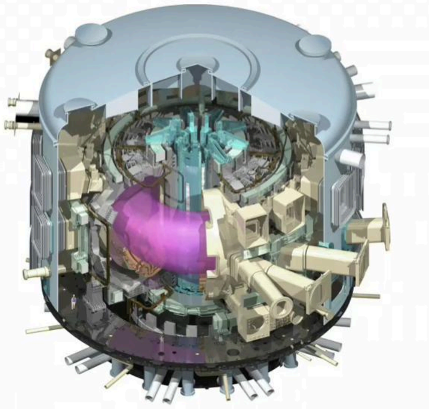
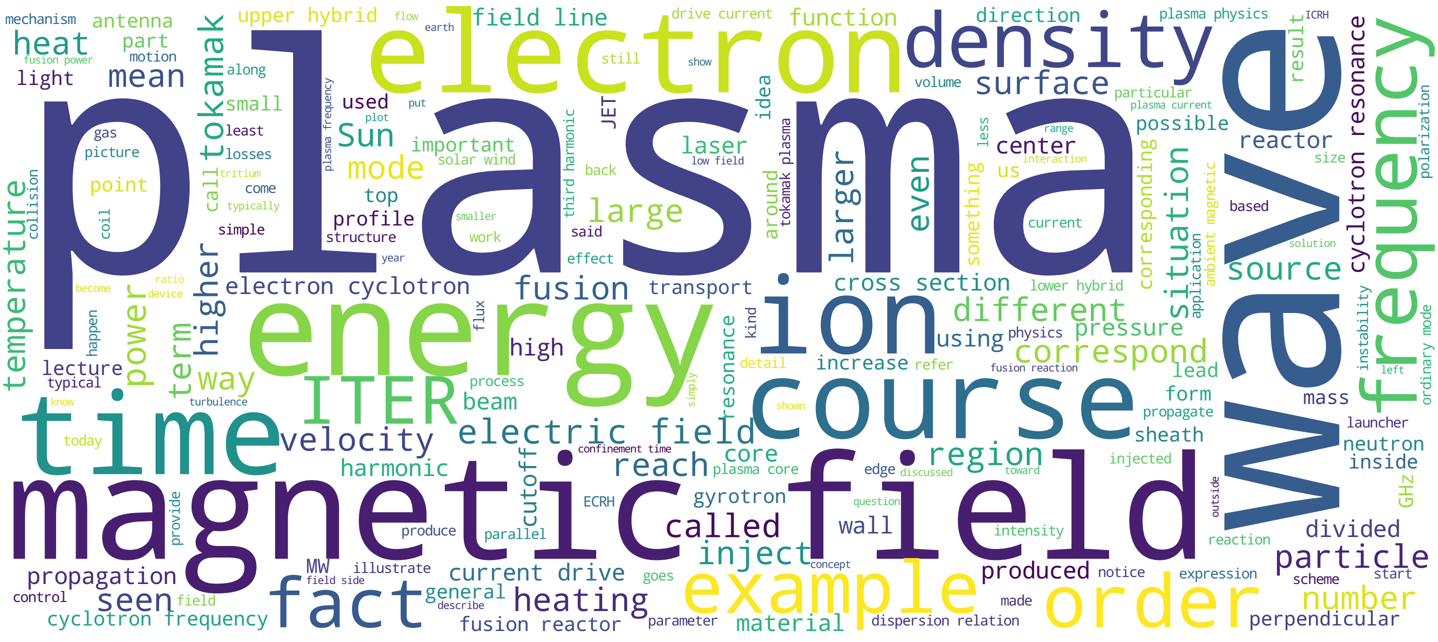


Heating and current drive by waves – ECRH

Plasma Physics and Application to Fusion Energy, Astrophysics and Industry

Lecture 7h

Ambrogio Fasoli



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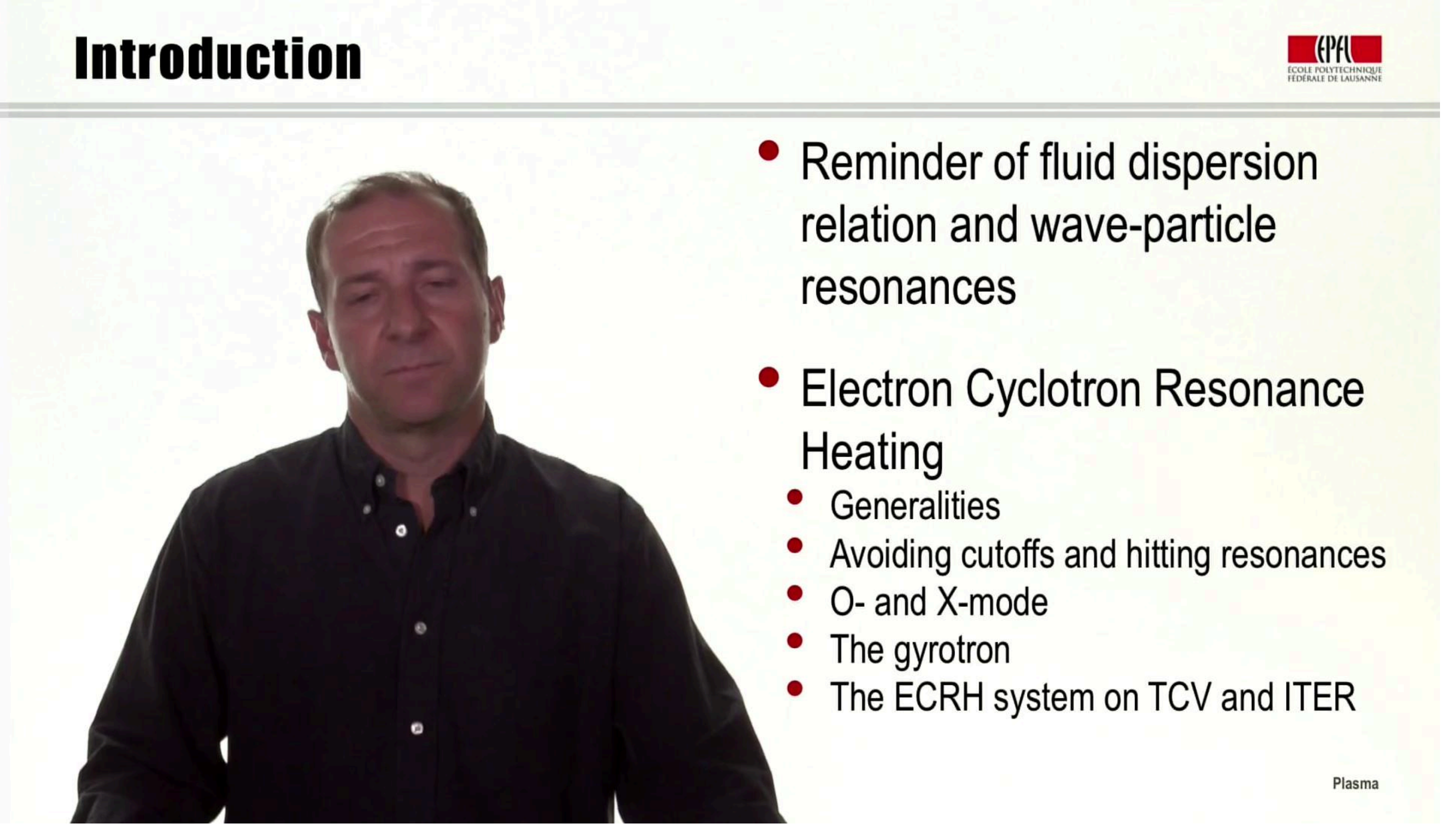
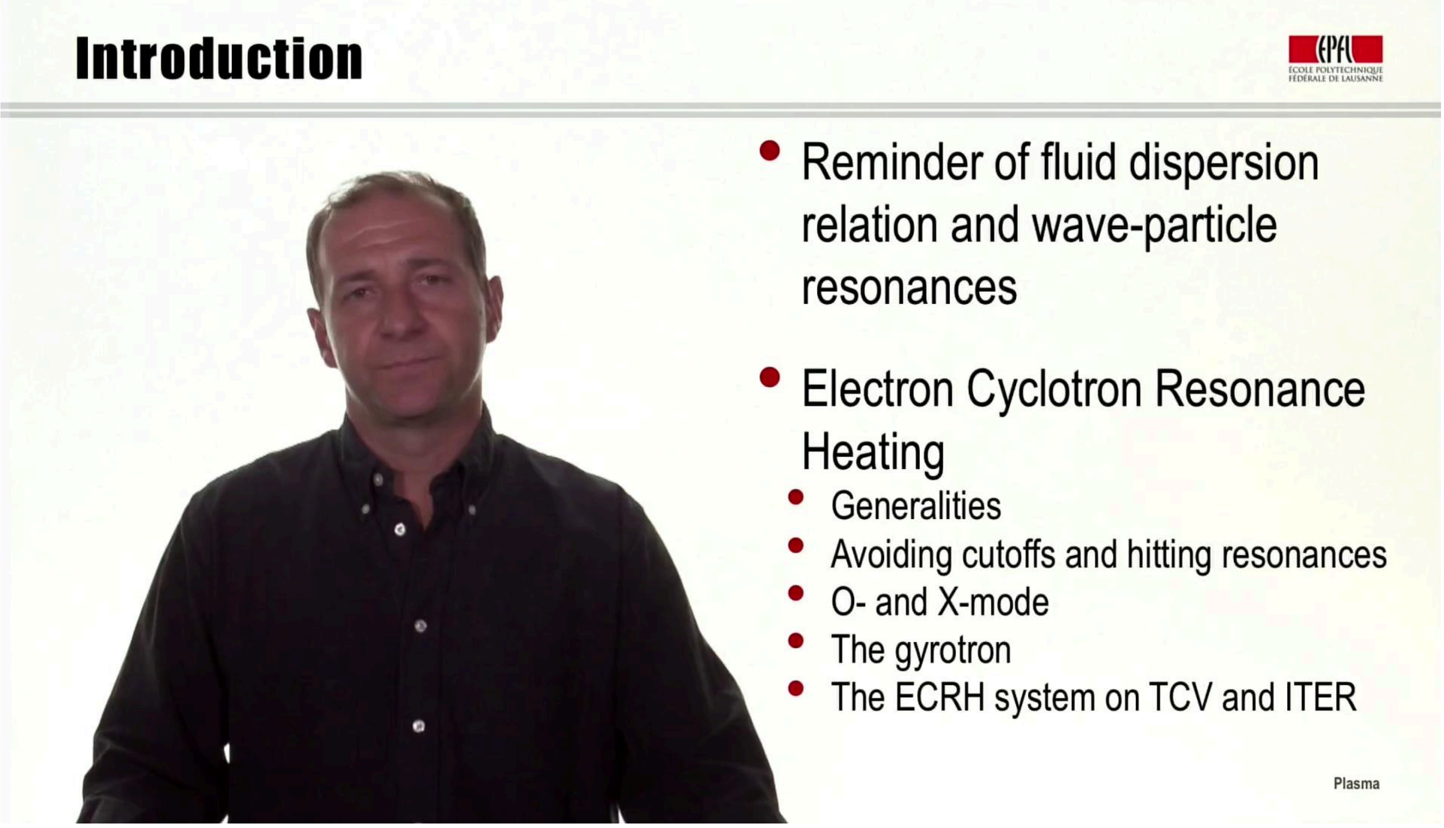


Welcome to the course on plasma physics and applications. Today we will continue our discussion on how we can heat the plasma and drive current in it using waves. After a brief reminder of the fluid dispersion relation — that is the condition that we need to impose in order for the waves to propagate in a plasma — and a brief reminder of the concept of wave-particle resonance, which is the mechanism by which we transfer energy from the wave to the plasma, we will focus on the electron cyclotron resonance heating system. We will see in some degree of detail what are the physical mechanisms that are behind it, how we can avoid the reflection layers for the wave in the plasma that we refer to as cutoffs in order to reach the absorption layers in the plasma that we refer to as resonances. And how we can use the two polarizations that characterize the perpendicular propagation of the wave in a plasma in order to do that — the ordinary and the extraordinary mode. We will see how we can build a source of microwaves that gives the power that we need to heat the plasma at the frequency we need to operate — that is the gyrotron.

Notes

Summary

0m 05s



Then we will illustrate a couple of examples of actual systems that are based on the ECRH principle to heat the plasma and drive current into it. One that already operates in an actual tokamak, is the system on the TCV tokamak here in Lausanne and the system that we foresee for ITER.

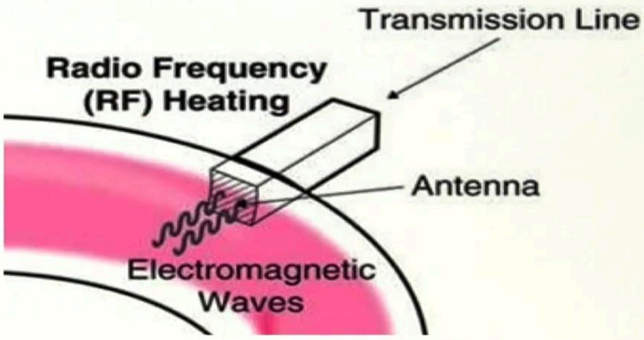
Notes

Summary

1m 25s

Heating the plasma with waves – reminder

- Magnetized plasmas support the propagation of many modes, which can be used to transfer energy, via an antenna, to the plasma core
- Frequency and/or wavelength must be chosen to satisfy the plasma dispersion relation and allow the wave to deposit its energy in a layer corresponding to a plasma resonance



Plasma

As a brief reminder, I'll just highlight the fact that in magnetized plasmas we can have the propagation of many modes. These modes can be used to transfer energy, typically via an antenna or a launcher into the plasma core. That's the basic principle of heating plasma using waves. But I'd also like to remind you that the frequency and/or the wavelength of these waves must be chosen in order to satisfy the plasma dispersion relation, that is, the condition for the wave to exist and propagate in the plasma. We also need to choose a scenario — that is a combination of frequency and wavelength — in order to allow the wave to deposit its energy in a layer that corresponds to a plasma resonance, typically in the plasma core.

Notes

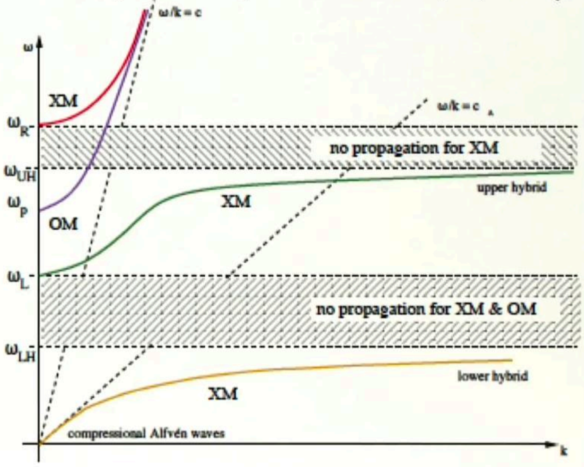
Summary

1m 45s

Wave-particle resonances - reminder

- Fluid model: no cyclotron resonance for propagation other than along $\mathbf{B}_0$
- Kinetic model: wave-particle resonances occur at $\omega - \mathbf{k} \cdot \mathbf{v} = n\Omega_c$ (n= 0, 1, 2,…), i.e. cyclotron resonances exist also for waves that don't propagate along $\mathbf{B}_0$
- To reach these resonances the waves must avoid the cut-offs, which can be identified in fluid dispersion relation (finite ω, $k \rightarrow 0$)

Fluid plasma dispersion relation perp to $\mathbf{B}_0$



Plasma

Again, as a reminder, I'll just highlight the fact that we have found that in a fluid model there are no cyclotron resonances for propagation, other than along the magnetic field of the plasma. This is a dispersion relation that we found in the fluid model in the direction perpendicular to the magnetic field and we see that the resonances corresponding to the situation in which the wave number goes to infinity for a finite frequency corresponds to the lower hybrid and upper hybrid frequencies, respectively, so no resonance for the cyclotron frequency. However, we have already seen in the last lecture that in the kinetic model, that is the model that goes one step beyond the fluid approach, considering that the velocities of the particles are not all the same, --so we have distributions that characterize the plasma-- in this model the wave-particle resonances exist and occur when the frequency seen by the moving particle, which is of course the frequency that we launched in the plasma Doppler-shifted by the k · v there corresponds either to zero, which means the plasma wave moves with a phase velocity that corresponds to the velocity of the particle or to multiples of the cyclotron frequencies.

Notes

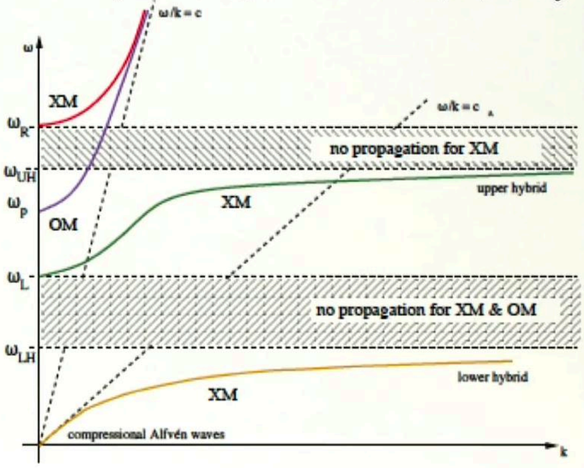
Summary

2m 29s

Wave-particle resonances - reminder

- Fluid model: no cyclotron resonance for propagation other than along $\mathbf{B}_0$
- Kinetic model: wave-particle resonances occur at $\omega - \mathbf{k} \cdot \mathbf{v} = n\Omega_c$ (n= 0, 1, 2,…), i.e. cyclotron resonances exist also for waves that don't propagate along $\mathbf{B}_0$
- To reach these resonances the waves must avoid the cut-offs, which can be identified in fluid dispersion relation (finite ω, $k \rightarrow 0$)

Fluid plasma dispersion relation perp to $\boldsymbol{B}_0$



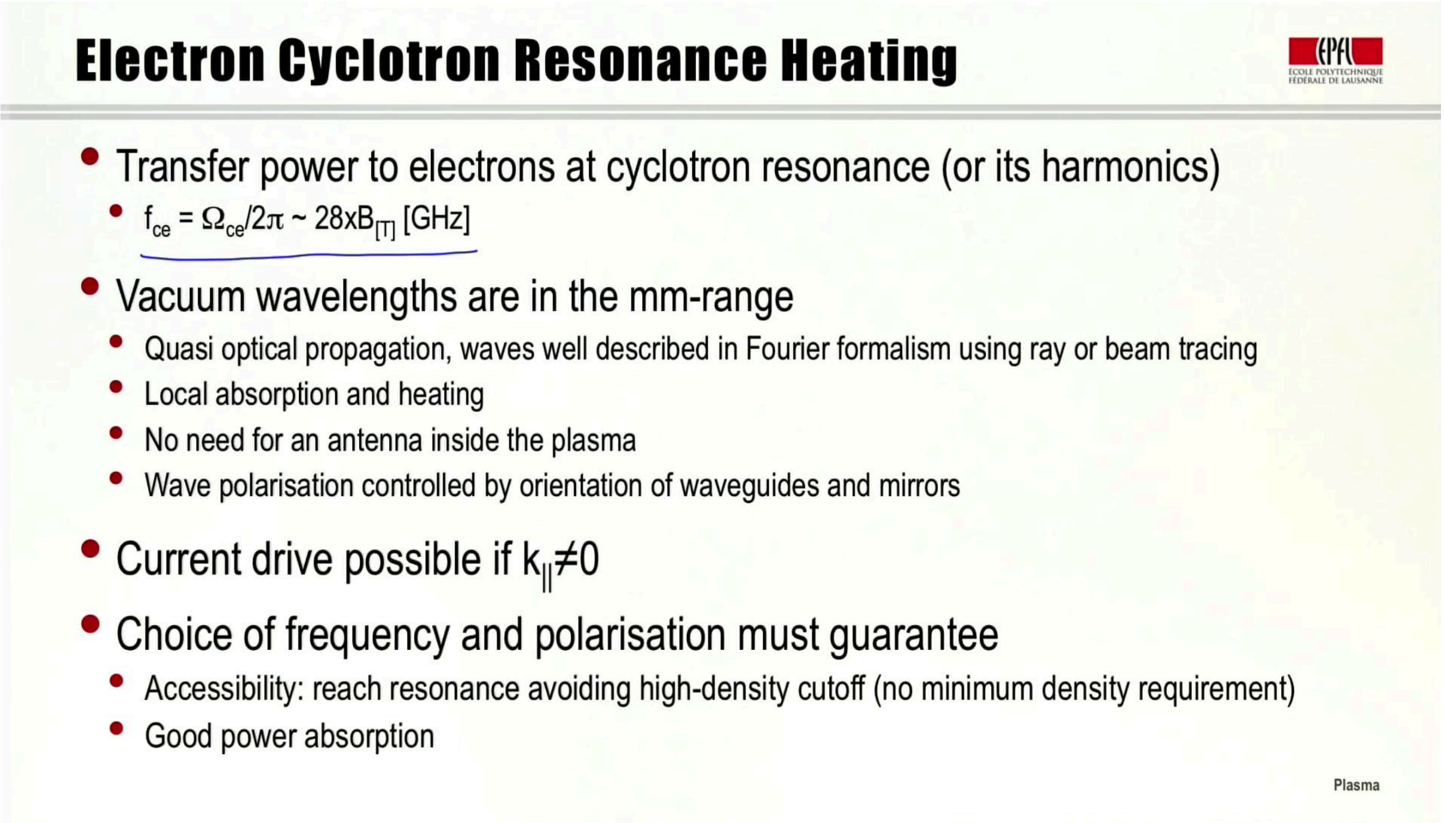
Plasma

So we do have cyclotron resonances in this more advanced model, even for waves that do not propagate along the magnetic field. So the game here is to reach these resonances, avoiding the cutoffs, which are the reflection points. Reflection points are characterized by an index of refraction going to zero that is typically finite ω and a wave number going to zero. Although the resonances cannot be identified by the fluid model, at least in perpendicular propagation or oblique propagation in general, the cutoffs can. In fact, in this dispersion relation that we have already seen before, we can identify already cutoff points such as ωL and ωR for the extraordinary mode (XM), the mode in which the oscillating electric field is perpendicular to the ambient magnetic field, or the ωp cutoff, which is the well-known cutoff for the ordinary mode, which corresponds to the polarization of the wave (OM) such that the oscillating electric field of the wave is actually parallel to the ambient magnetic field.

Notes

Summary

3m 52s

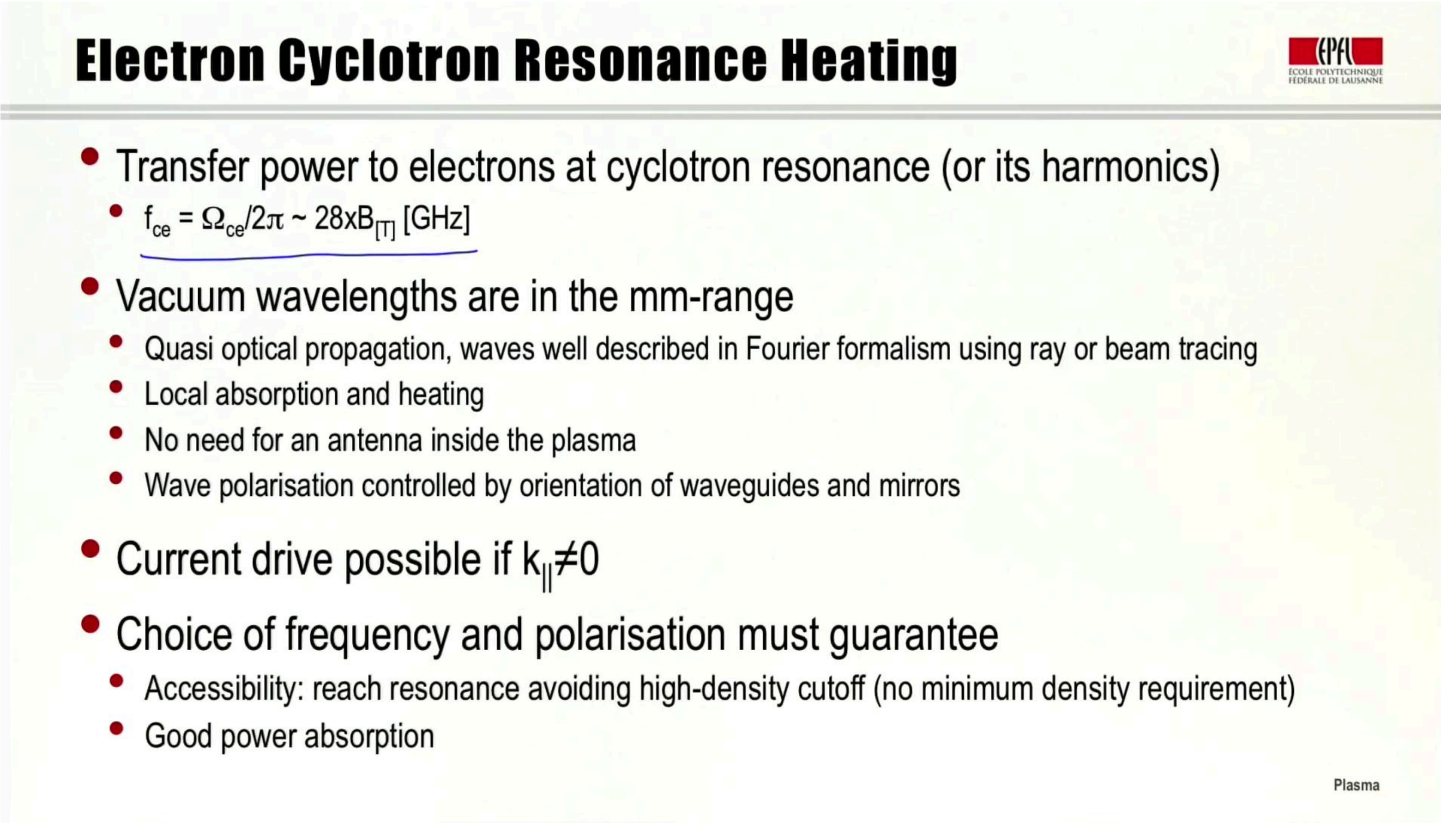


So these are general concepts that apply to different kinds of waves and we're now focusing on the electron cyclotron resonance heating scheme. The idea here is to transfer power to the electrons at the cyclotron resonance or at its harmonics. If I take the fundamental cyclotronic frequency, so n = 1, if you like, in the previous expression, and if I express that in terms of gigahertz [GHz], the value that I have is about 28 times the magnetic field expressed in tesla. So for a three-tesla device, we have something on the order of 100 GHz of frequency for the electron cyclotron resonance. At these high frequencies, the vacuum wavelengths are relatively small — they are in the millimeter range. That implies that the wave propagates in a quasi-optical manner, also that the wave is — reasonably well described in Fourier formalism and one can use ray or beam tracing to the describe the propagation of it into the plasma. Because the wave is a well-focused beam we can have local absorption and therefore local heating and even local current drive. Another important point is there is no need for an antenna to be placed inside a plasma, because of this quasi-optical propagation of the wave.

Notes

Summary

5m 06s

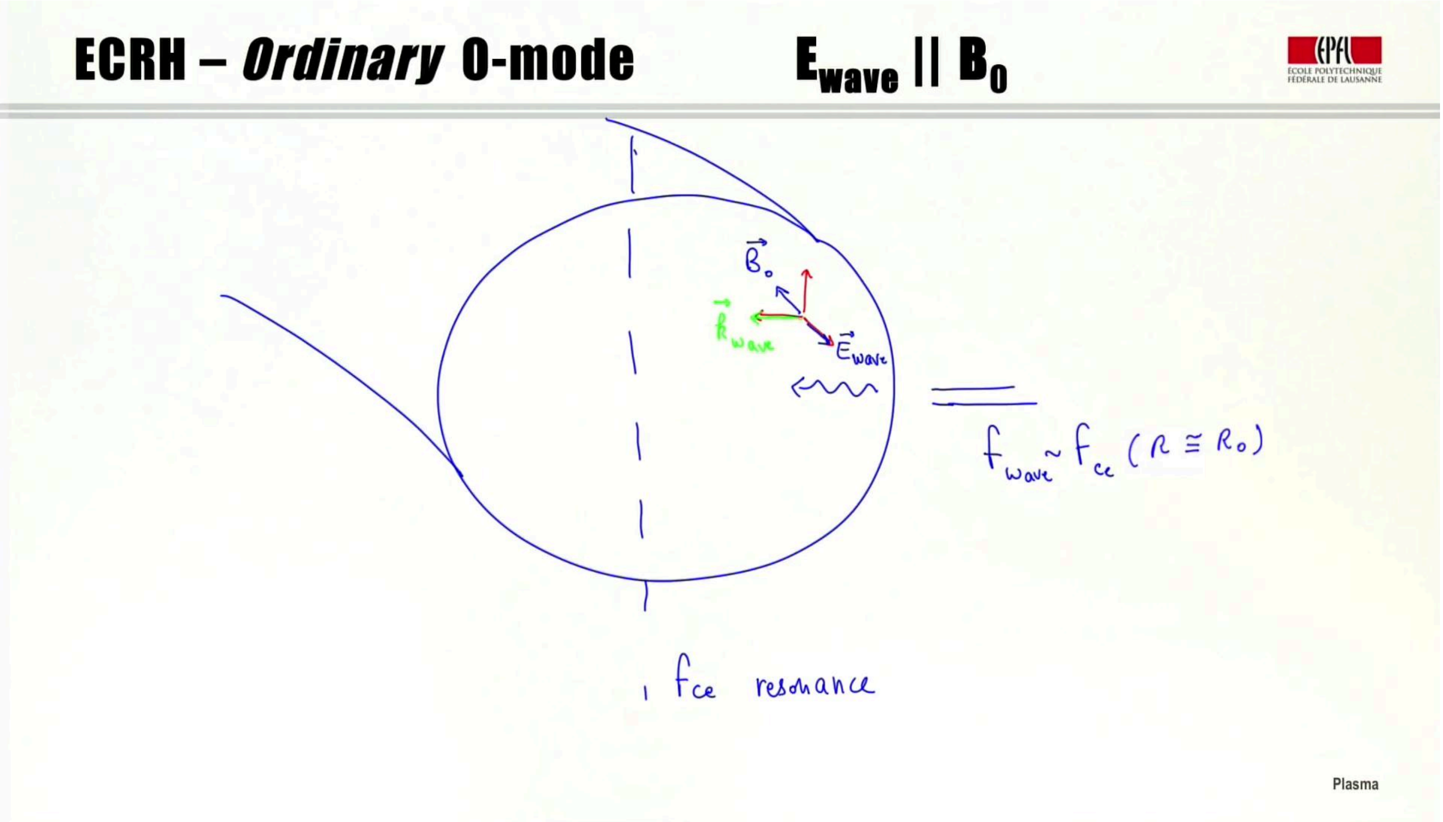


We need to have a launcher and/or mirror to steer the beam in the direction we'd like to go. The polarization of the wave can be determined by different components and controlled by the orientation of the waveguides and mirrors. If we inject the wave with a parallel wave number that's not zero, in other words we give it a direction with a component along the magnetic field that's not zero, we can drive current with the wave. So now we have to choose the frequency and the polarization that are adequate to guarantee two things— to guarantee what we call accessibility, that is, again, to reach the resonance avoiding the cutoff, which normally is implied by the presence of a density that's too high. I notice that in fact, there is no minimum density requirement for this scheme, as opposed to ICRH and lower hybrid and also, in order to have a good power absorption in a plasma.

Notes

Summary

6m 29s

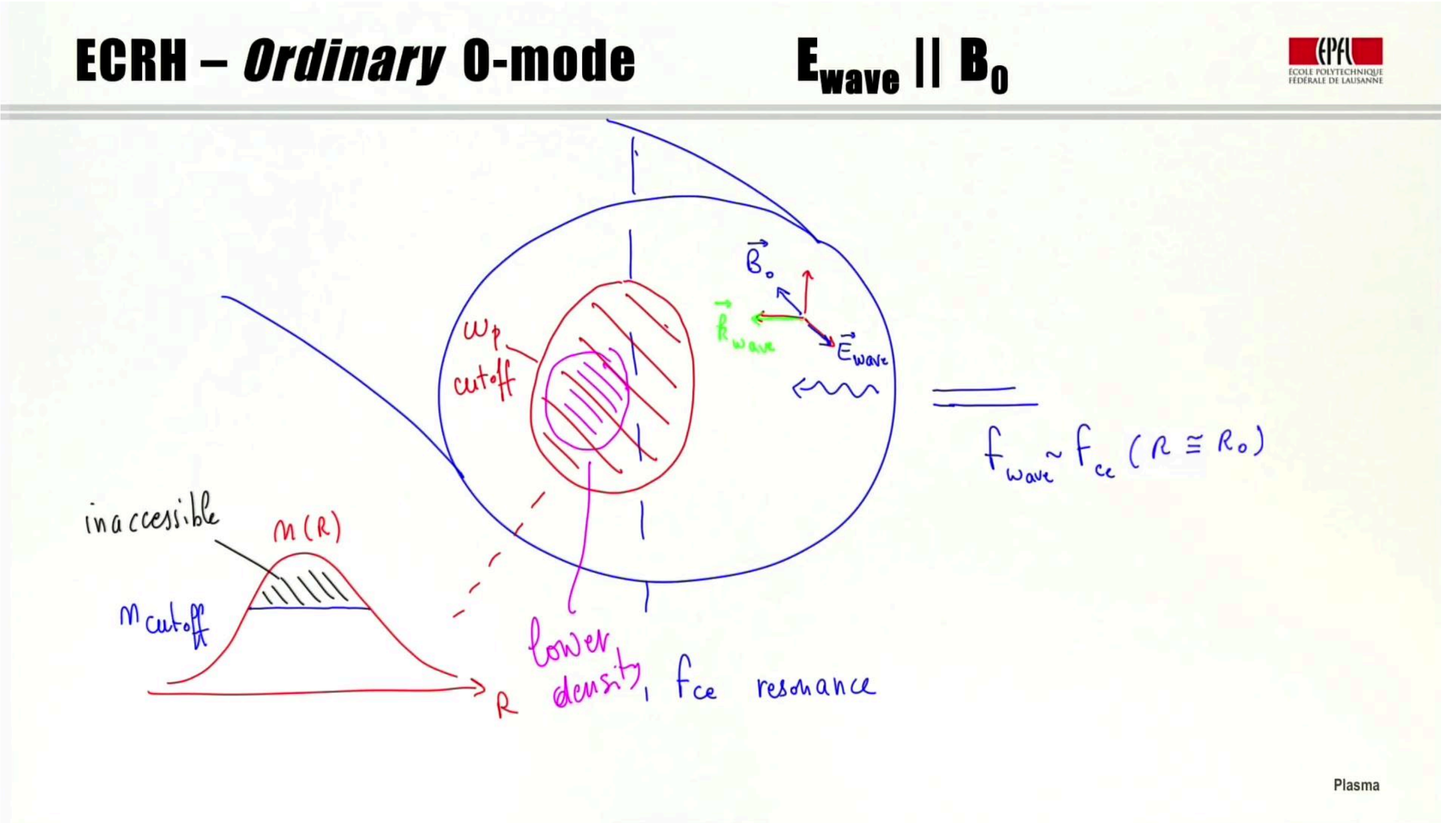


The first scheme we can think of is the so-called ordinary mode. As I said before, this is a mode in which the wave electric field is parallel to the ambient magnetic field. Let's illustrate the scenario that we can operate with. This is my tokamak plasma cross-section. I'm coming for practical reasons from the low field side, that is, from the outside part of the tokamak and I inject my wave in the radial direction, perpendicular to B_0, to the ambient magnetic field. Now this is the ordinary mode, so if I take a reference frame here, I would have a propagation that would be in the radial direction, a wave electric field that would be aligned with the magnetic field — of course the wave electric field will oscillate up and down its sign, and from the plasma point of view, we need to consider where are the cutoffs and where is the resonance. Suppose I choose a frequency for my wave that corresponds to the cyclotron frequency at the center of the plasma, or roughly at the center of the plasma. I'd like to reach that resonance, but what do I have to make sure of? I have to make sure that I don't hit a cutoff before that.

Notes

Summary

7m 29s

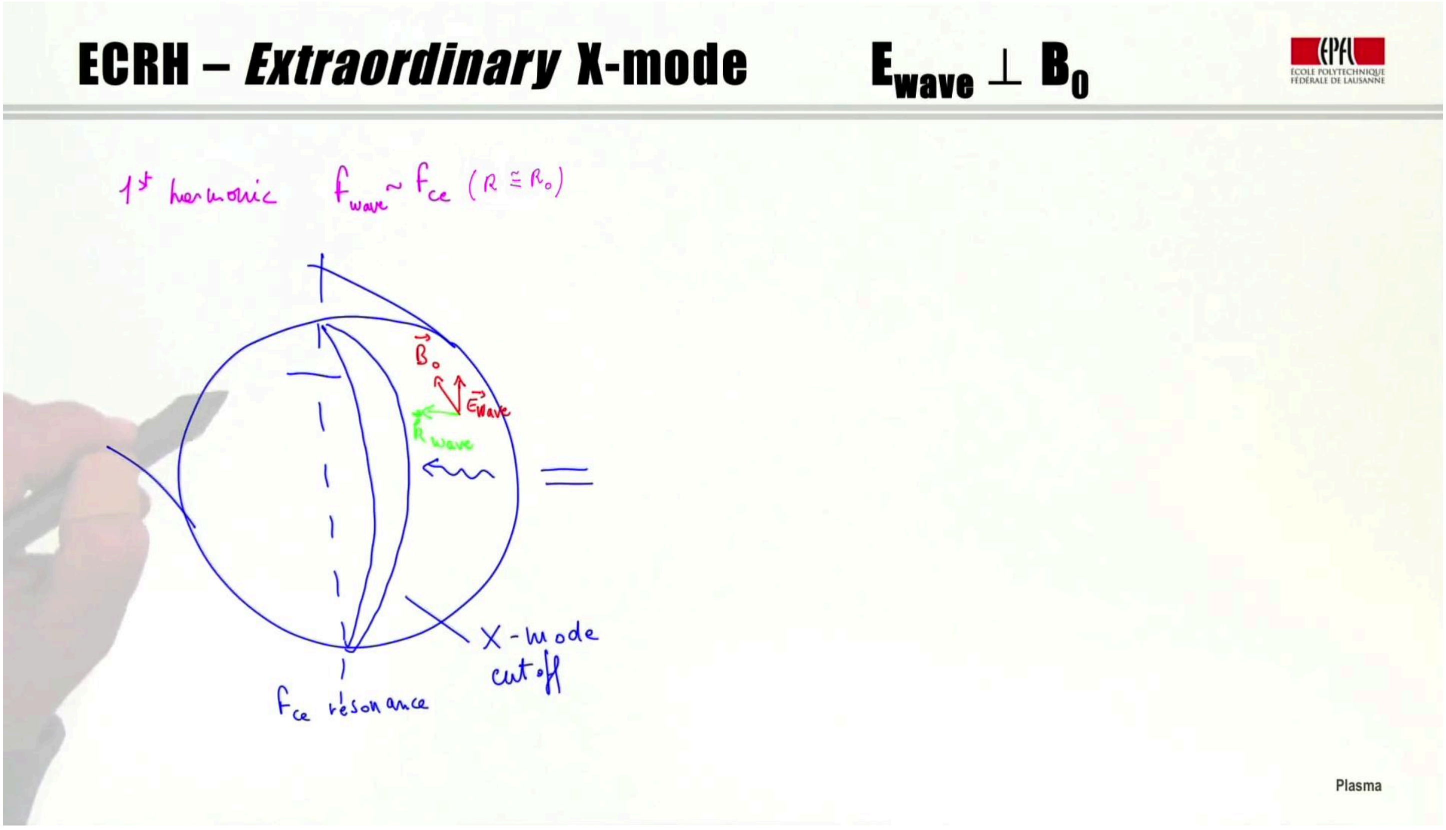


The cutoff for the ordinary mode is the plasma frequency [ωp] cutoff, so there will be a region that will be inaccessible to my wave because the frequency will correspond to a density that will be larger than the cutoff density. I'm illustrating that in a profile of the density itself. The black region above the cutoff density is inaccessible. So in the example here, I have my wave coming and before it reaches the resonance, which is corresponding to the wave frequency being equal to the local cyclotron frequency— and I was hoping that that would be in the center— I hit the cutoff relative to the ωp, to the plasma frequency which you have seen in the previous part of the course. So I can't have access to this resonance I was trying to reach. The only way I can go about that is to reduce the density in order to reach the resonant frequency corresponding to fc before I reach the corresponding cutoff. So say I take a lower density. Then I can indeed heat the plasma by heating the resonance before I reach the cutoff, which corresponds to a reflection point. So O-mode heating is possible but only up to a certain density value.

Notes

Summary

8m 55s

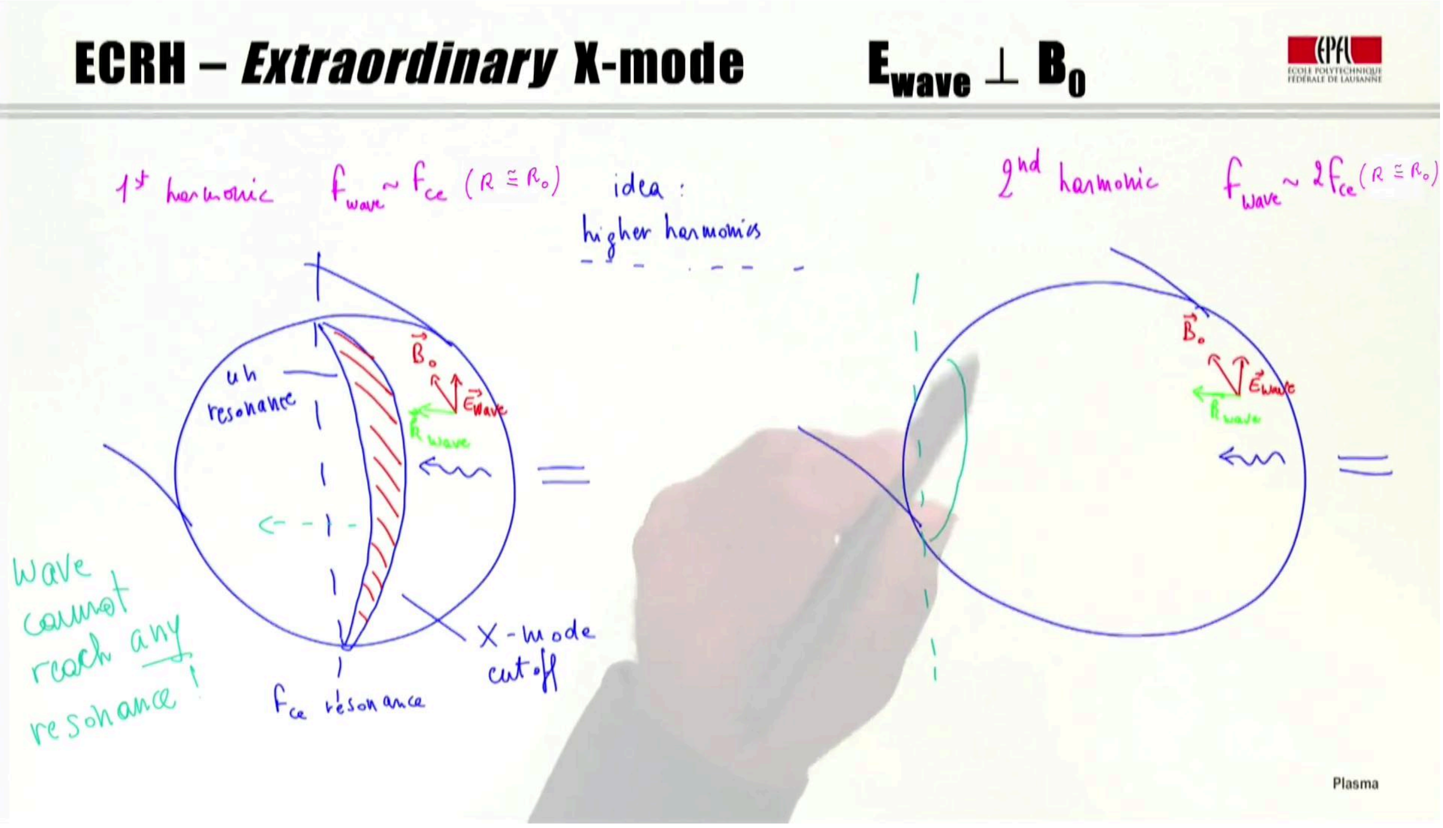


Let us now explore a second option that we have for the polarization, the so-called extraordinary mode or X-mode in which the oscillating field of the wave is perpendicular to the magnetic field. As we have seen, the dispersion relation for this mode is quite different from the ordinary mode. Let's consider first the first harmonic, that is, we have the frequency of the wave, roughly chosen to be corresponding to the resonance frequency of the electron cyclotron motion at, say, the plasma core. I draw my tokamak, I inject as before from the low field side with a waveguide that launches the waves towards the core. Polarization now is different. We have the wave electric field that's perpendicular to the ambient magnetic field, and the wave vector that is perpendicular to both and is directed in the radial direction. So we have, say, the cyclotron frequency roughly in the center. That's the fc resonance. But for the extraordinary mode, we also have the upper hybrid resonance, whose shape is dictated by the combination of the magnetic field and of the plasma density. And we have the x-mode cutoff, which is well represented by the fluid, the special relation, which is to the right-hand side of the upper hybrid resonance.

Notes

Summary

10m 22s

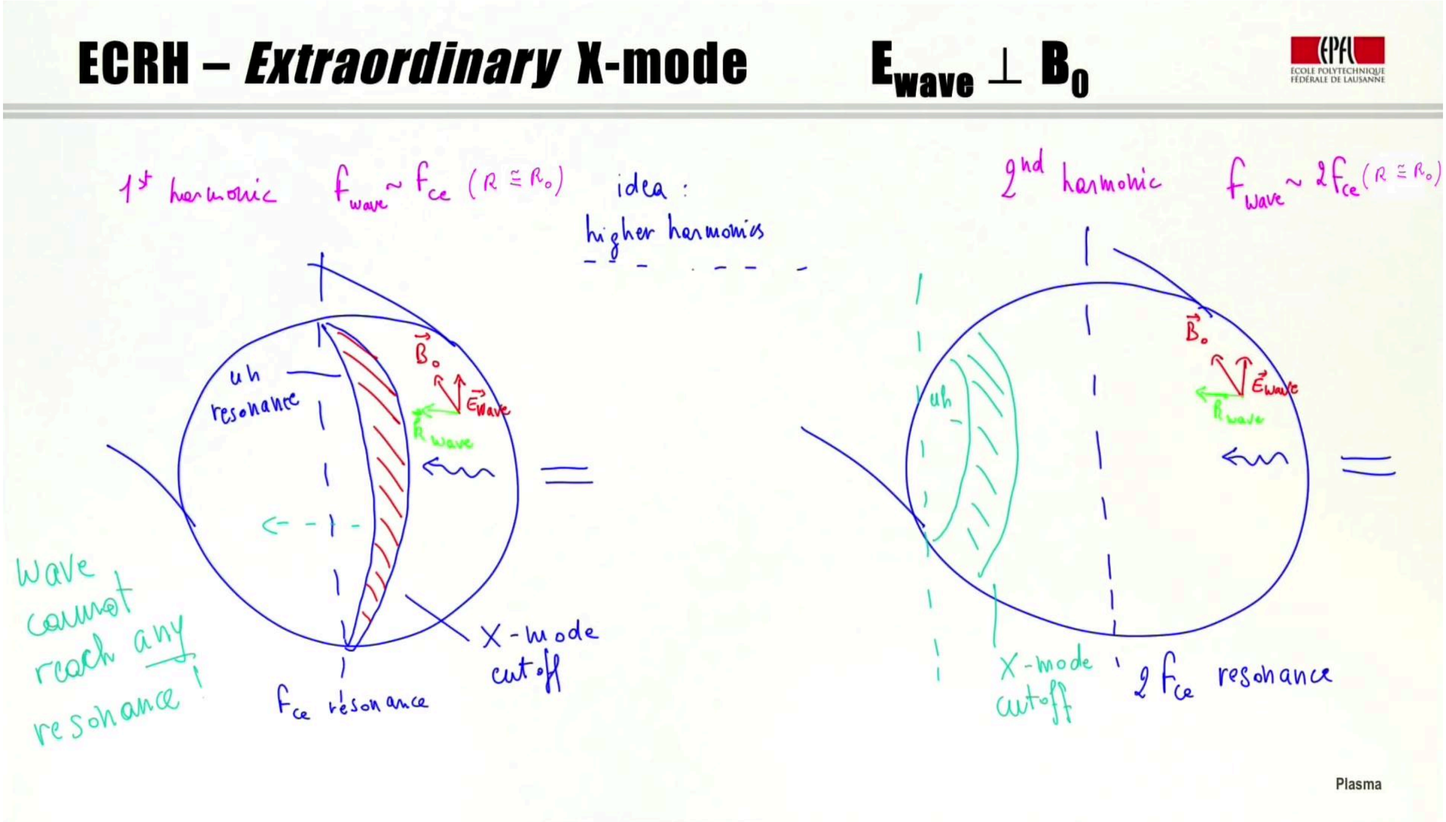


So this is my resonance, upper hybrid resonance, and this is the cutoff layer. So in fact, that means there's a forbidden area for propagation between the two. And if the wave comes from the low field side, it's bound to meet first the cutoff layer before it can have a chance of meeting the upper hybrid or the electron cyclotron resonance. So this cannot work because the wave cannot reach any resonance. So what can we do to improve the situation? The idea is to go to higher harmonics — say the second or even third harmonic of the electron cyclotron frequency. Let's take the example of the second harmonic. The frequency of the wave will be chosen to correspond roughly to two times the electron cyclotron frequency in the plasma core or close to the center. I'm still coming from the low field side with my wave, exact same way as before. Electric field perpendicular to B_0 and with a wave vector that's directed radially. Why does this help me? What have I done to improve the situation? Well, I have essentially taken the first harmonic resonance and the upper hybrid resonance and the cutoff all the way to the left. I have moved them all the way to the left so that they can be — the fc can even be outside a plasma — it doesn't really matter anymore.

Notes

Summary

11m 56s



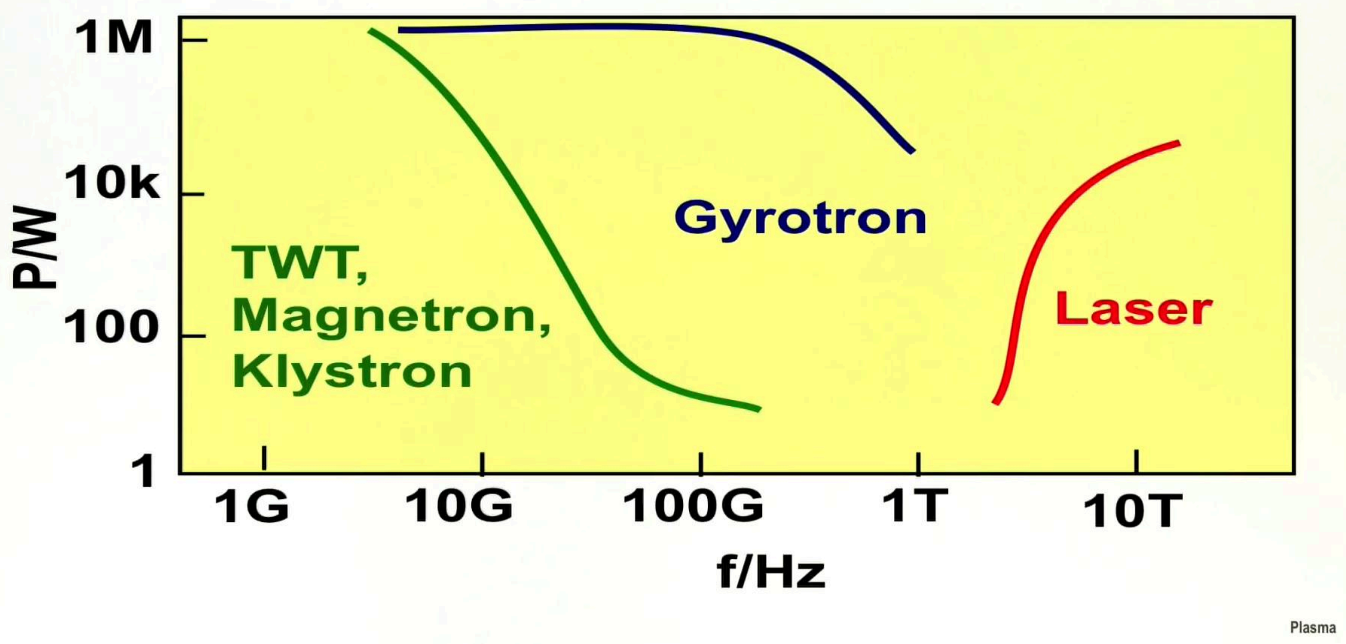
Upper hybrid would be somewhere in the plasma, of course — this is my upper hybrid layer — this is the X-mode cutoff. And the point is that the resonance that I'm trying to reach, which is the 2fce resonance, is now in front of the cutoff layer. So my wave coming from the right can indeed hit that resonance before it hits any cutoff layer, so before it's reflected back from the plasma back to the antenna on the launcher. So this is a situation which we can envisage to heat the plasma and even, if we direct the wave in a particular direction, drive current non-inductively through it. Now we note we can't really continue the scheme — we can think of having the third harmonic also, and therefore increase the density value corresponding to the X-mode cutoff but we can't do that indefinitely because we have, first of all, a reduced absorption efficiency as we go to higher and higher harmonics. Second of all, it will become difficult to have the availability of high-power sources at such increasingly high frequencies.

Notes

Summary

13m 46s

Power source for ECRH



In fact, as we said, the fundamental frequency for a 3-4 teslas device is of the order of 100 GHz. If we take the second harmonic, that will be 200 GHz, which is already quite difficult for a high-power source. What kind of power sources do we have in this range? This is illustrated in the picture where we can see the power that sources can provide on a logarithmic scale, see, 100, 10 kilowatt and 1 megawatt, as a function of the frequency. 100 GHZ is in this range, where we can see that the power that can be provided by relatively simple and conventional sources such as the traveling wave tube amplifier [TWT] or the Magnetron or the Klystron is actually very, very small. We're not yet in the frequency range where lasers can provide power, so what can we have as a source? We have something that's called a gyrotron. That's typically a source that covers the 10 to 100, 150, 200 GHz range of frequency.

Notes

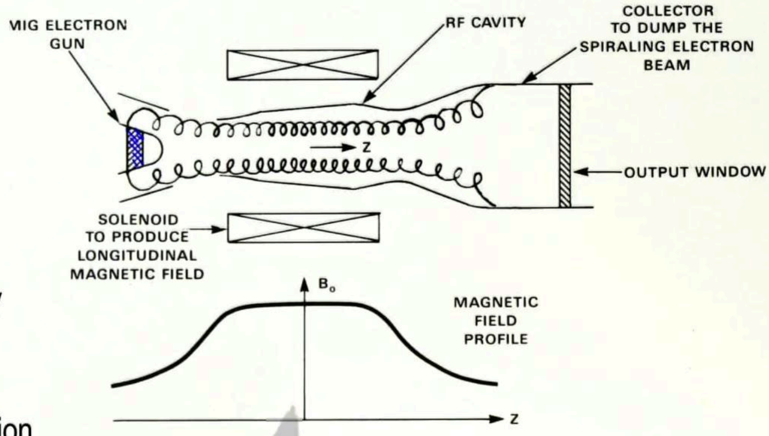
Summary

15m 07s

The gyrotron – basic principle

Principle based on Cyclotron Resonance Maser instability, a relativistic effect

- Annular electron beam
  - Source of free energy
- Magnetic field
  - Guides the e^- and determines the frequency
- Resonant cavity
  - Cylinder with a smoothly varying cross-section Resonant interaction between electrons and cavity mode



Plasma

What is a gyrotron? Let's look at the basic principles behind its functioning in very simple terms. The function is based on the so-called cyclotron resonance master instability, which is a relativistic effect associated with the bunching of the electron motion as they gyrate around the field lines. There are three essential components in a gyrotron. There's an electron beam that's annular, which is produced by a cathode, here, illustrated by this shadowed area, the electron beam propagates in the axial direction here guided by a strong magnetic field which is produced by the coils of which we see the cross-sections here, which again confines the electrons but also determines the frequency at which they gyrate around the field lines. Where the electron beam propagates and where the magnetic field is produced and where it's actually flat in its intensity, we have a resonant cavity. That's the third component of the gyrotron. It's essentially a cylinder with a smoothly varying cross-section and its resonant cavity allows resonant interaction between the electrons and the modes in the cavity — again, wave-particle resonance. The same kind that we are actually using, in some sense, to heat the plasma once the wave is launched into it.

Notes

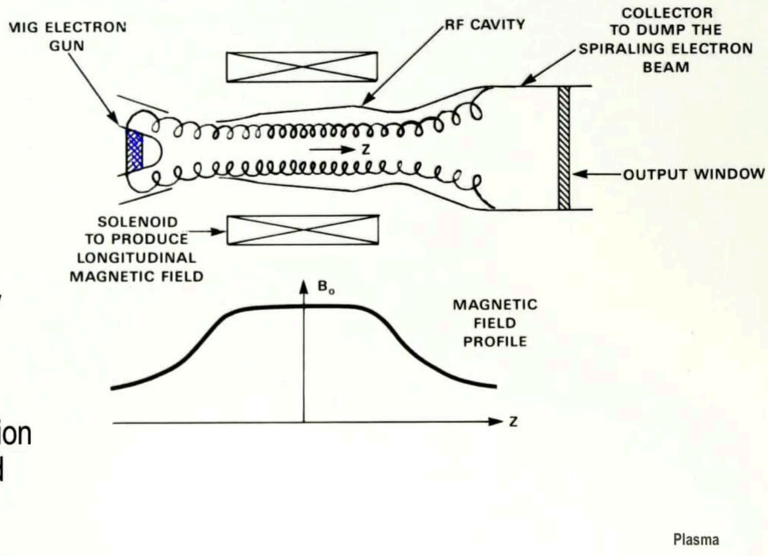
Summary

16m 19s

The gyrotron – basic principle

Principle based on Cyclotron Resonance Maser instability, a relativistic effect

- Annular electron beam
  - Source of free energy
- Magnetic field
  - Guides the e^- and determines the frequency
- Resonant cavity
  - Cylinder with a smoothly varying cross-section Resonant interaction between electrons and cavity mode



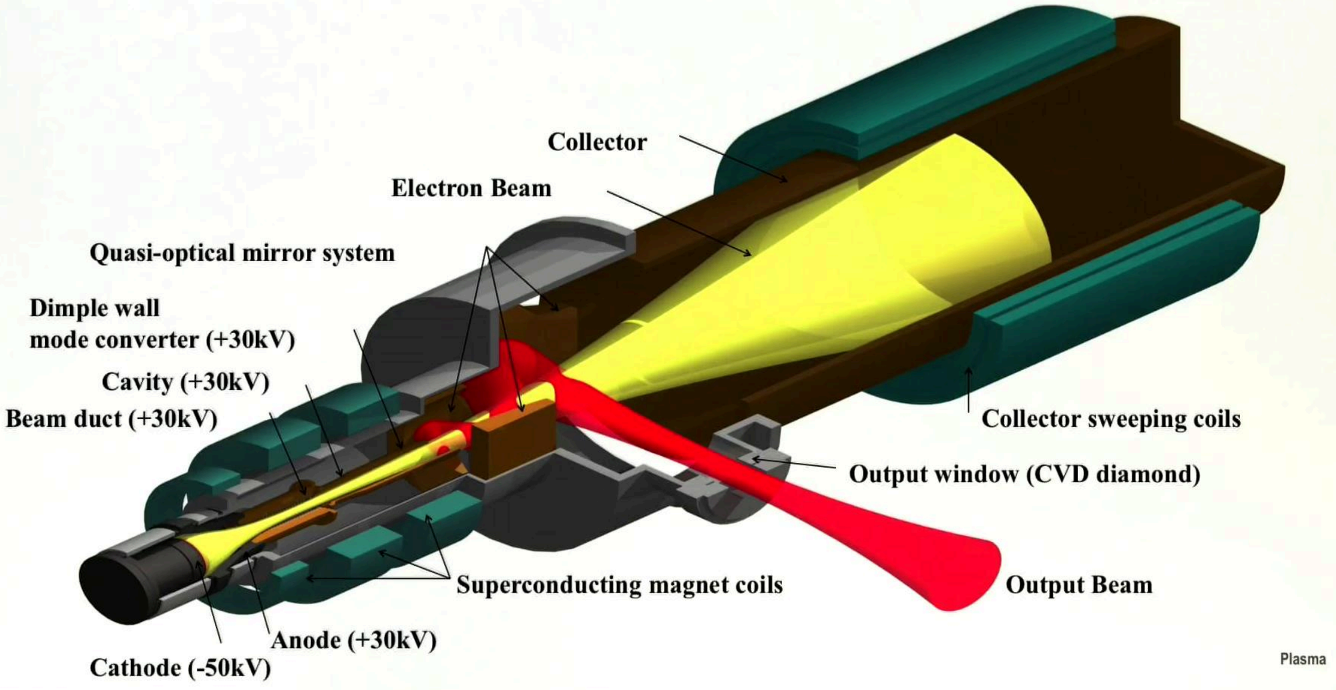
So what remains to be done is simply to extract the energy from this cavity using a window in the form of a particular polarization for an electromagnetic wave that will propagate in waveguides all the way to our tokamak plasma. Naturally, we need to dump the energy of the remaining electrons that have passed through the cavity and that have provided their energy or part of their energy to the electromagnetic wave in the cavity.

Notes

Summary

17m 45s

The gyrotron – layout

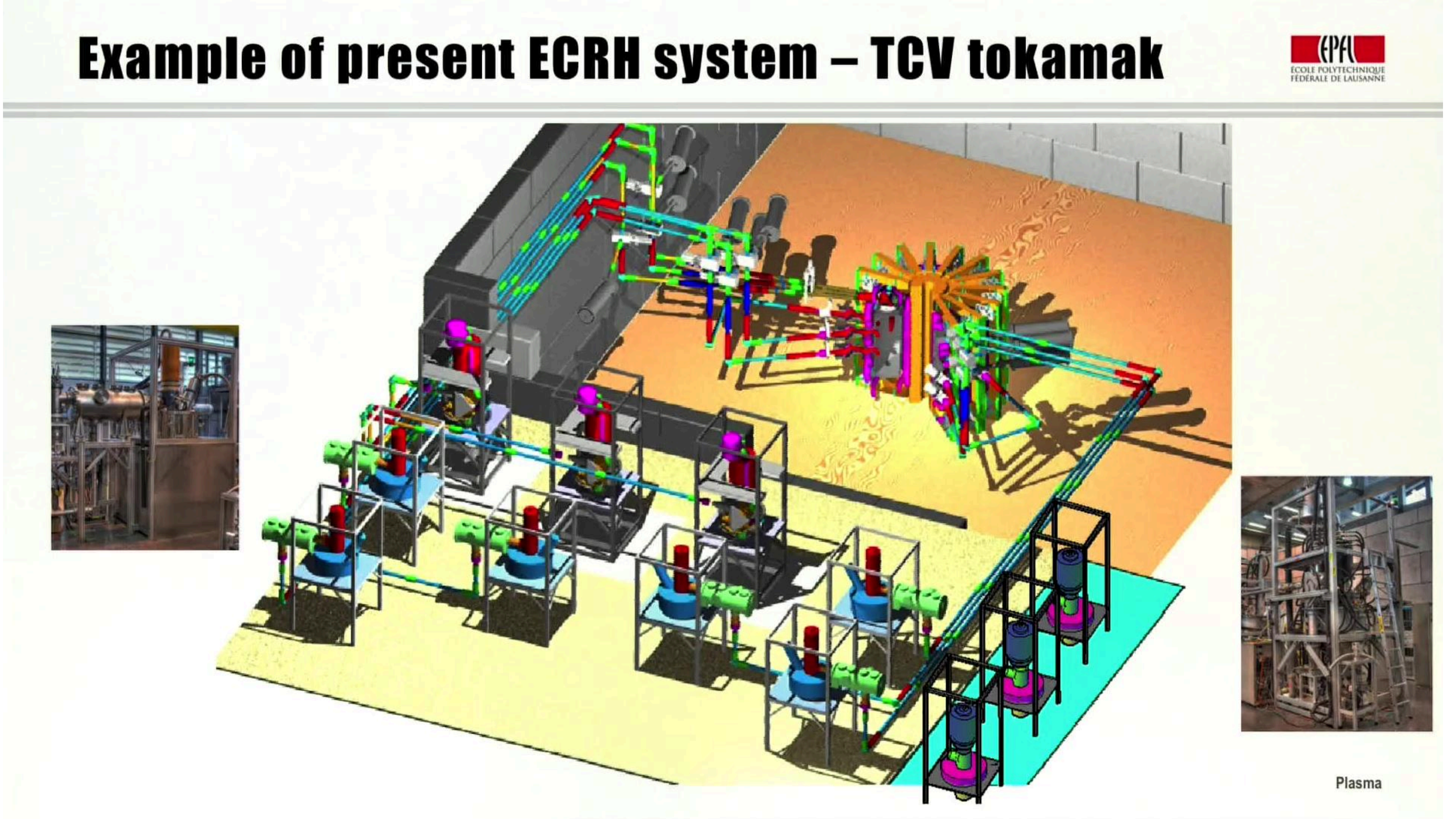


Here we see a broken view of the gyrotron — its layout. Once again, there's a cathode on this side, the annular beam, which is now represented in a yellow color; the guiding magnetic field, which is produced by a superconducting coil, typically; the resonant cavity; and the output window, through which we extract the electromagnetic wave in the form of a beam. The window typically needs to allow close to 100% of the power to be extracted, so it has to absorb very low amounts of the microwave power and typically is made of a CVD diamond. Then we of course have the collector that collects the electrons and their remaining energy.

Notes

Summary

18m 17s

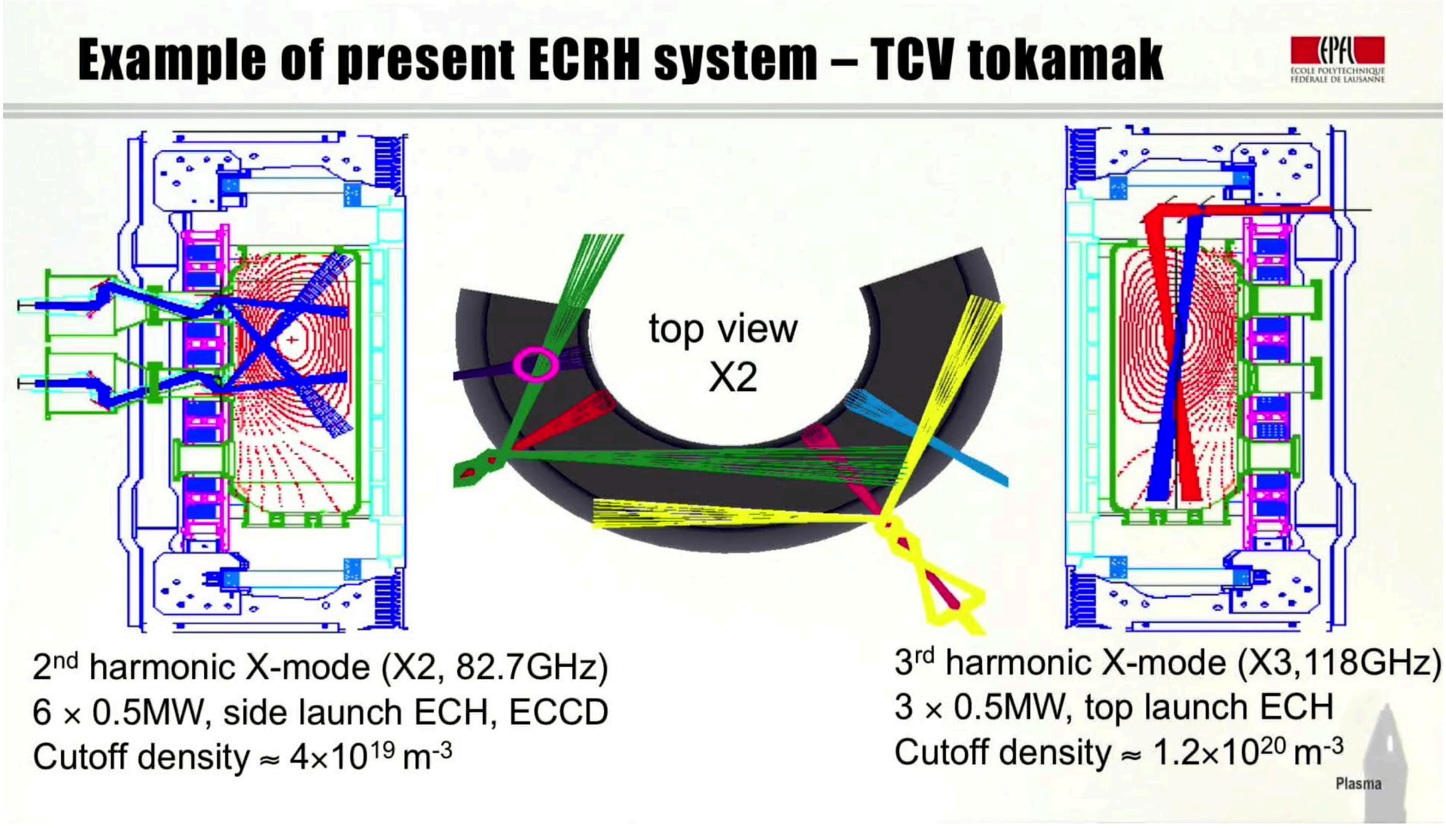


Let's look at the layout of an existing ECRH system — that's the system that we have on the TCV tokamak in Lausanne. There are two kinds of sources at two different frequencies, although all of them are gyrotrons, we can see here the different sources installed tens of meters away from the tokamak and connected to the tokamak by oversized, overmoded waveguides which guarantee the transport of the wave energy with very low amounts of losses. Then there is an injection of the wave energy into the tokamak plasma.

Notes

Summary

19m 13s

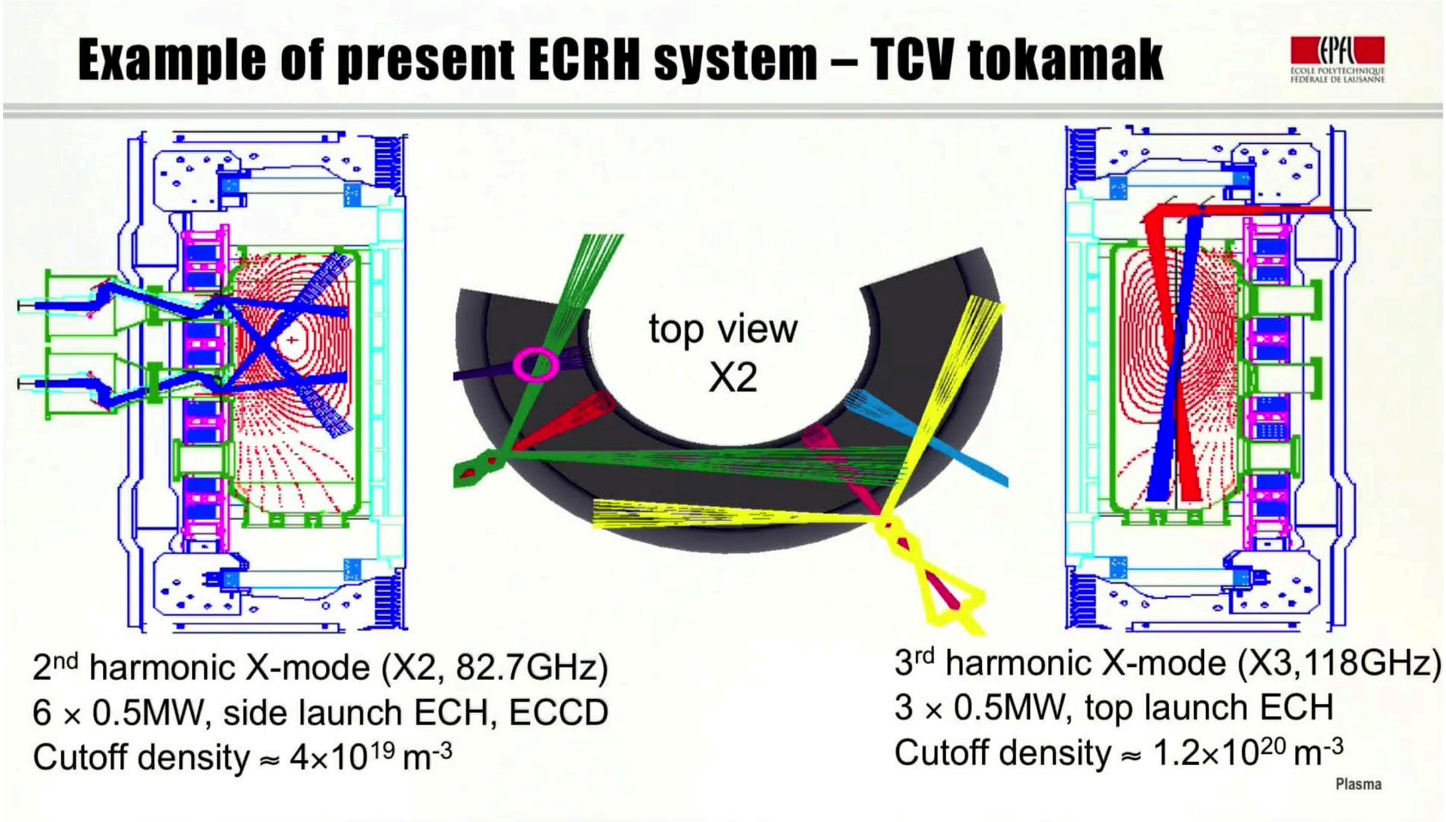


More specifically, to give you an idea of the parameters of the ECRH system, we have two subsystems. The one at the second harmonic X-mode, this is exactly the schema of operation we illustrated in simple terms a few minutes ago. We refer to that as X2. The actual frequency is about 83 gigaherz. There are six sources at this frequency, each one having half a megawatt, and we inject their power through side launchers, both to heat the plasma in determined locations inside the tokamak, and to launch waves with a particular direction, therefore to drive a current in the plasma, which we refer to as the ECCD scheme — electron cyclotron current drive scheme. Second harmonic X-mode has a cutoff density of a few times 10^{19} per cubic meter. If we see the top view of the injection points of the tokamak, we can see that by moving the steering mirror, we can in fact give an angle to the injection of the wave and determine the propagation in one direction or the other and therefore determine, also, current drive in one direction or the other. Current drive can be off-axis or on-axis depending, again, on the choice of the injection geometry. The second subsystem that we have is the system working at the third harmonic X-mode, referred to as X3.

Notes

Summary

19m 52s

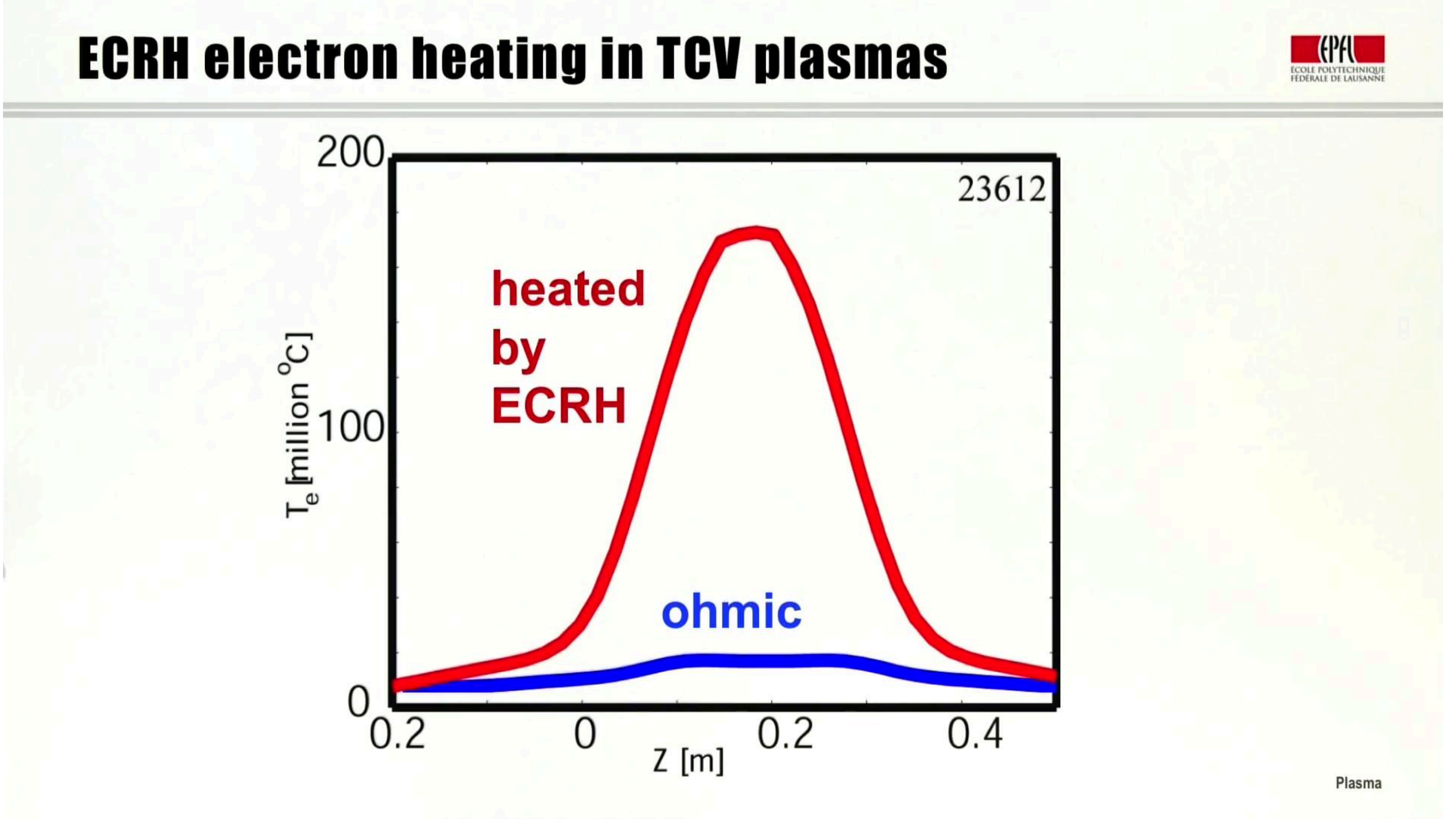


The frequency is in this case 118 GHz. We have so far 3 sources of half a megawatt each. They are injected from the top. As I said before in very qualitative terms, as we increase the harmonic number, so as we go higher and higher in frequency, the absorption efficiency is less and less. That's exactly why we inject from the top, so we have actually more plasma to go through in order for the absorption to reach good levels, even at the third harmonic. The advantage of the third harmonic is that its cutoff density, the density above which the wave cannot penetrate to the core, is higher, about 1.2 x 10^{20} per cubic meter.

Notes

Summary

21m 33s



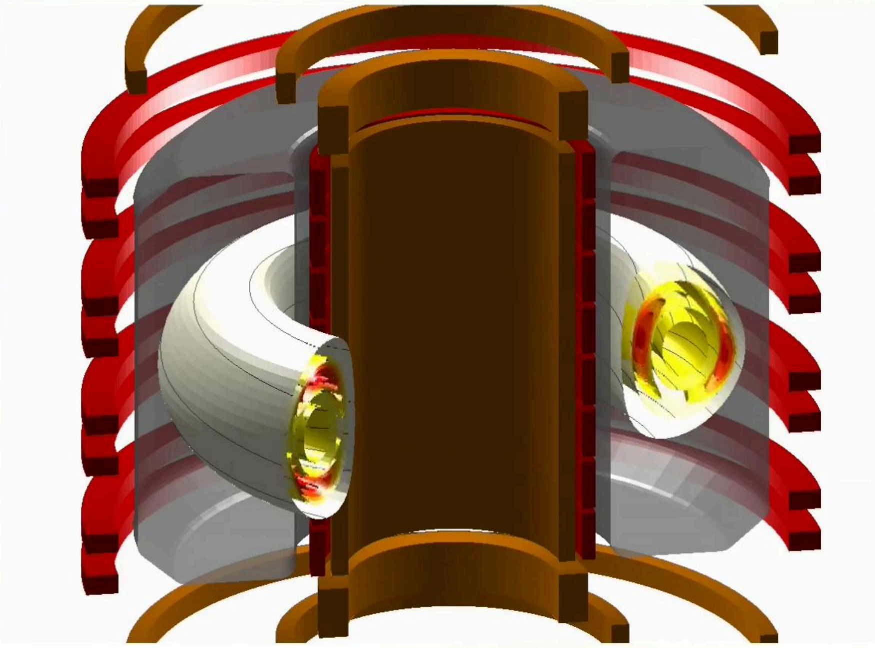
So we do inject these waves, first of all to heat the plasma, and how does plasma respond? I'd like to show just one very simple example. This is the profile of the electron temperature, expressed in millions of degrees. In the ohmic situation, that is the plasma which is only heated by the electrical current flowing in it, we have a fairly low and even a fairly flat temperature profile. If we inject these waves at the second harmonic or the X-mode, then we have very big and very high-profile, reaching values above 150 million degrees.

Notes

Summary

22m 21s

ECRH for instability control - tearing modes on TCV

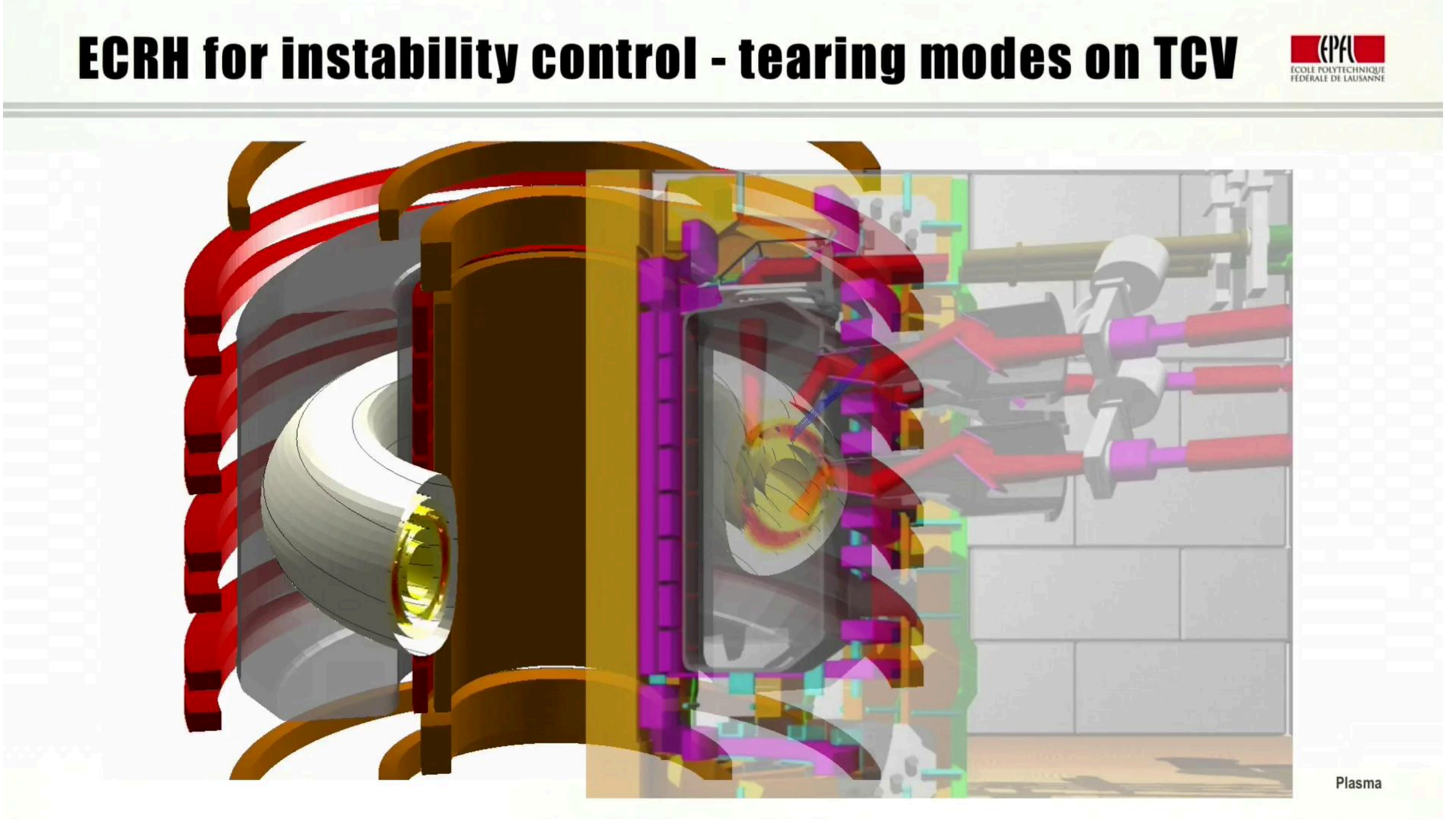


Another important point that was discovered in a number of experiments including TCV is that using ECRH power, locally deposited in particular points in a plasma some instabilities can be controlled or even suppressed completely. That's the case of the so-called tearing modes, which are instabilities that develop in the core of the plasma and provide a change even in the topology of the plasma, creating islands in the magnetic fields inside the plasma, therefore leading to a loss of heat from the core of the plasma.

Notes

Summary

23m 04s



You can see in this movie that this instability can develop in the TCV tokamak and can actually lead to a degradation of its performance. The point is that if we can inject a microwave beam exactly on top of that instability — the details of interaction between the beam and the magnetic island are too complicated to be discussed in this course — we can actually eliminate this instability, eliminate this bubble that leads to a degradation of performance.

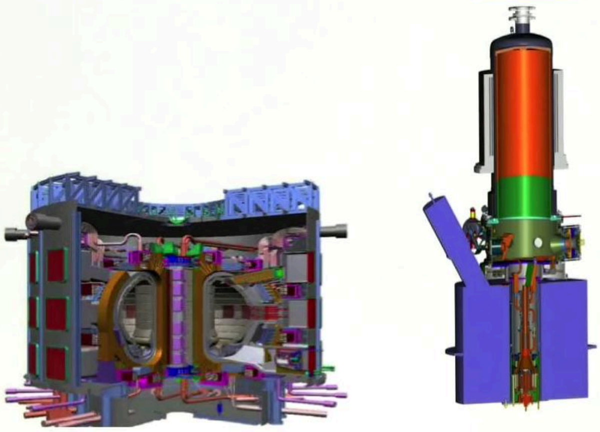
Notes

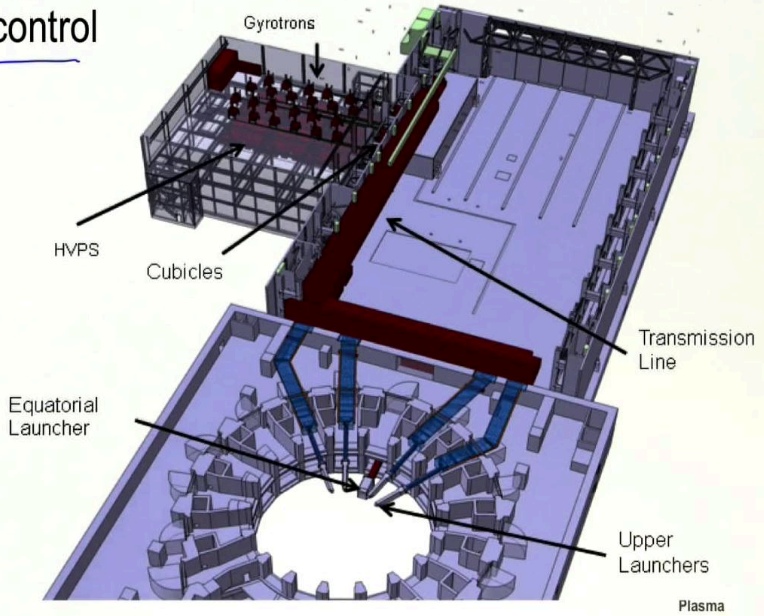
Summary

23m 45s

The ECRH system for ITER

Frequency 170GHz (O1 scheme), 24 gyrotrons x 1MW, continuous, for ionisation, heating, current drive and instability control





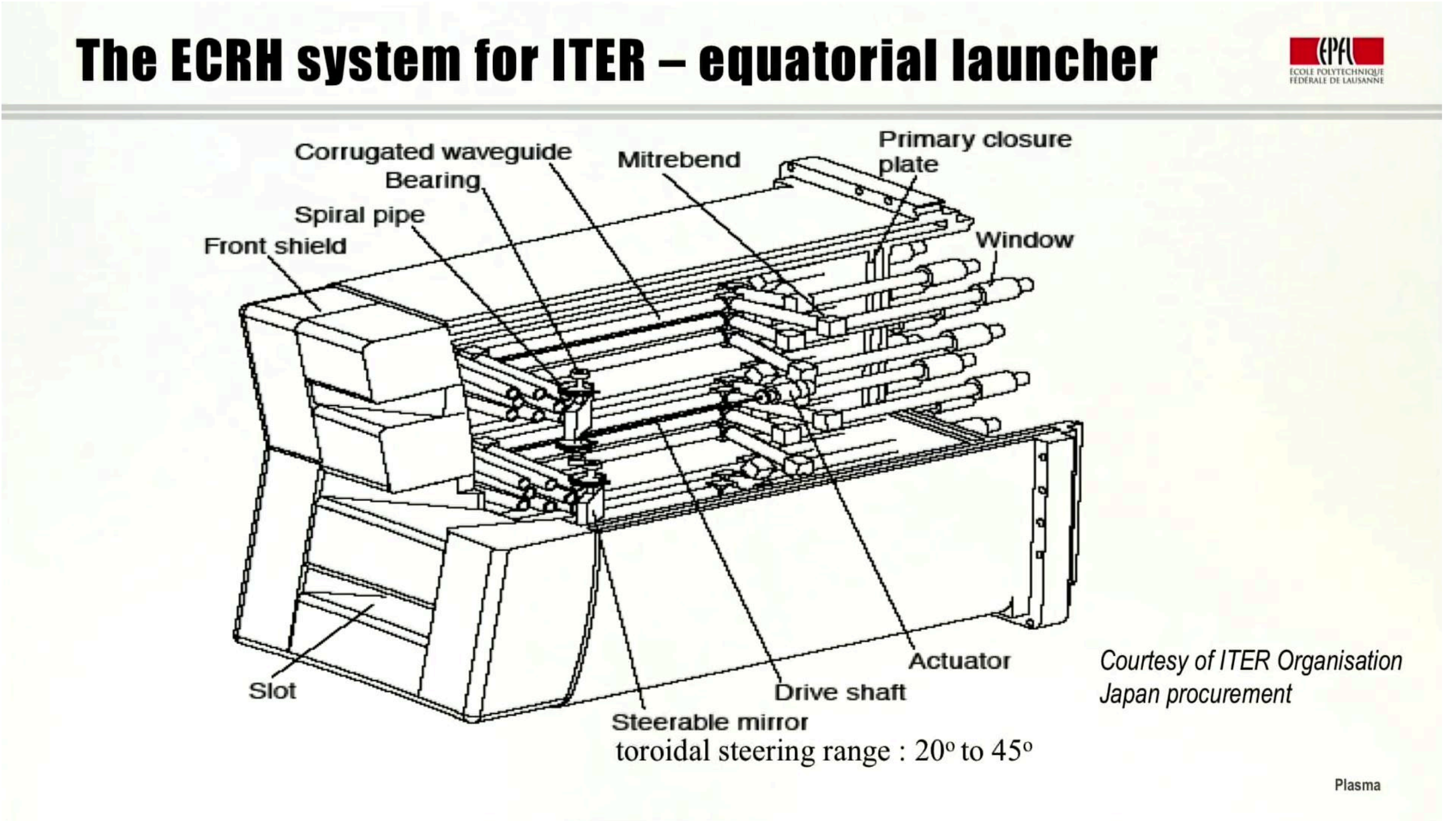
Courtesy of ITER Organisation

Let's now look at the ECRH system as it is being developed for ITER. ITER has a higher magnetic field than TCV, so it would be very hard, if not impossible, to find sources of microwaves at the second or third harmonic of the fce. That's why we're actually working with a so-called O1 scheme, that is, the first scheme we have seen together, the ordinary mode, being injected to deposit energy at the fundamental frequency f = fce. In ITER that corresponds to 170GHz. The system foresees 24 gyrotrons of 1 MW each in continuous wave operation - that's of course 24 MW — that will be used for a number of things in addition to heating: for ionizing the plasma to begin with and initiate the discharge, of course to heat the plasma core, to drive current non-inductively, to control the plasma current profile, and lengthen the ohmic pulse, eventually, and, as we have seen in the example of TCV, very importantly, to control the instability development. In fact, in ITER, this will be the primary goal of the ECRH system. Here you see an image of the layout of the system with the gyrotron sources — with 24 of them, quite far away from the tokamak hall, a set of transmission lines, and a set of launchers for injecting the power into the tokamak plasma.

Notes

Summary

24m 23s



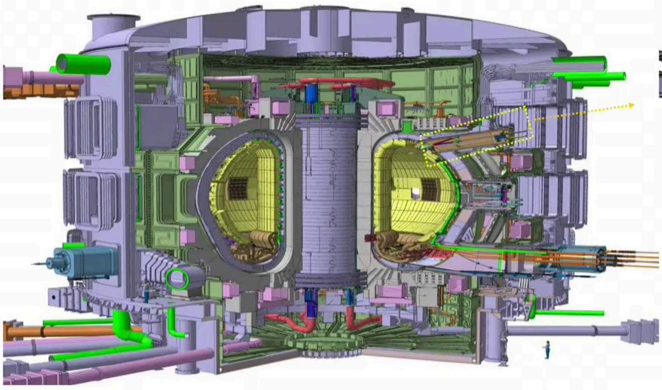
There will be one equatorial launcher to inject the power at the equatorial plane of ITER, and besides the details into which we will not go. I'd like to note that there's a steerable mirror so that there's a toroidal steering range from 20 to 45 degrees in the toroidal direction. This is a development that's been undertaken in Japan.

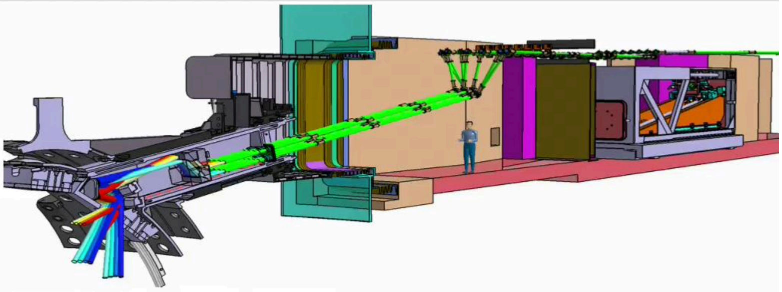
Notes

Summary

26m 09s

The ECRH system for ITER – upper launcher





4.5m, 50 tons, 8 x 1MW beams at 170GHz

Role: heat locally and stabilise plasma mode

Steering range: larger than ±6°

Tight focusing of the beam at the resonance surface to increase CD efficiency

Courtesy of ITER Organisation
EU / F4E procurement

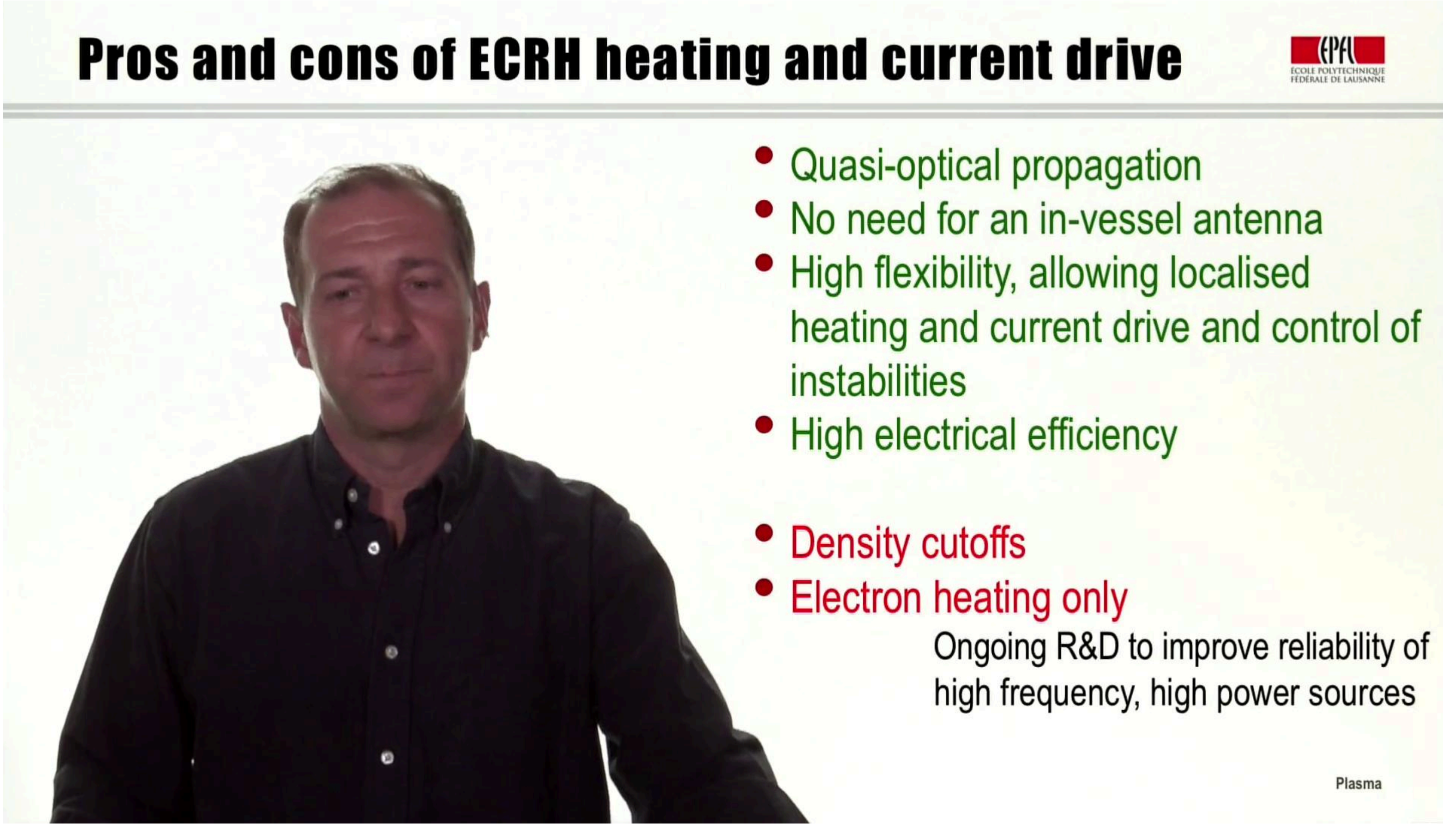
Plasma

There will also be a launcher from the top of the device, referred to as the upper launcher, which is being developed in a European context, and that launcher, - which in TCV is about 1 m long,- in this case is almost 5 m long, something that weighs 50 tons, and it has to pass 8 times 1 MW beams. at again, the electron cyclotron frequency for the ITER core, which is about 170 GHz. So the idea here is to be able to steer in real time the microwave beam to locally heat and stabilize the plasma instability in the same way we have discussed before. It's important to preserve the focusing of this beam, even after a very long travel from the original source so that the beam can be injected in a very localized way at a resonant surface and have a very good current drive efficiency for the local cure of the instability.

Notes

Summary

26m 33s

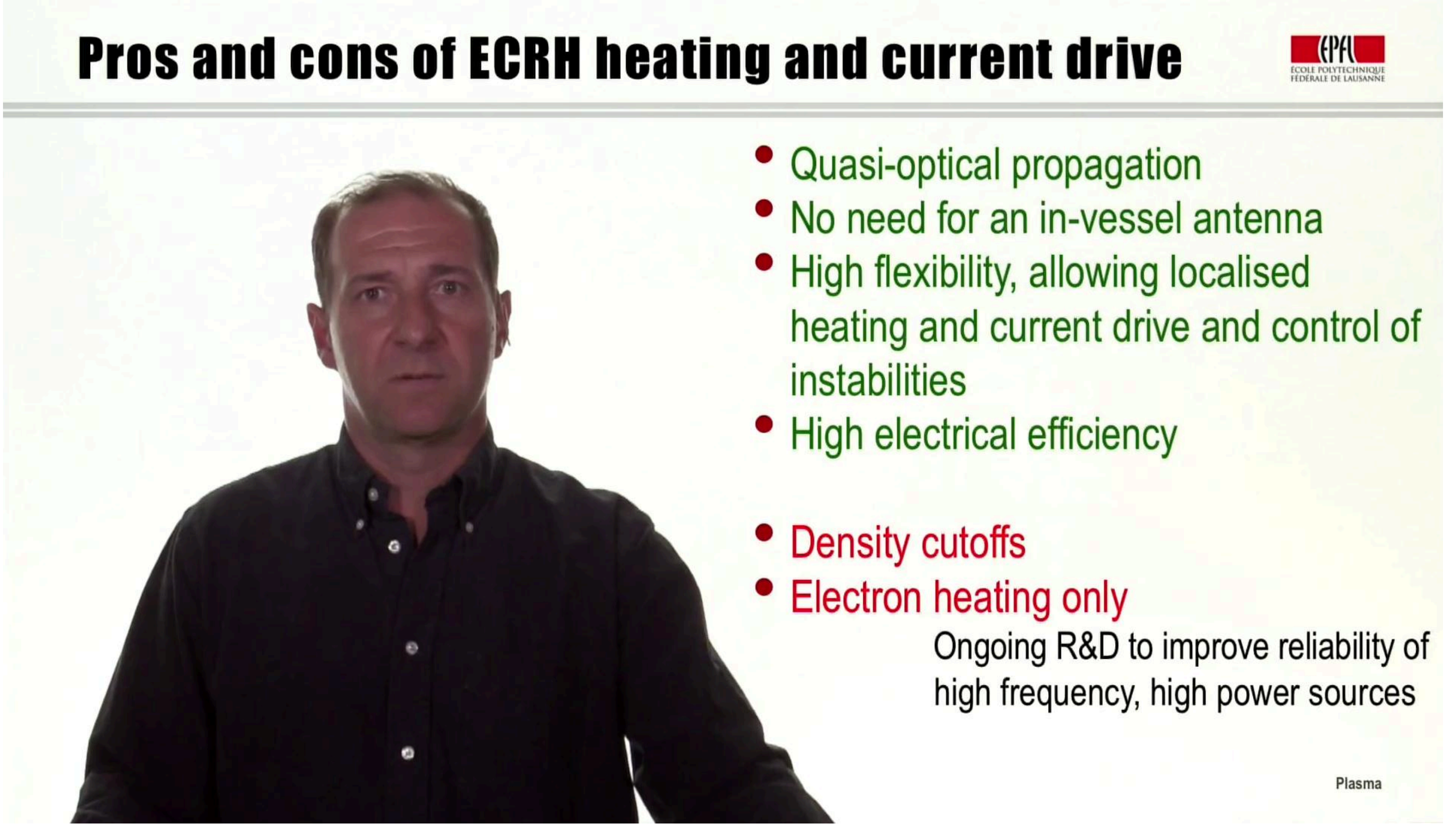


Let me just briefly discuss the advantages and disadvantages as I see them — a personal point of view of ECRH heating and current drive for ITER but also in general for fusion reactors. First of all, the high frequency of ECRH allows quasi-optical propagation, so you can have a source that is very far away from the plasma. There is no need for an in-vessel antenna. There is a high degree of flexibility, which allows localized heating and current drive and therefore a very good degree of capability of controlling instabilities locally in the plasma. There's an instrinsic advantage, at least a very important potential advantage, in the high electrical efficiency of the sources for microwaves. They are foreseen to go up to 50% in efficiency, which is very important for the fusion reactors in the future. Some drawbacks can be mentioned. There is still the issue of the density cutoffs, which are different in different schemes, so we cannot heat above a certain density, and of course, electron cyclotron resonance heating heats electrons which don't provide fusion reactions, so we will have to have a collisional transfer of the electron energy to ion energy after we have deposited our heating to the electrons used in the ECRH.

Notes

Summary

27m 41s



I'd like to mention that the question of the reliability of the high-frequency and high-power sources is being addressed at the moment — the hope is to go to very high levels of reliability in the future so that will become actually a pro rather than a con.

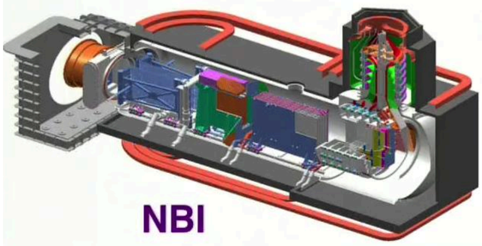
Notes

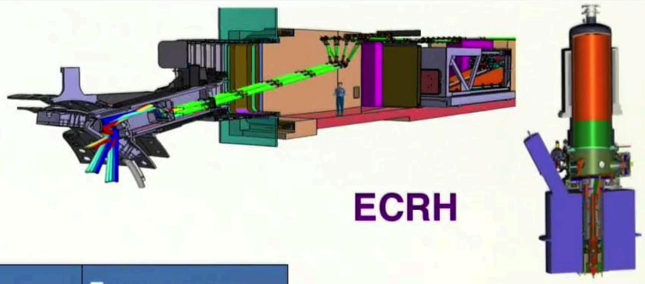
Summary

29m 11s

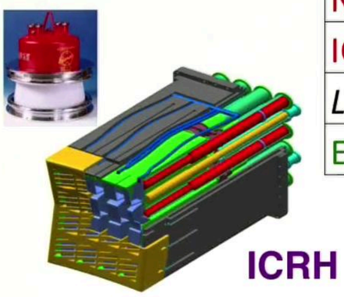
The plasma additional heating systems for ITER

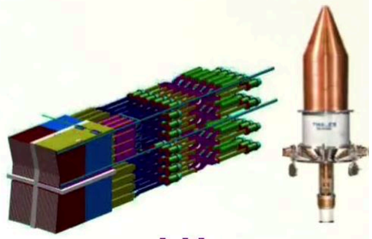
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE





System	Power [MW]	Frequency
NBI	33 MW	N/A
ICRH	20 MW	40-55 MHz
LH	*20 MW (second stage)*	*5 GHz*
ECRH	24 MW	170 GHz





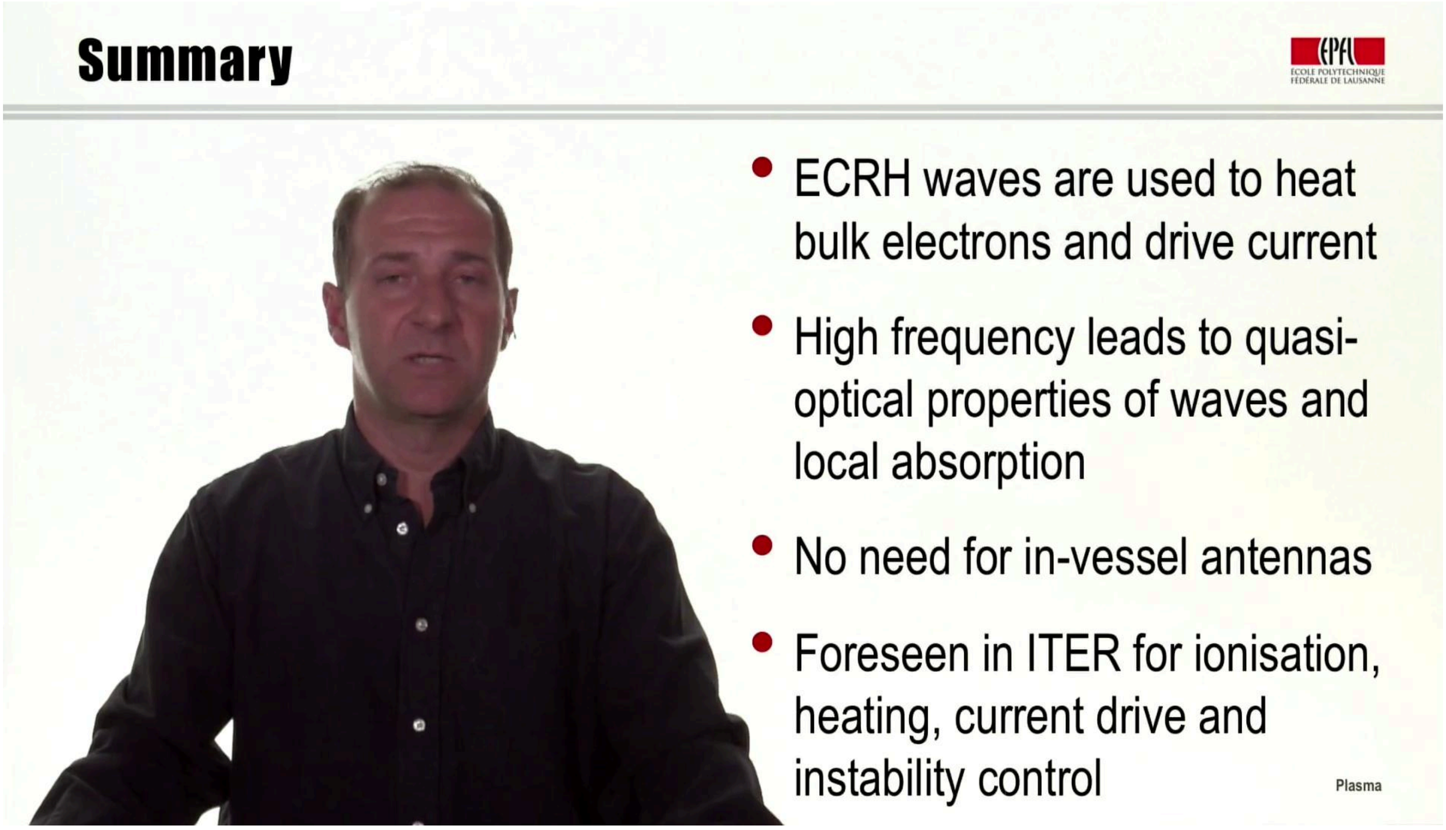
Plasma

So as a summary of these three lectures on additional heating of the plasma, I put here a table with the systems foreseen for ITER, that in a sense summarizes the state of the art in this field. For ITER we are foreseeing to have a neutral beam injector with a power of 33 MW. Of course we can't define the frequency for that; it's not based on the wave principle. That's for heating and current drive. We have an ICRH system of 20 MW with a frequency between 40 and 55 MHz resonating with the ion species in the core of the heated plasma, mostly for heating. We are anticipating to install the lower hybrid heating and current drive system, but only in the second stage, so that's not the system that's foreseen for the first stage of the ITER operation. Also, with a power of about 20 MW and a frequency corresponding to the lower hybrid wave in the core of the ITER plasma of about 5 GHz. Finally, we are also preparing an ECRH system which will have 24 MW of power, as we have seen, at a frequency 170 GHz, and the reason I put this in green, is that this is the only system that would be needed for day 1 of the ITER operation.

Notes

Summary

29m 27s



We are now ready to very briefly summarize this lecture. We have seen that ECRH waves are used to heat bulk electrons and to drive current in the plasma. The high frequency of these waves leads to quasi-optical properties of them, and to local absorption, which is essential for heating, for driving current, and for controlling instabilities in the plasma. There is no need for in-vessel antennas, so all the problems we have discussed for ICRH and lower hybrid waves are overcome. Of course, the ECRH system is foreseen in ITER — for ionizing the plasma to begin with, for heating the plasma, for driving current in the plasma, and most importantly for controlling these instabilities.

Notes

Summary

31m 01s