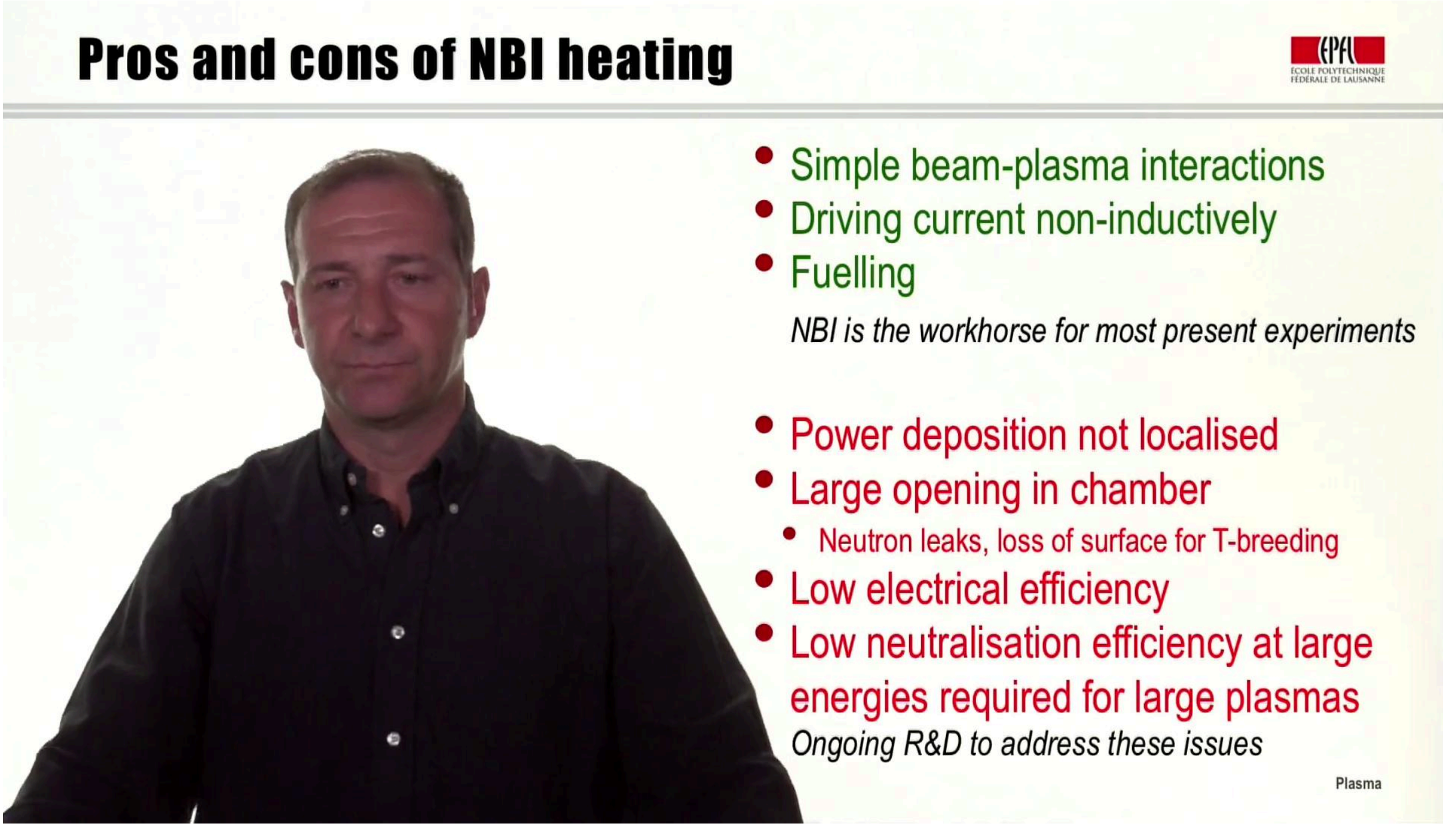


We are now ready to discuss, in a simple way, the possible advantages and disadvantages of the NBI heating system. We have seen that the interaction between the beam and the plasma is fairly simple. There are three essential processes, of which in fact two dominate: charge exchange and ionization by ions, depending on the beam energy. The beam has an advantage that can be used to drive current non-inductively, if it's directed in a tangential way. It also has the advantage that it can provide fuelling of the plasma, and in fact provide fuelling on the plasma in the core of the plasma, if the penetration depth is sufficient. And in fact these advantages are the reason why in present experiments I can say that the NBI represents the workhorse, particularly for high-performance operation. On the other hand, there may be some cons. The position of the power is not that localized, so it may be a little bit difficult to determine exactly a localization for the heating or the current drive. The beam implies a relatively large beam duct, as we have seen, so there would be a relatively large opening in the chamber to make the beam pass through.

Notes

Summary

40m 02s



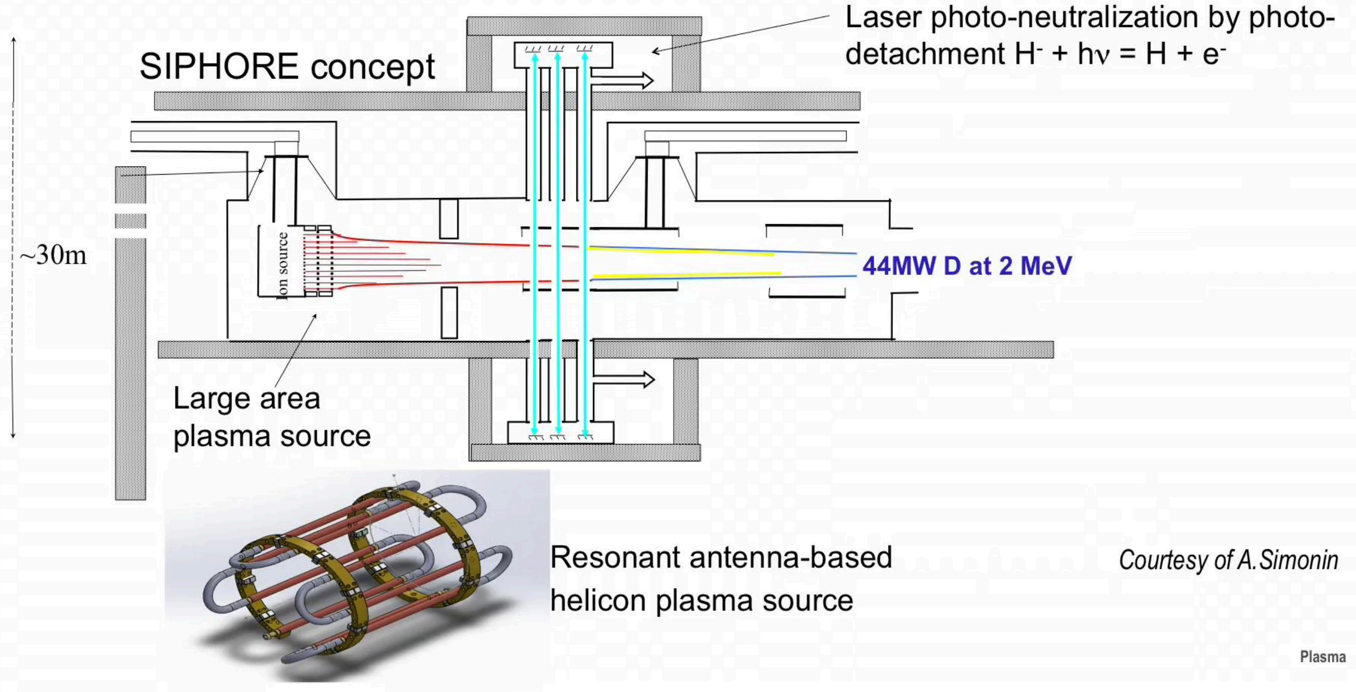
That means that we have to be careful about the leaking of neutrons out of the thermonuclear region, and also we're losing some surface that we could use for the blanket to breed tritium. The present technology of the beams has relatively low electrical efficiency, which of course in the future reactor is a problem, and also, even if we go for negative ions at large energies, at large energies we do have relatively small neutralization efficiency, not much better than 60%. For these two potential problems, nevertheless, there are significant R&D activities going on to improve the situation. We'll just give you one example of them.

Notes

Summary

41m 24s

Example of European R&D for optimising NBI for DEMO

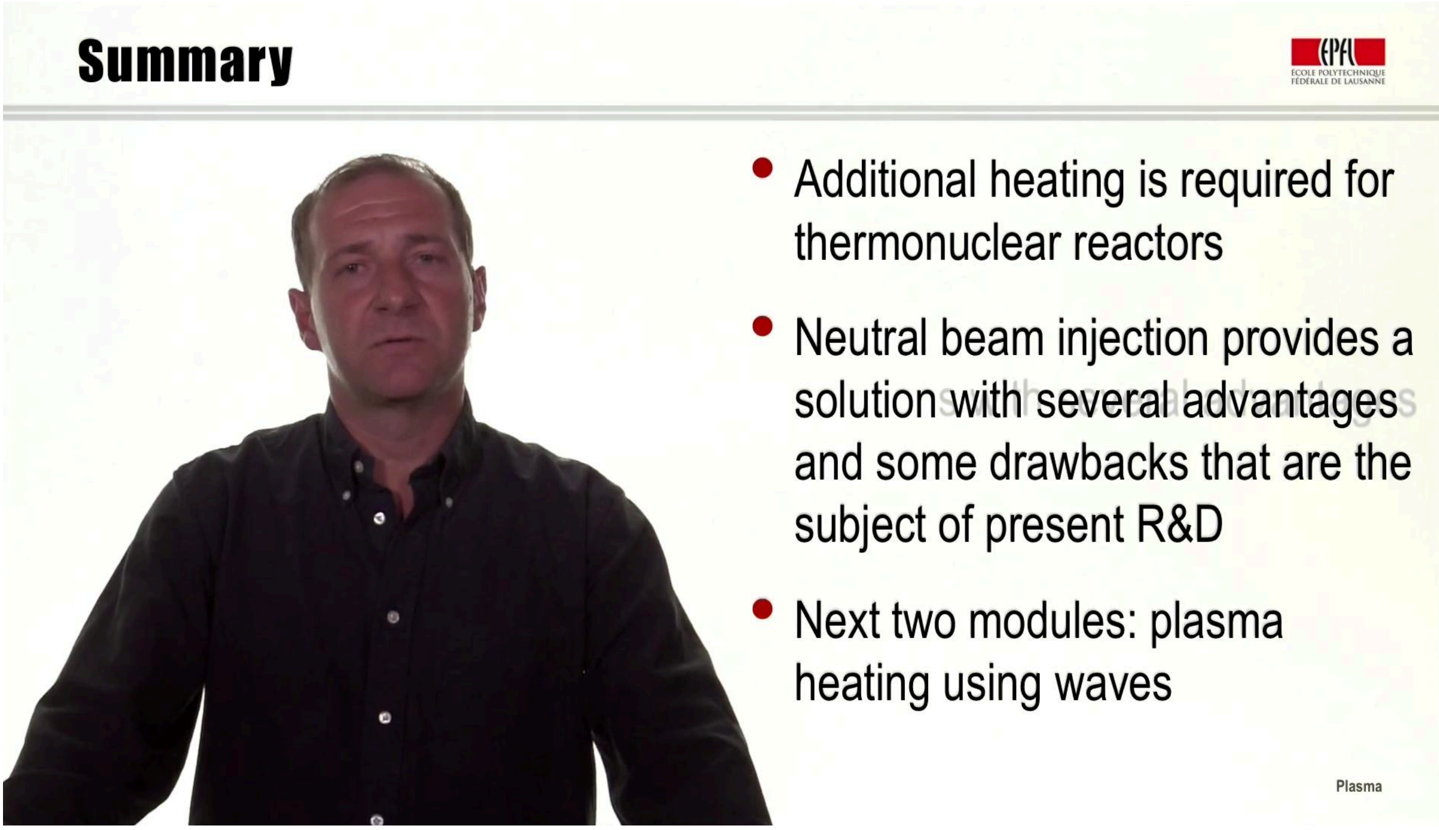


This example is provided by the so-called SIPHORE concept, in which a new technology for the plasma source [is developed] This technology is based on the resonant antenna that drives the plasma, using helicon waves. In fact, helicon waves are a kind of waves that you have seen in a previous course, focused on the physics of plasma waves. We can refer to them also as *whistler* waves. Incidentally, this reminds you of the importance of plasma waves in many, many applications. Once the plasma is producing that source, and ions are extracted from that source region, of course they need to be neutralized, and we have seen that the neutralization efficiency is one of the problems we're facing. But the idea in this proposal is to use light to increase efficiency by providing photoneutralization. Photoneutralization acts by photodetachment, so we have a negative ion, in this case the example of hydrogen, on which we inject a photon, and that provides neutralization of that negative ion, and of course the emission of an electron, which can then be deflected by the electron magnet later on. This is a concept that's been investigated, and may potentially provide both higher electrical efficiency for the plasma production in the source, and higher neutralization efficiency using laser light.

Notes

Summary

42m 13s



In summary, we have seen that additional heating is required for thermonuclear reactors. By additional heating we mean heating that comes on top of the Ohmic heating, which is a consequence of electrical current flowing into the plasma. The first system we have investigated today was the neutral beam injector. A neutral beam provides a solution that has a number of advantages, but some drawbacks, although some of the drawbacks can be overcome, and that's why we are doing significant amounts of research and development on this issue. In the next two modules, we'll investigate how we can heat the plasma using plasma waves at different frequencies.

Notes

Summary

43m 52s