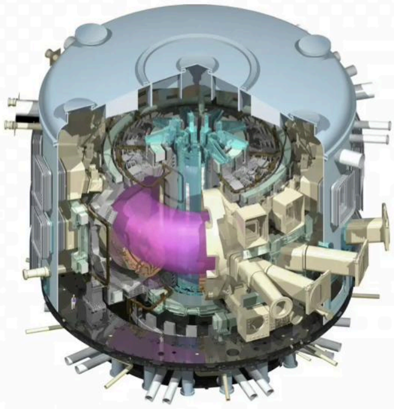
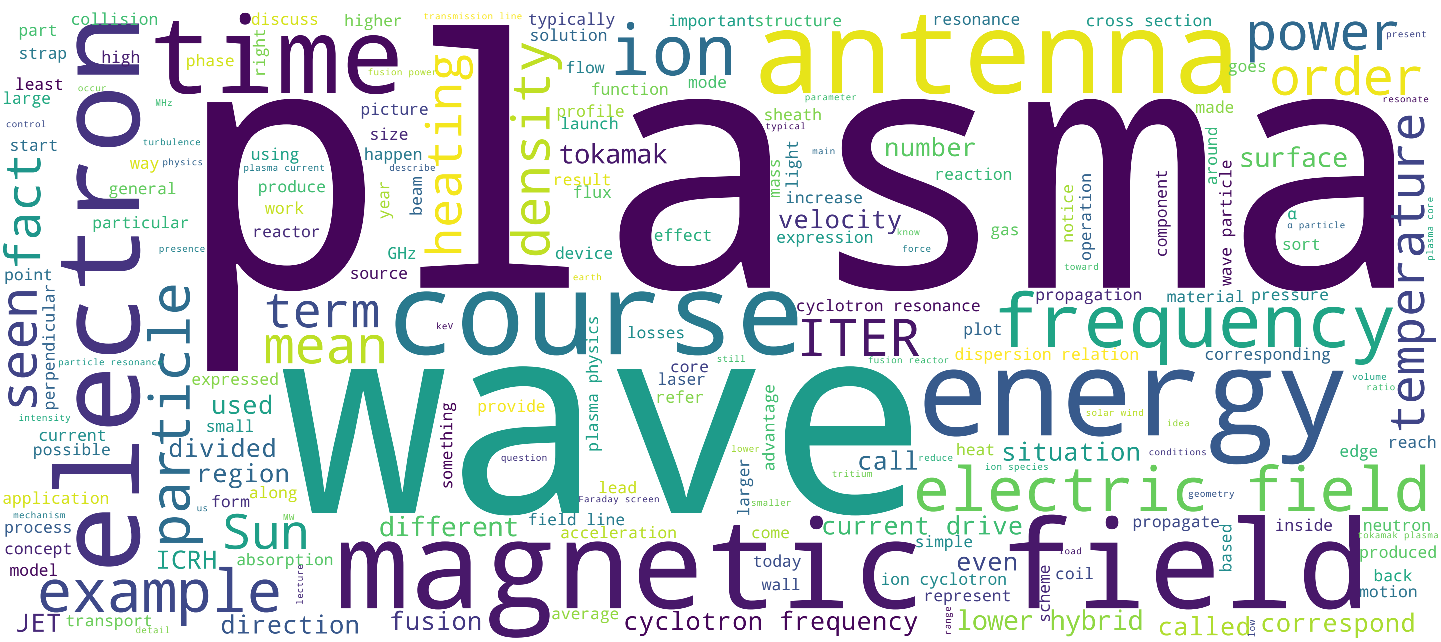


# Heating and current drive by waves – ICRH and LH

## Plasma Physics and Application to Fusion Energy, Astrophysics and Industry

**Lecture 7g**

Ambrogio Fasoli

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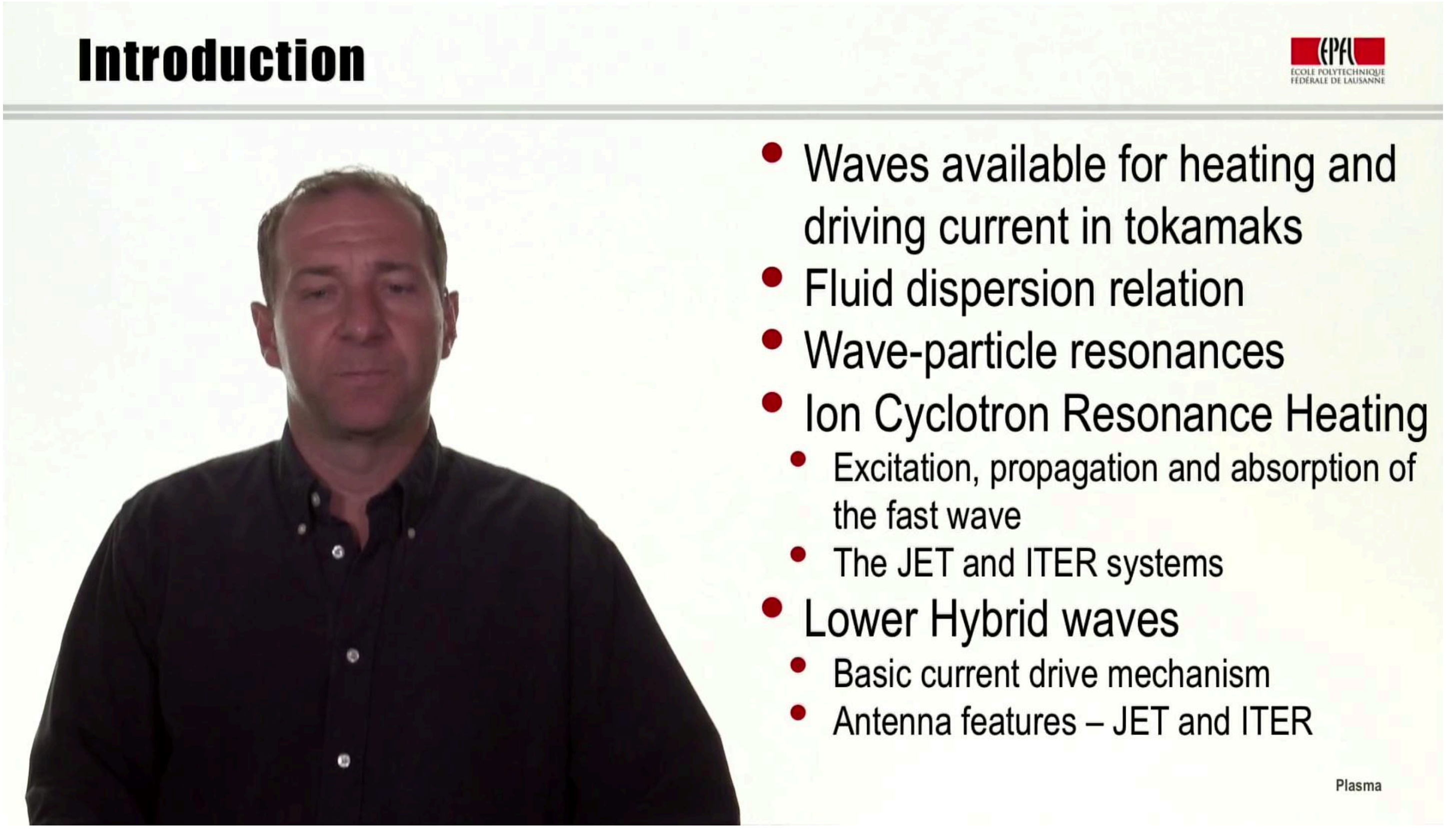
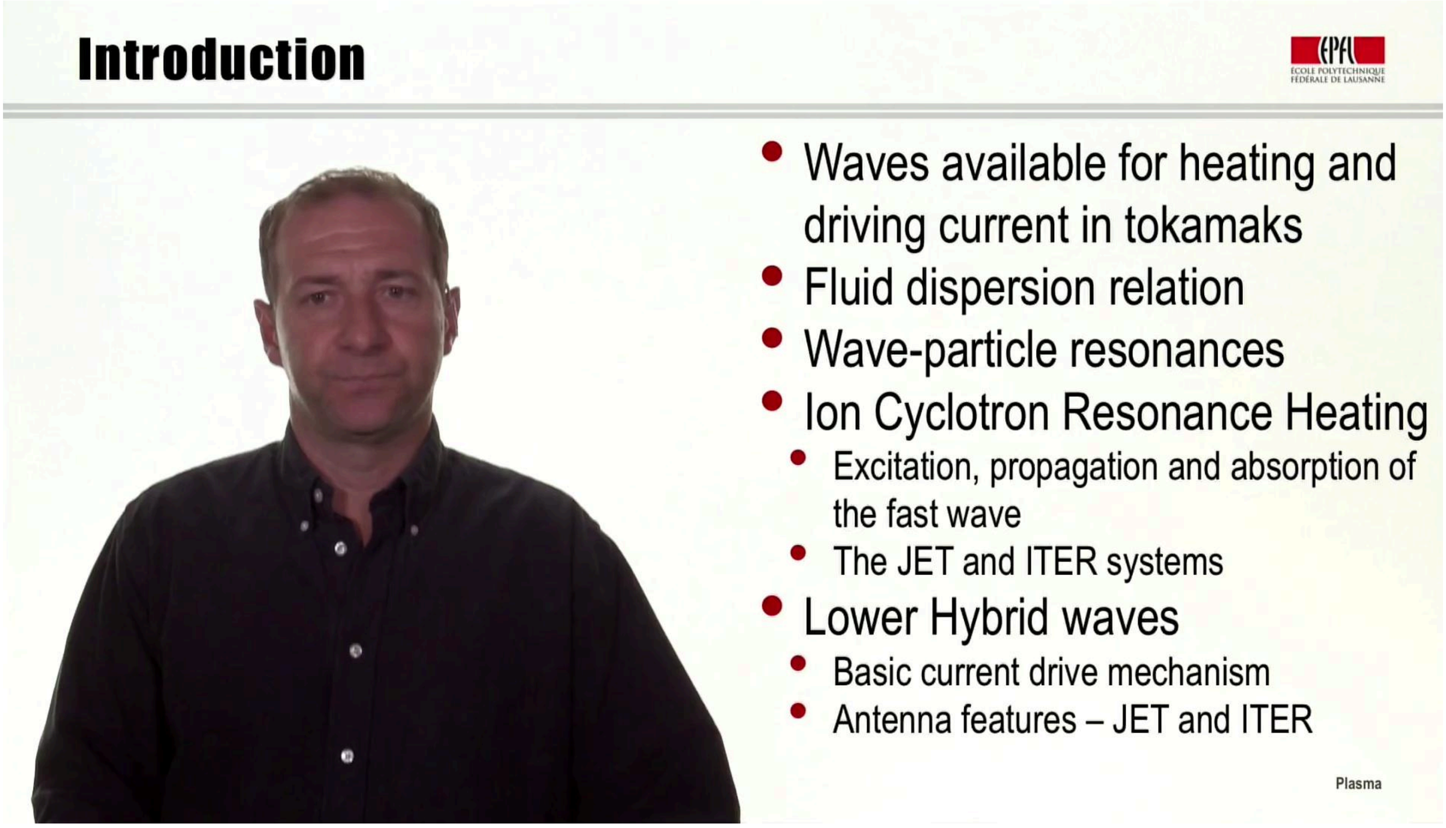



Welcome to the course on plasma physics and applications. We have seen in the last lecture that we need to go beyond ohmic heating of a plasma to reach thermonuclear conditions, that is beyond the heating that can be provided by the electric current that flows into the plasma. Today, we will address the heating and current drive that we can obtain using waves in a plasma. We will explore what waves are available for heating and current drive in tokamaks in particular. We will investigate the fluid dispersion relation that you have derived in the first part of the course and how that can be used to decide what waves can be employed for heating the plasma. We'll investigate the resonance between waves and particles that are necessary to transfer energy from the waves to the plasma and then we'll focus on two systems: the ion cyclotron resonance heating system, that's based on the resonance between the wave and the ion population. We will look at the excitation, propagation, and absorption of the wave that carries the energy in this frequency range and at practical systems that we have available today. For example, in JET and that we are developing for ITER.

Notes

Summary

0m 05s



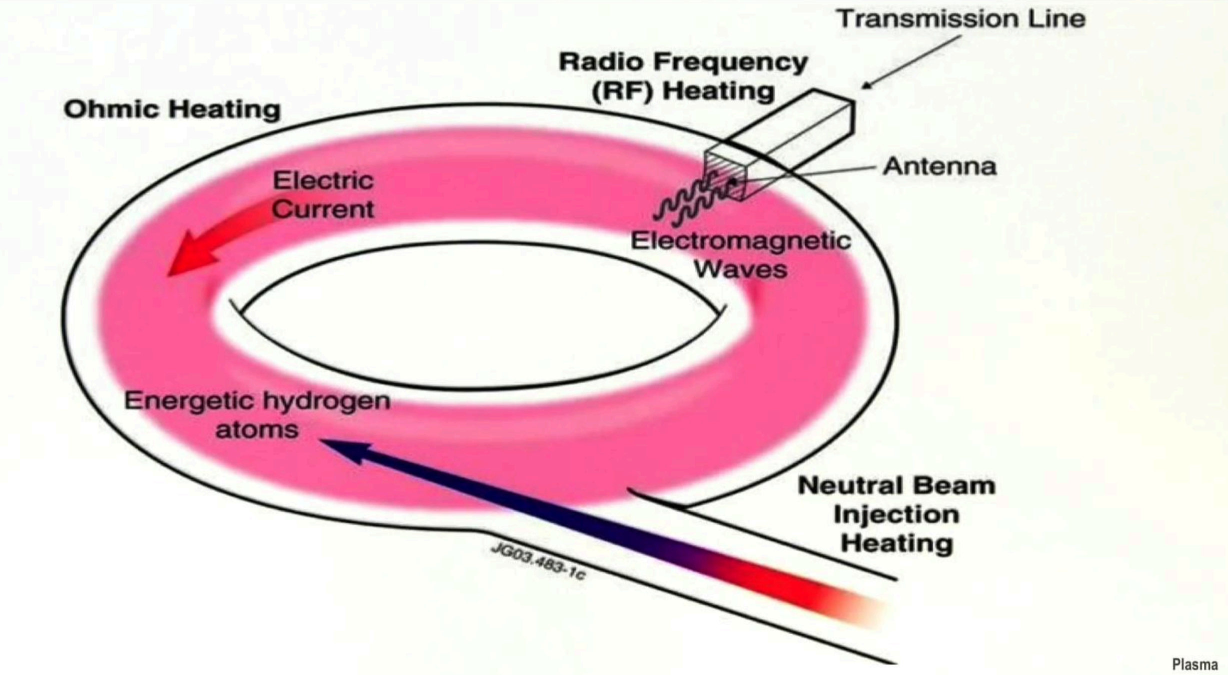

We will then look at the lower hybrid wave system for basically driving non-inductive current in the plasma and explore some of the antenna features again for an existing system that of JET and for the system for seen for ITER.

Notes

Summary

1m 26s

# Additional plasma heating




I just remind you that among the different possibilities we have to heat the plasma, in addition to the electrical current that we have seen is not sufficient to reach thermonuclear temperatures, we have the injection of a neutral beams that we have explored in the last lecture and the injection of electro-magnetic waves, which is, again, the subject of this particular lecture. That works by having a transmission line to which we couple power from an external generator, an antenna, that's used to launch the waves. Of course, the waves themselves, they have to propagate into the plasma and need to be absorbed at some layer possibly in the core of the plasma.

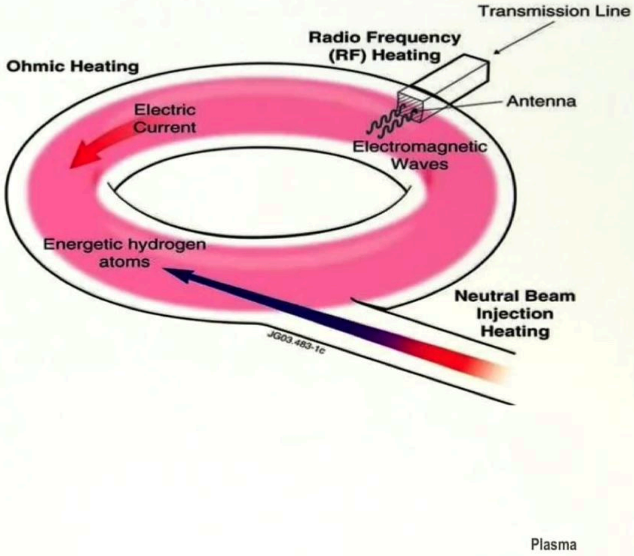
Notes

Summary

1m 43s

# Additional plasma heating – *and current drive*

- Heating effect can be combined with the driving of current non-inductively
- Non-inductive current drive can lead to longer tokamak pulses (in principle to steady-state), and also be used to locally modify current profile and cure instabilities
- Current drive requires direct momentum injection (e.g. using NBI), or a modification of phase space distribution of plasma particles (e.g. using waves)




In fact in general, not only for the waves but also for the neutral beams that we have seen last time, the heating effect can be combined with a driving of current non-inductively. By non-inductively, I mean driving a current that's not based on the transformer action that's the main principle of the tokamak idea. That means that we can in fact, lengthen the tokamak pulses in principle all the way to steady-state and we can use the this non-inductive current to locally modify the current profile and cure instabilities that can develop in the plasma. Current drive requires direct momentum injection that can be, for example, achieved using NBI, so these are just particles going in a particular direction, that transfer momentum by collisions, or by modifying the phase space distribution of plasma particles, for example, using waves.

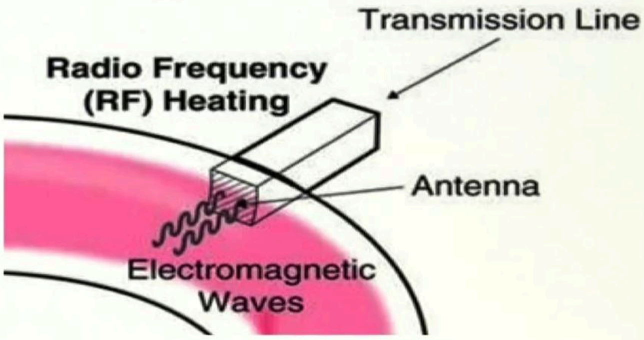
Notes

Summary

2m 27s

# Heating the plasma with waves – generalities

- 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

And indeed let's focus on using waves. Magnetized plasmas support the propagation of many modes, some of which you have already seen in the first part of the course, and these modes can be used to transfer energy, being coupled via an antenna to the plasma core. In order to launch your wave into the plasma, the frequency and/or the wavelength of the antenna wave must be chosen to satisfy the plasma dispersion relation. We also need to choose the frequency and the wavelength, so that the energy is the deposited in a layer corresponding to a plasma resonance that's where we want to deposit the energy, that is typically in the core of the plasma, not on its surface, not on its edge.

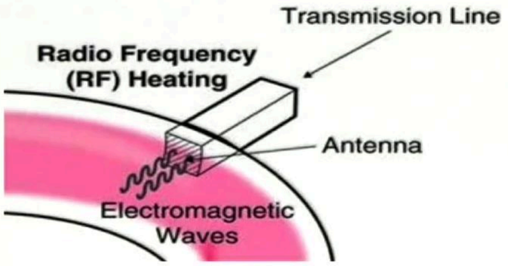
Notes

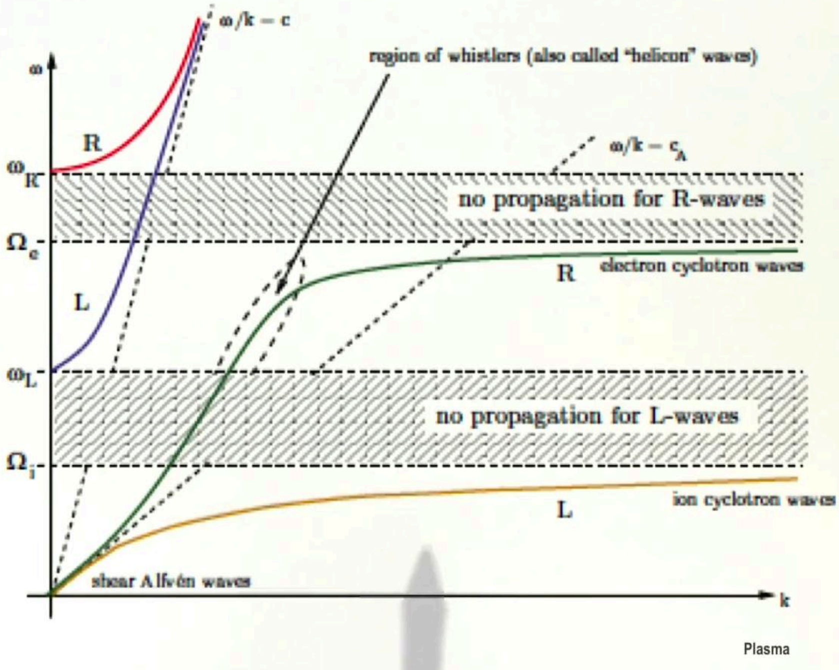
Summary

3m 25s

# The fluid plasma dispersion relation parallel to $B_0$

Note that tokamak geometry makes it difficult to launch waves along $\mathbf{B}_0$



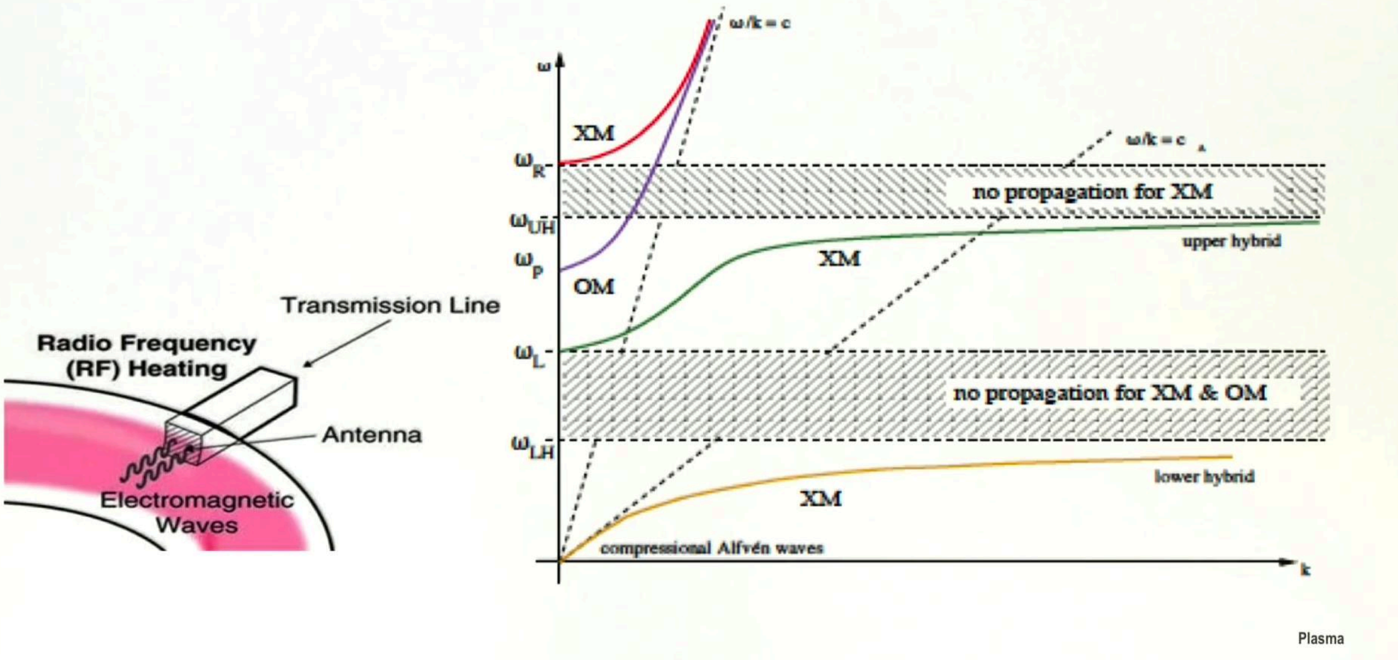

I'd like to remind you the main properties of the plasma dispersion relation. First, in the direction parallel to the local ambient magnetic field, which we call $B_0$, and using the fluid model that you have developed and used in the first part of the course. Here we can represent the dispersion relation in terms of the frequency of the wave as a function of the wavenumber of the wave and we notice that there are different branches, that is, different solutions of the dispersion equation, corresponding to different propagating modes R and L refer to the polarization of the wave. The right hand polarization corresponding to the electric field turning clockwise as the wave propagates. Then the left hand polarization, L, is the other one, the electric field is turning counter-clockwise as the wave propagates into the plasma. And because of this character of their polarization the R and L waves have different resonances -in the fluid sense here- with electron and ion populations respectively. So the R wave is the one that resonates with the electron population because it's electric field rotates in phase with the motion of the electron, of course, if we reach the frequency at which we also go on a same period as the electron gyromotion around the field line.

Notes

Summary

4m 13s

# The fluid plasma dispersion relation perp to $B_0$

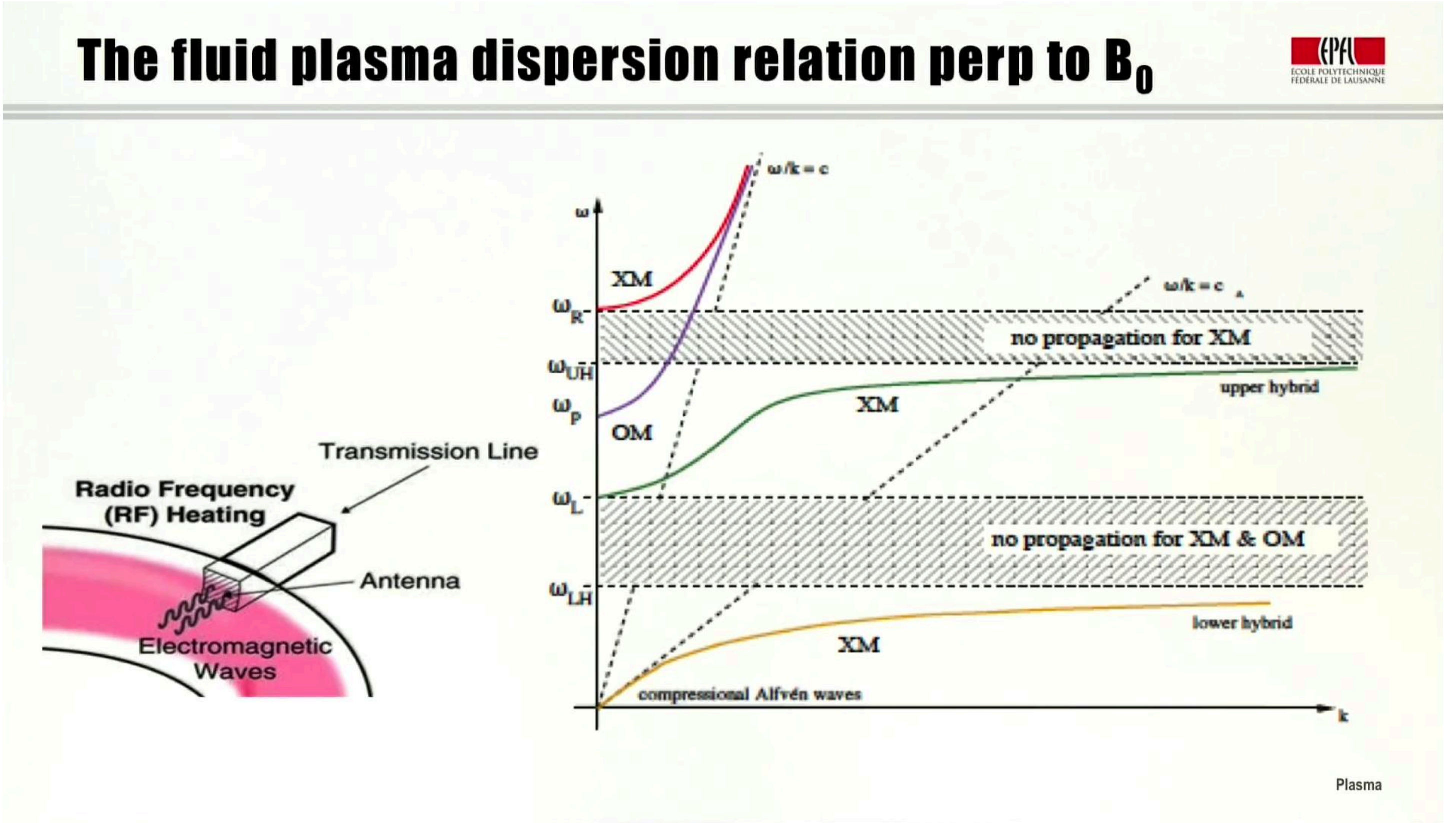



The same happens for the L wave but for the ions and of course that would be at much lower frequency. So this could be two resonant frequencies at which we could transfer energy into the plasma using waves but we notice that this parallel propagation and to launch parallel propagating waves into a tokamak plasma, or in fusion devices in general, is actually quite complicated if the device has a toroidal geometry. So we look at the dispersion relation in the direction perpendicular to the magnetic field, which is quite different. And our little sketch here of the antenna injecting energy into the plasma reminds us that this would be the direction we would prefer, in practical terms. Again, frequency versus wavenumber, here we have branches that are indicated as XM, *extraordinary mode*, or OM, *ordinary mode* depending on the direction of the oscillating electric field with respect to the magnetic field. We also have as we have seen in the previous picture bands in which there is no solution of the dispersion relation. That implies that frequencies corresponding to these bands, for example, in this case don't correspond to any propagating mode in a plasma.

Notes

Summary

5m 47s

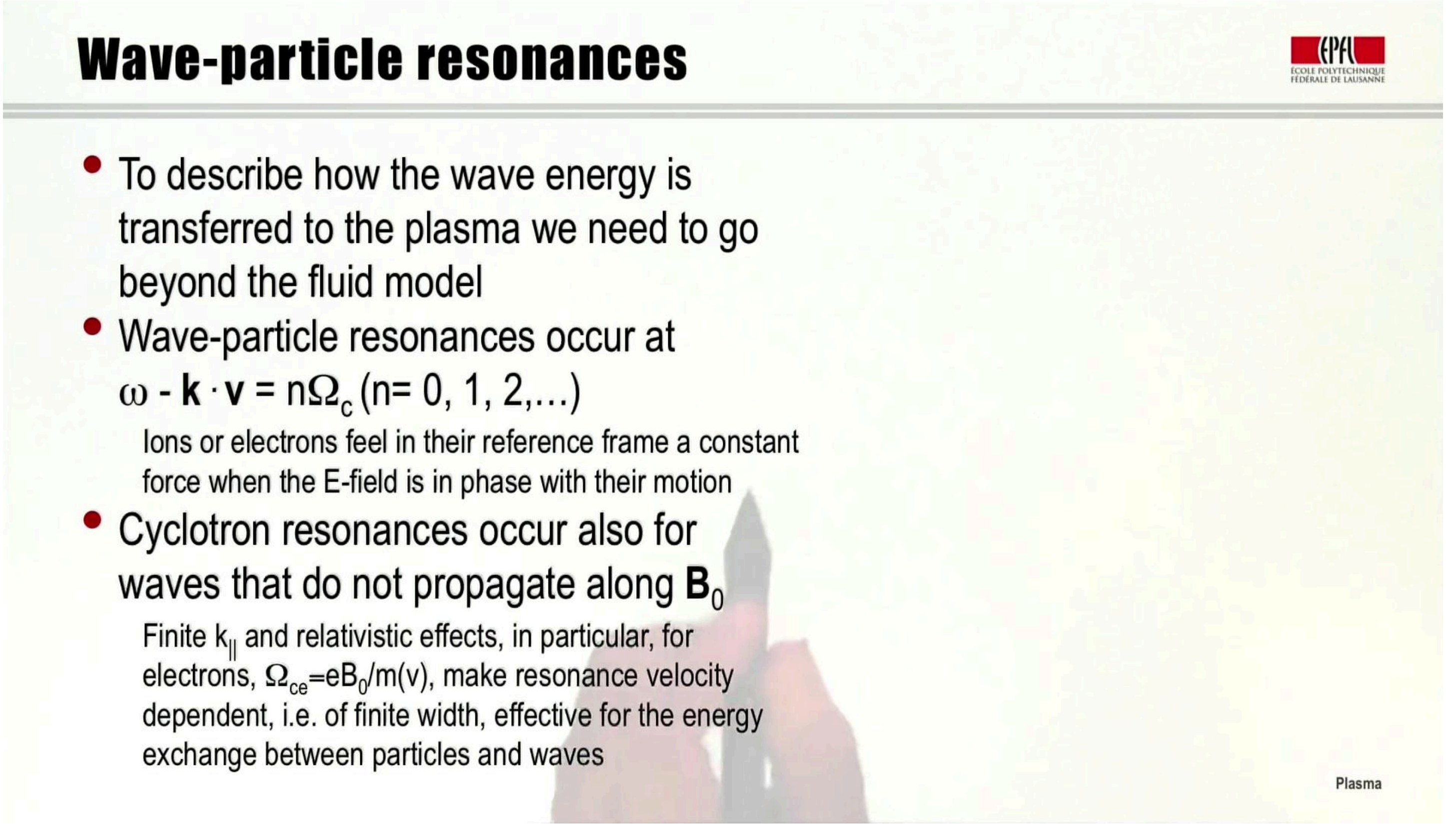



We have two resonances corresponding to where the frequency remains finite and the wave number goes to infinity respectively the lower hybrid and the upper hybrid resonances, lower and higher frequency. These will be resonances that could transfer effectively power into the plasma. In the fluid sense, a resonance corresponds to the situation in which the index of refraction goes to infinity and so there should be absorption of the power from the wave to the plasma.

Notes

Summary

7m 06s




However, the fluid model only gives us a general framework to consider which waves can propagate and in which geometry in a plasma, particularly in the presence of a magnetic field. But to describe how the wave energy is actually transferred to the plasma we need to go beyond the fluid model. In principle, we need to treat the plasma kinetically so that we don't forget that there are frequencies corresponding to different ions or electrons. the two the main species that we have in the plasma. In this frame we can have a resonance between the wave and the particle, a resonance that corresponds to a situation in which the particle feels in its reference frame an essentially constant force because the electric field is in phase with its motion. So typically we can write ($\omega$ - $k \cdot v$) is equal to a multiple of the cyclotron frequency, ($\omega$ - $k \cdot v$) is the frequency that the particle perceives for the wave because it's a Doppler shifted frequency. v is the velocity of the particle, k is the wavenumber of the wave and when that Doppler shifted frequency corresponds to either zero or other multiples of the cyclotron frequency then we can have an acceleration of the particle that is, an effective transfer of energy from the wave to the particle.

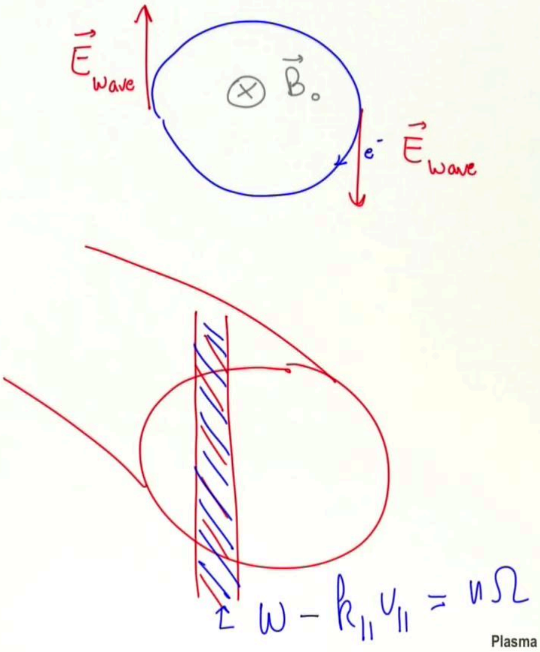
Notes

Summary

7m 43s

# Wave-particle resonances

- To describe how the wave energy is transferred to the plasma we need to go beyond the fluid model
- Wave-particle resonances occur at $\omega - \mathbf{k} \cdot \mathbf{v} = n\Omega_c$ (n= 0, 1, 2,…)
  - Ions or electrons feel in their reference frame a constant force when the E-field is in phase with their motion
- Cyclotron resonances occur also for waves that do not propagate along $\mathbf{B}_0$
  - Finite $k_{||}$ and relativistic effects, in particular, for electrons, $\Omega_{ce}=eB_0/m(v)$, make resonance velocity dependent, i.e. of finite width, effective for the energy exchange between particles and waves




Plasma

We can sketch this situation in a simple way: take a magnetic field in the plasma that goes into the board and there would be an electron circulating around the magnetic field lines and we can sketch the situation of a resonance in which the electric field has the right frequency and the right polarization to resonate with the electron. meaning, it is essentially providing a force that's constant as seen by the electron. So they can be energisation of the electron in a very effective way. The other point I'd like to underline is that in the model that goes beyond the fluid approach in which we consider a distribution of particles that are not corresponding to a single velocity for all the individuals, we can indeed have cyclotron resonances also for waves that do not propagate along the magnetic field. So if I sketch the situation in the geometry of a tokamak, I have the resonance corresponding to the cyclotron frequency being equal to the frequency of the wave as seen by my particle corresponding to a particular layer. Let's color this layer in a different color here. So it is important to say also that this layer is not infinitely narrow because of two reasons.

Notes

Summary

9m 08s

# Wave-particle resonances

- To describe how the wave energy is transferred to the plasma we need to go beyond the fluid model
- Wave-particle resonances occur at $\omega - \mathbf{k} \cdot \mathbf{v} = n\Omega_c$ (n= 0, 1, 2,…)
  - Ions or electrons feel in their reference frame a constant force when the E-field is in phase with their motion
- Cyclotron resonances occur also for waves that do not propagate along $\mathbf{B}_0$
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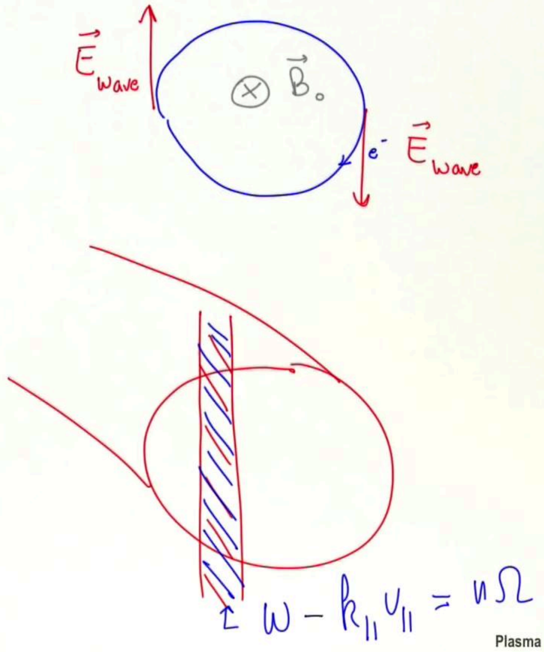



Plasma

First of all, because there's a distribution in their parallel velocity of the particles and if k∥ is not zero that will give a certain width to this wave particle resonance and second of all, also because the cyclotron frequency in particular, of course, for the case of electrons, is subject to the relativistic effect in which essentially the mass of the electron which appears in the definition of the cyclotron frequency is a function of velocity. So the resonance becomes velocity dependent and of finite width which is much more effective for an energy exchange between particles and waves. So wave particle resonances help us in transferring the wave energy into the plasma and it also reminds us that that can happen even in perpendicular or oblique propagation at the cyclotron frequencies as perceived by the moving particle is their frame of reference.

Notes

Summary

10m 48s

# Ion and electron cyclotron resonance frequencies

- Resonance with ions for Ion Cyclotron Resonance Heating (ICRH)

$$f = f_{ci} = \Omega_{ci}/2\pi \sim 15xB_{[T]} \text{ [MHz] for } H^+$$

- Resonance with electrons for Electron Cyclotron Resonance Heating (ECRH)

$$f = f_{ce} = \Omega_{ce}/2\pi \sim 28xB_{[T]} \text{ [GHz]}$$

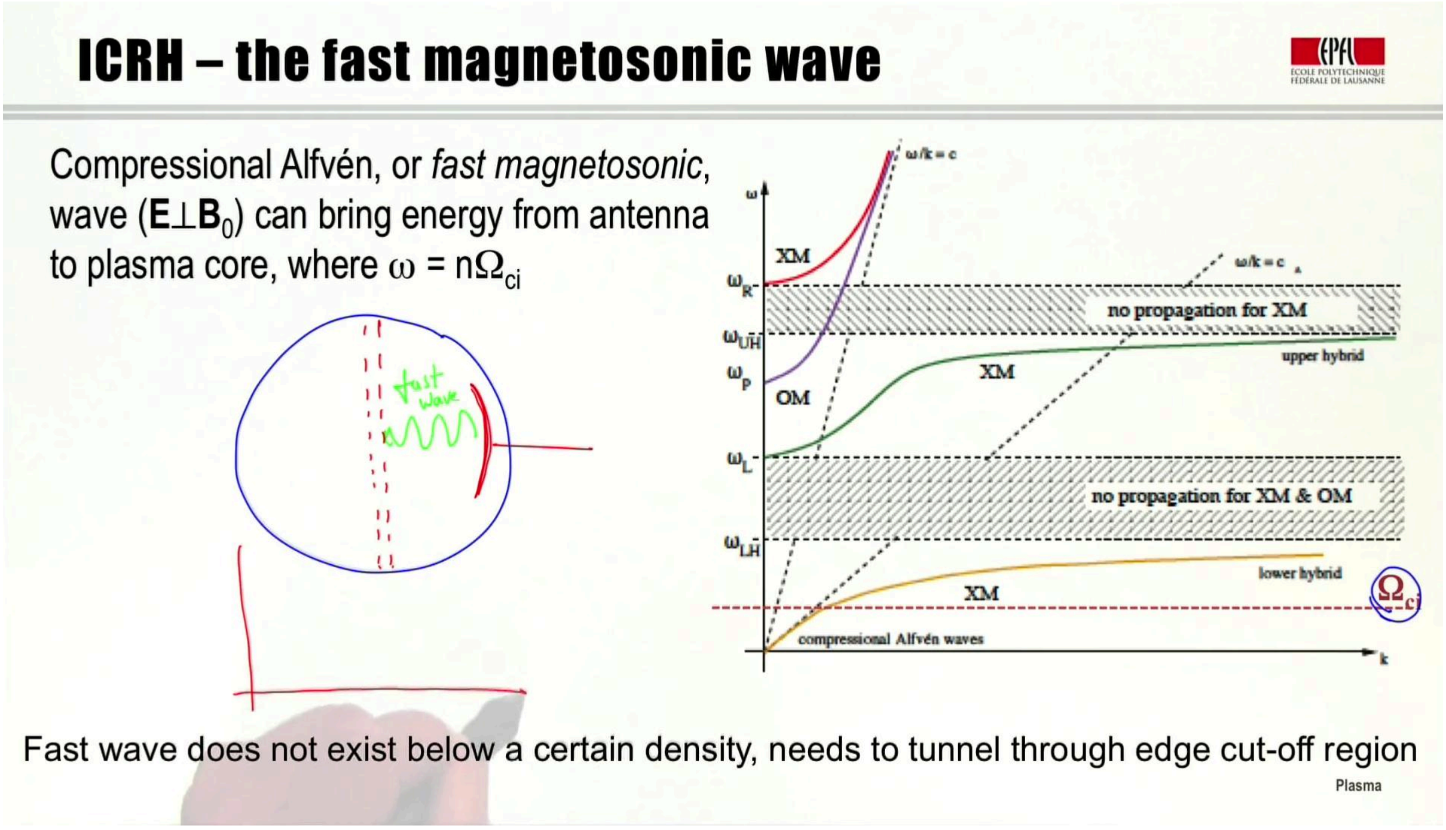
Plasma

Let's estimate the order of magnitude of the frequencies that we are considering here both for the ions and for the electrons. The resonance with the ions occur at the ion cyclotron resonance frequency, which would be used for heating and the order of magnitude of that frequency-- if we speak of course the frequency is the angular frequency divided by 2 π is about 15 times the value of the magnetic field in tesla if the frequency is expressed in MHz and that's for a hydrogen species, for protons that is. So that means that if we have a field of say 3T, we have about 45 MHz of frequency for the ion cyclotron resonance. As it is intuitive if we now consider the case of electrons, the frequency for their electron cyclotron resonance will be much higher and that's about 28 B in GHzH if B is expressed in tesla. So for a typical tokamak device of today and of tomorrow we have something between 100 and 180, 200 GHz.

Notes

Summary

11m 48s




Let us now concentrate on the cases of ICRH, ion cyclotron resonance heating. Let's bring up again the dispersion relation because we need to now choose which wave we use to carry the energy that we want to launch into the plasma core from our antenna. Now the cyclotron frequency for the ions is typically here and is much lower than the lower hybrid frequency, which corresponds to a resonance. So we are on the branch for the extraordinary mode here, that's well below the first resonance. So we are in a range that's actually reasonably well described even in the context of the MHD model corresponding to so-called compressional Alfvén wave or fast magnetosonic wave. We'll refer to this wave as the *fast wave* for simplicity. This is the next mode, so we have to have a wave that has an electric field oscillating perpendicularly to the ambient magnetic field. So in practice what we'd like to do is -say this is our tokamak cross-section- is to have an antenna that's sitting towards the edge of the device, of course, that launches a wave, which is the fast wave and that wave should reach the resonance corresponding to, for example, the ion cyclotron resonance of the ion species we want to heat.

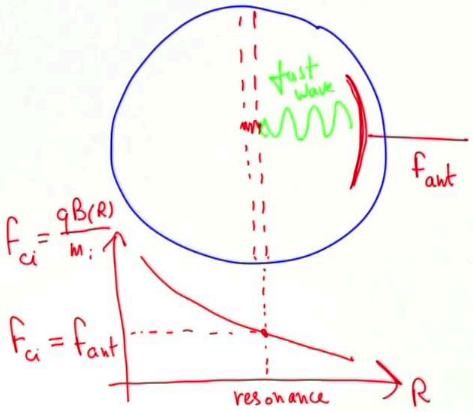
Notes

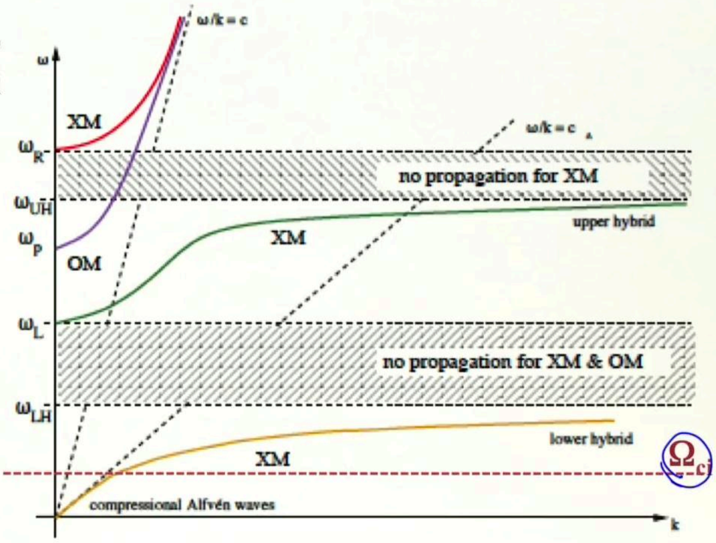
Summary

13m 03s

# ICRH – the fast magnetosonic wave

Compressional Alfvén, or *fast magnetosonic*, wave ($\mathbf{E} \perp \mathbf{B}_0$) can bring energy from antenna to plasma core, where $\omega = n\Omega_{ci}$




Fast wave does not exist below a certain density, needs to tunnel through edge cut-off region

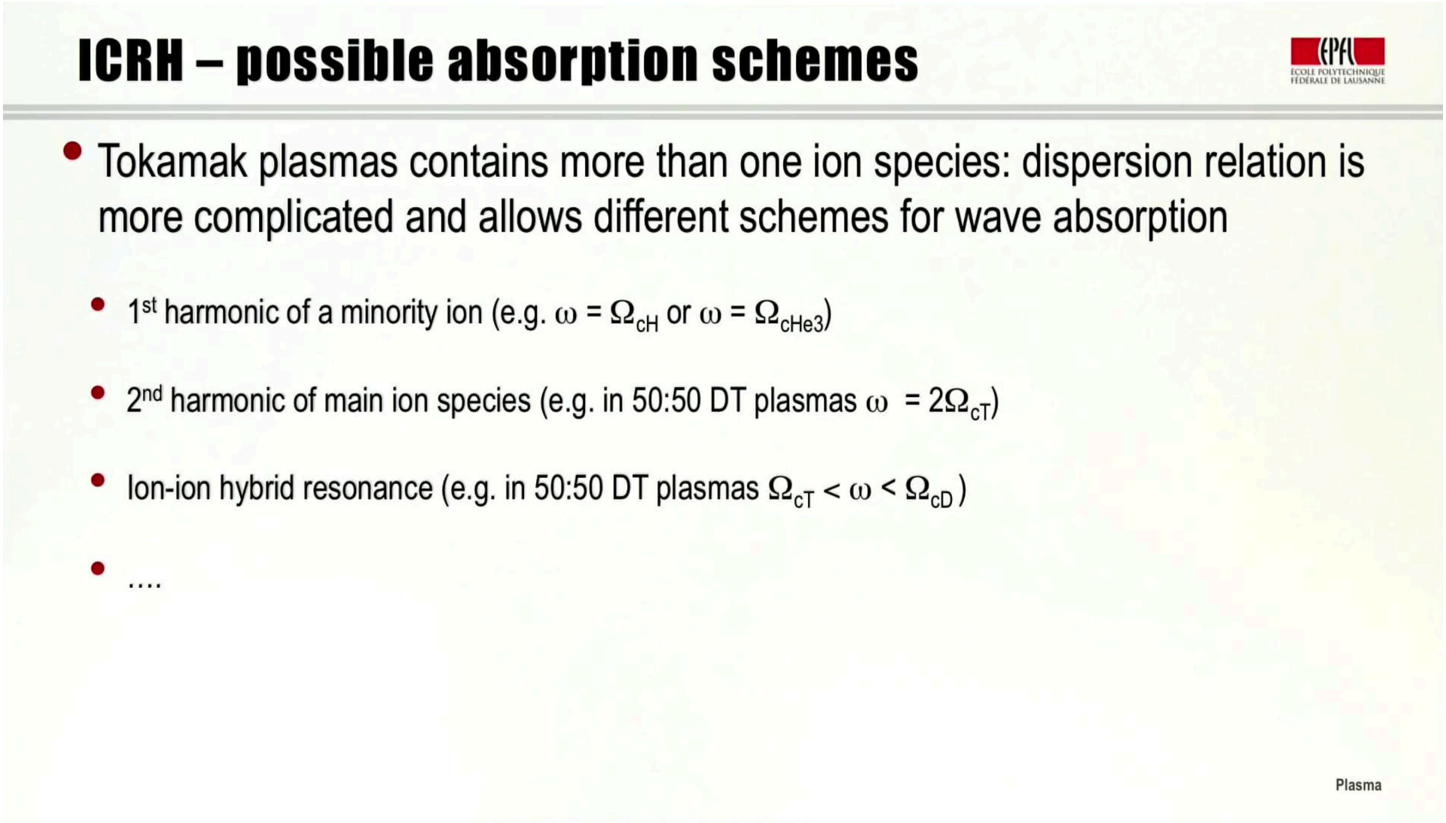
Plasma

So if I represent here the ion cyclotron frequency for that species, that will be q B(R) / mi typically the field goes as 1/R, so I can draw that in a simple way and the resonance corresponds to the point-- let's call this resonance where fCI -- so the ion cyclotron frequency is equal to the frequency I provide the plasma with, that is the antenna frequency. Let's call that fant, the frequency of the wave I'm launching with my antenna. At the resonant layer effects a little bit more complicated than we have the pretention of explaining here occur, but in general, we expect an absorption of the power that we launch from the antenna by the plasma. Now without going into the details of this phenomenon which is relatively complicated, I just noticed that the fast wave cannot propagate if the density is below a certain value, so you will need to tunnel through a cut-off region at the edge of the plasma, which is thin enough for the wave to tunnel through it but which we can't completely disregard in our model.

Notes

Summary

14m 37s




The wave physics in a tokamak plasma is rather complex, and one of the aspects of these complexity is that tokamak plasmas contain more than one ion species. That means that the dispersal relation is more complicated but at the same time it has the advantage of allowing different schemes for the wave propagation. For example, we can use a scheme in which we absorb the energy of the wave by a minority ion species, at the first harmonic. So that means that we chose the frequency or the antenna corresponding to the cyclotron frequency, for example, hydrogen say in a deuterium plasma or Helium 3. Again, for example, the deuterium plasma. Or, we can use the second harmonic of one of the main ion species, for example, in a DT plasma we can launch a wave at two times the cyclotron frequency for the tritons. That's indeed one of the schemes foreseen for ITER. Or we could use this called *ion-ion hybrid resonance* which we have not calculated in the models but which essentially is the resonant frequency that's given by the fact that we have two different ion species and the value of this resonant frequency is between the cyclotron frequency of the heavier species and the cyclotron frequency of the lighter one, and other schemes.

Notes

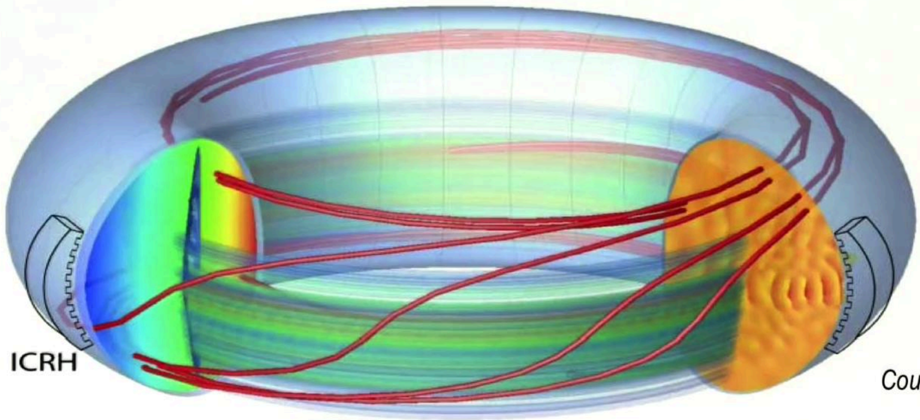
Summary

16m 01s

# Energetic ions from ICRH

Wave fields at $\omega \sim n\Omega_{ci}$ give energy to ion perpendicular motion, creating anisotropic distribution functions and mostly trapped ion orbits

Depending on absorption scheme, which determines the energisation of the resonant ions, the collisional energy transfer can be to plasma bulk ions or electrons




Courtesy of J.Graves and M.Jucker

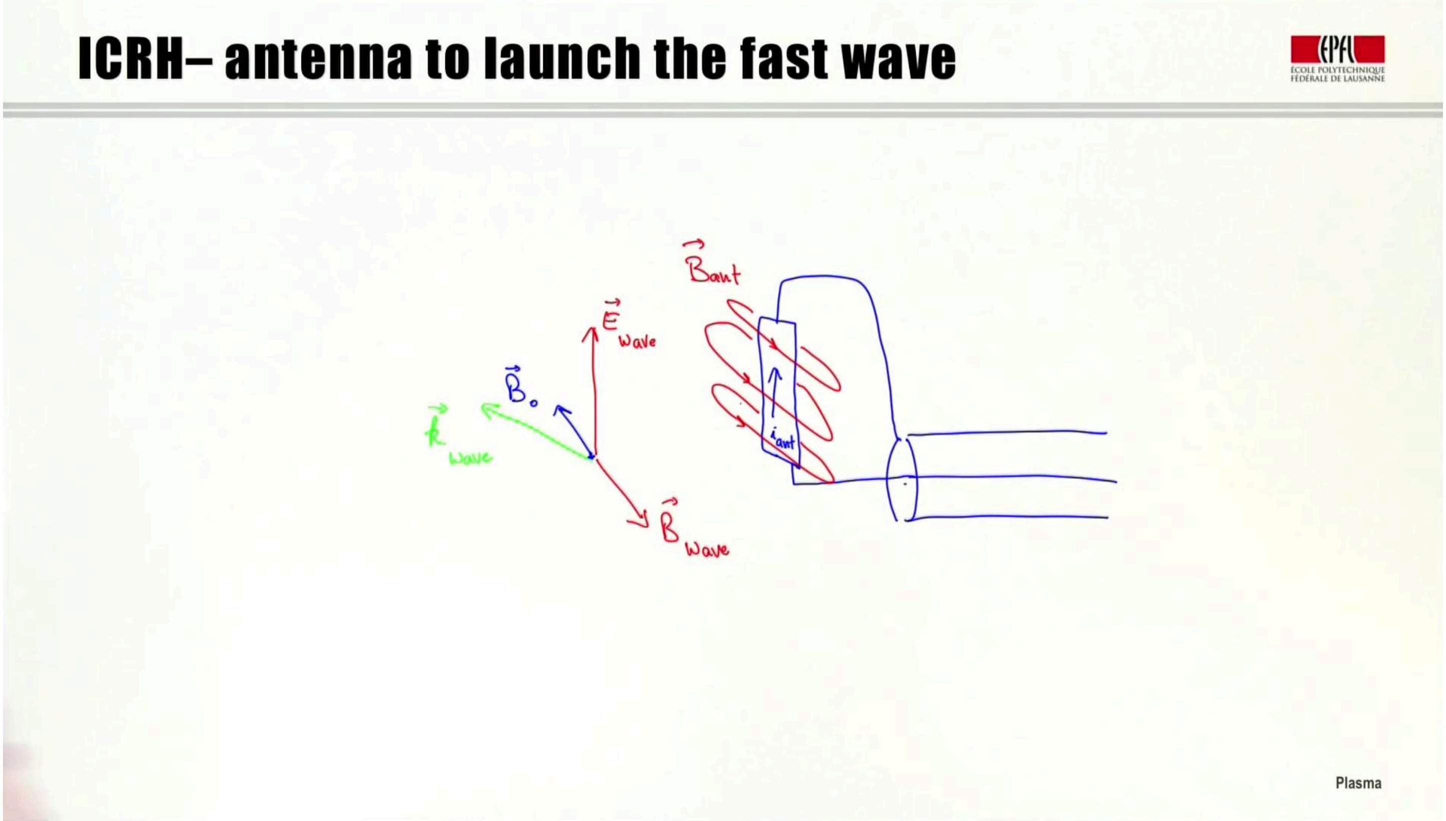
Plasma

Now in all the schemes the wave fields at the resonant frequency give energy to the perpendicular motion of the resonant ions, therefore, creating an isotropic distribution function and mostly trapped ions orbits. Depending on which scheme we choose for the absorption, which determines the way the energisation of the resonant ions take place, then we can have a collisional energy transfer that can be to either the plasma bulk ions or the plasma electrons. If we create very energetic resonant ions then the collisional transfer will be mainly on electrons, whereas if the energetic resonant ions have a lower energy spectrum then the collisional transfer will be primarily to the plasma bulk ions. This figure illustrates the complexity both of the wave field, we are generating with an antenna and the ion cyclotron resonance frequency scheme, and the orbits of the energetic ions that are in fact energized by absorbing the power of the ICRH antenna.

Notes

Summary

17m 23s

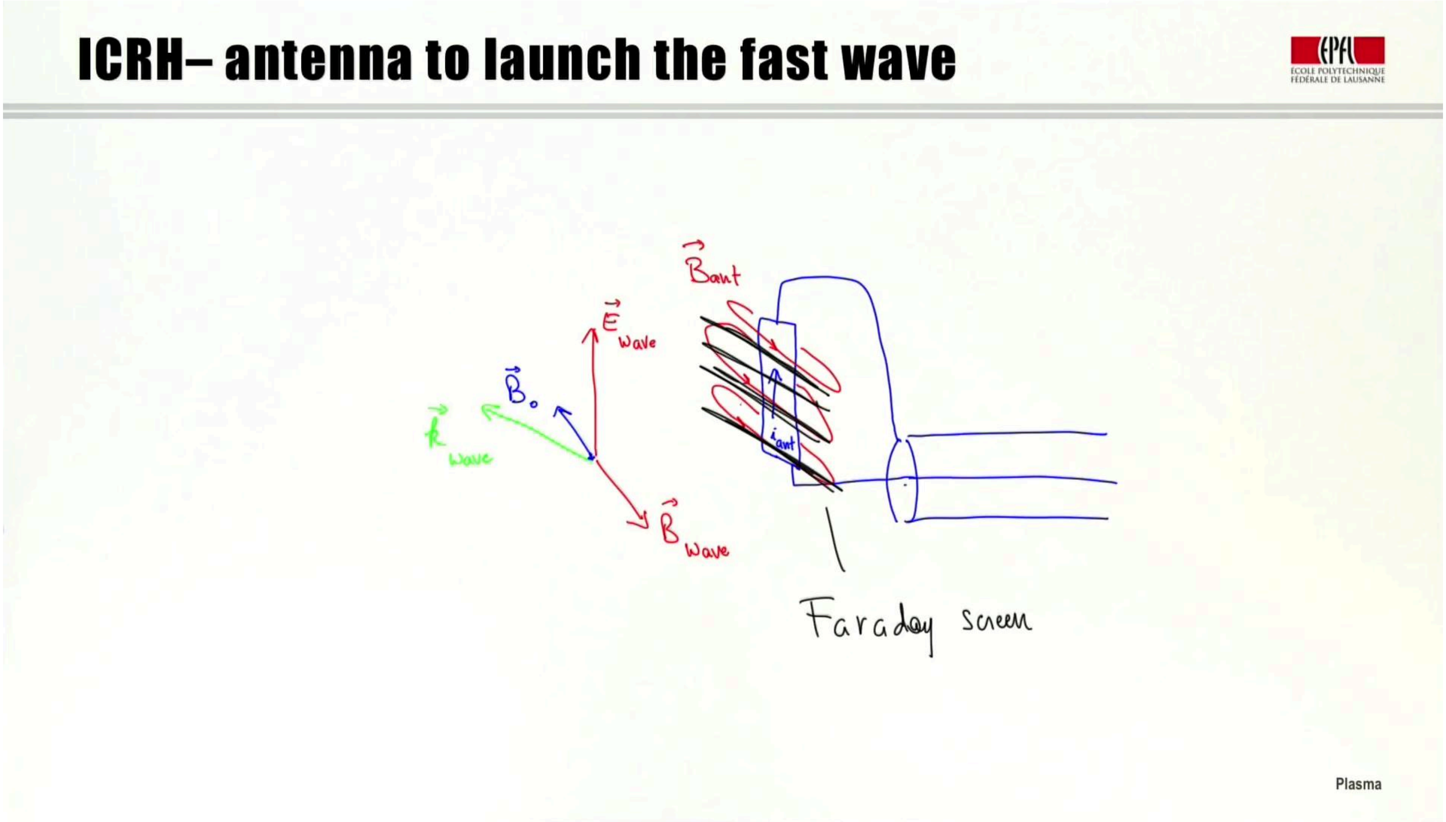



Now we can look a little bit at the details of the antenna system that we need to launch the fast wave, that is our energy carrier to plasma core. So in this schematic way: we come with a coaxial line in the plasma we connect that to a metal plate, we call it a "strap", then we have a certain current. Close the circuit to ground this current, which of course would be an oscillating current at 10's of MHz of frequency. This oscillating current will give rise to an oscillating magnetic field, let's call that Bant for B-antenna. And of course, an oscillating electric field as well. So let's draw that geometry. So we say the Bant, in fact, respects the right hand rule. Let's say the electric field of that wave that we're launching is along the direction of the oscillating current, the magnetic field of the wave we're launching is perpendicular to it and then say there is a background magnetic field, $B_0$ in this direction, and the wave propagation vector that could be in a direction oblique to the magnetic field of the tokamak. So this is the way to respect the polarization we need to have, because we want to have an electric field of the wave that is perpendicular to $B_0$, that's an essential element for launching the fast magnetosonic wave.

Notes

Summary

18m 39s



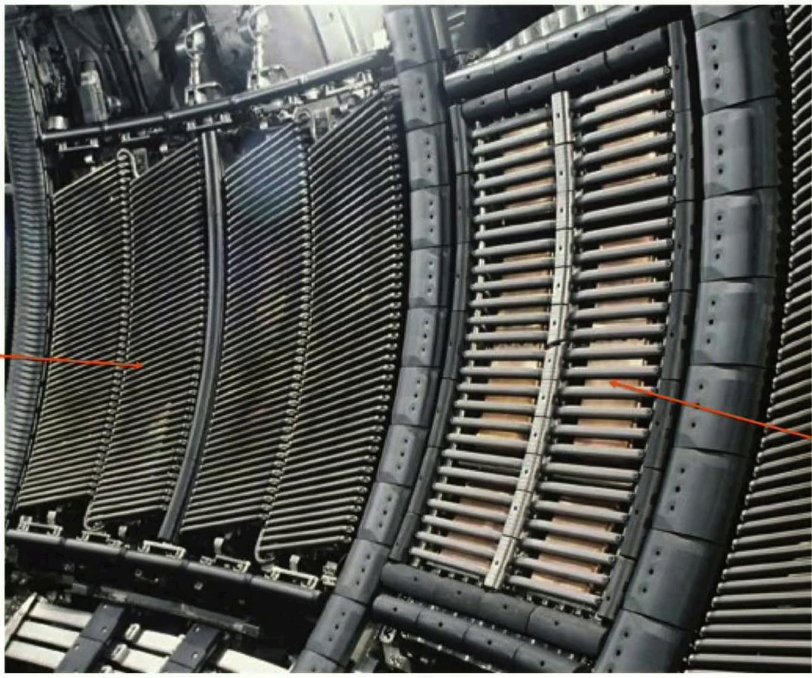

Now what we want to have is a transfer of the-- if you like, the oscillating current energy into the wave energy. What we don't want to have is an acceleration of charged particles in the proximity of the antenna with the large electric fields that are provided by the antenna itself. So we like to avoid that by putting a screen, which we refer to as a *Faraday screen* in front of the antenna, that at least in the direction of $B_0$, in the direction of the ambiant magnetic field, prevents the creation of electric fields and that is done by having conductors that are aligned with the magnetic field lines. So the Faraday screen is there for a structure that short-circuits electric fields, at least in the direction of the local magnetic field, which will be the dangerous direction for the acceleration of the charged particles. Of course, the acceleration of charged particles by the electric field is possible in parallel to the magnetic field. Acceleration of fast particles of ions, in particular, we want to avoid because that will lead to a very energetic collisions of these ions onto the material surfaces around the antenna, on the antenna itself, both damaging these surfaces and producing a very strong impurity influx.

Notes

Summary

20m 28s

# Example of present ICRH system: JET antennas



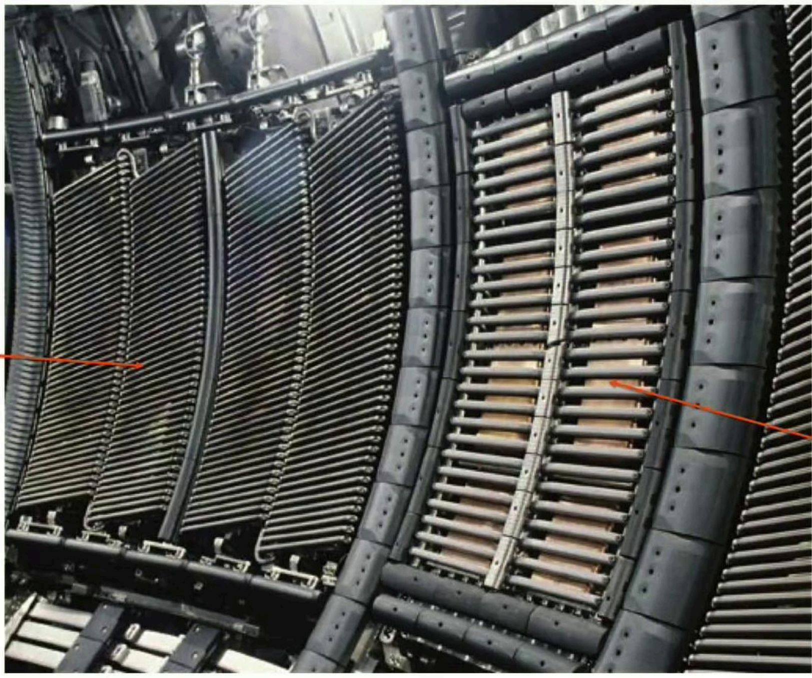

So how does an antenna for ICRH look like in practice? Here's a picture of several antennas of the JET tokamak. We have the 'old' version that has been used for many years that has two straps per antenna producing a power surface density of a little less than two megawatts per square meter and the more recent concept that has been tested in the last few years, so called ITER-like antenna because it's sort of a prototype for the installation on ITER and each model has four straps, which allows to reduce the electric field produced by the antennas locally and a higher power density of about 8 megawatts per square meter. You can also see the bars that produce the Faraday screen in both cases. One of the issues of the antennas in a tokamak is the question of impedance matching, of course, the impedance of the load has to matched to that of the transmission line and the generator to optimize the power transfer but the antenna plasma system has an impedance that can vary with the plasma conditions, in particular at the edge, including variations of the conditions that are associated with very high frequency and very violent instabilities that happen at the edge.

Notes

Summary

22m 01s

# Example of present ICRH system: JET antennas



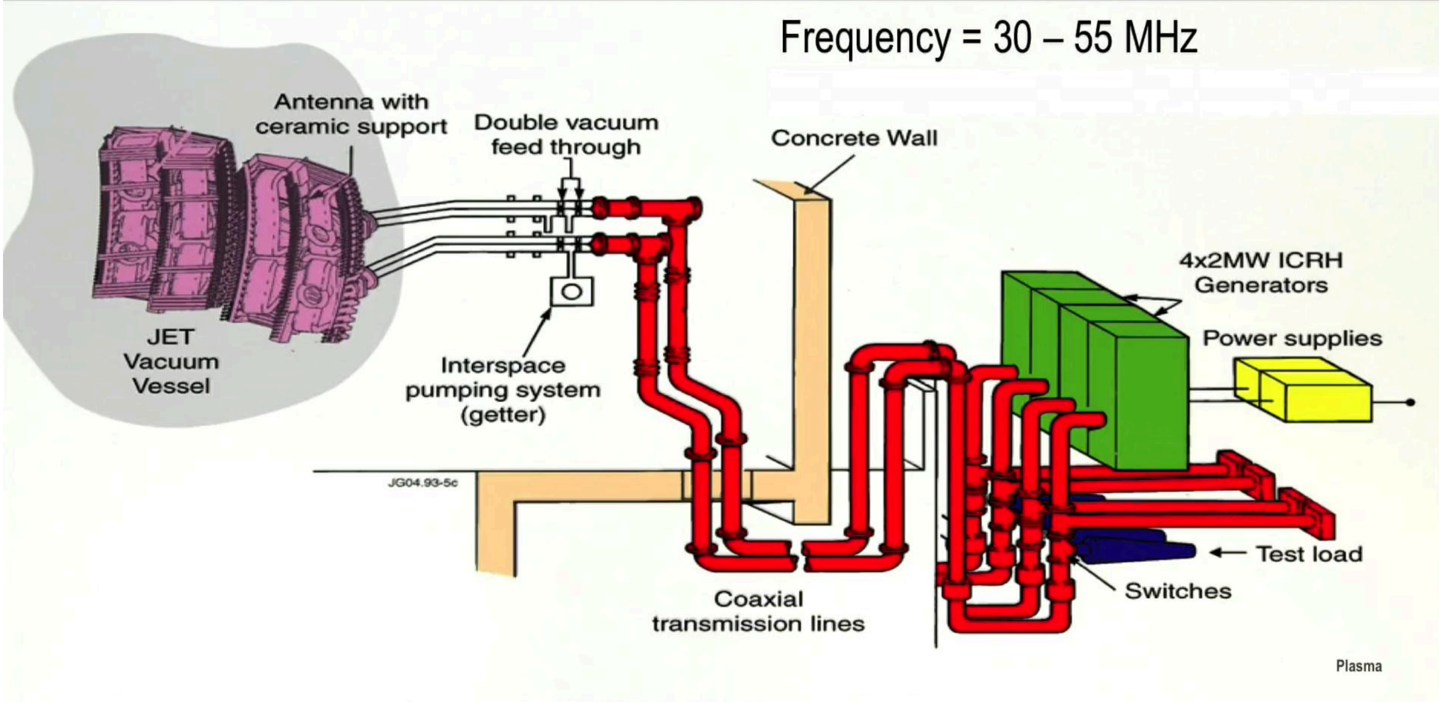

So the different concepts also need to address this issue by compensating one strap with the other, for example, and develop some sort of resilience with respect to the sudden variation of the load that edge phenomena can lead.

Notes

Summary

23m 39s

# Example of present ICRH system: JET




We've seen the antenna systems in JET. Let's take a look at the whole system. Going back from the antenna, which is of course installed in the vacuum vessel. You can even see the two straps in easier way here because they are sketched without the Faraday screen. There is a vacuum feed through. There is a set of coaxial transmission lines to transmit the power with very small levels of losses. The frequency of the ICRH system in JET is between 30 and 55 MHz. You have the switches that allow you to test your generators on dummy loads or of course to inject the power to the transmission line that eventually goes to the antennas and you have the generators.

Notes

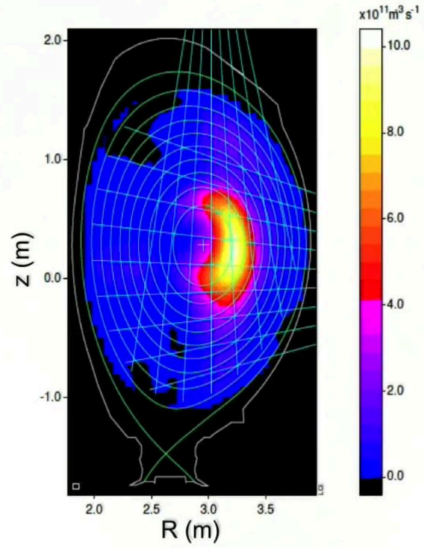
Summary

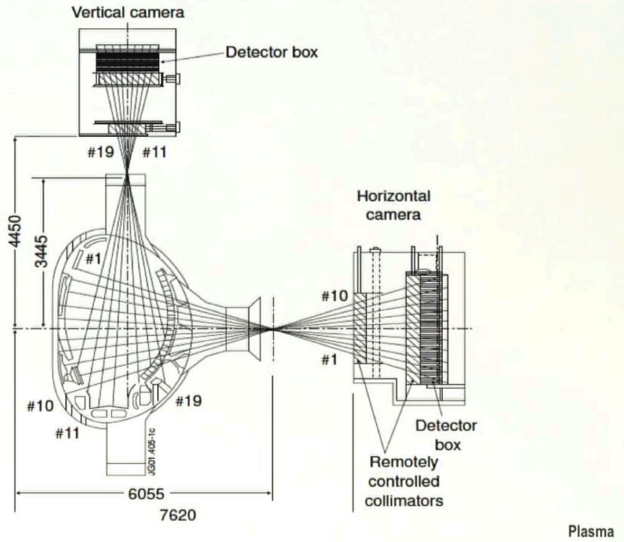
23m 52s

# Evidence for ICRH-generated fast ions in JET

- $^4$He acceleration by ICRH at $f = 3f_{ci}(^4He)$
- Emission profiles of γ-rays from reaction $^9Be(\alpha,n\gamma)^{12}C$ ($E_\alpha \geq 2MeV$)

Courtesy of V.Kiptily



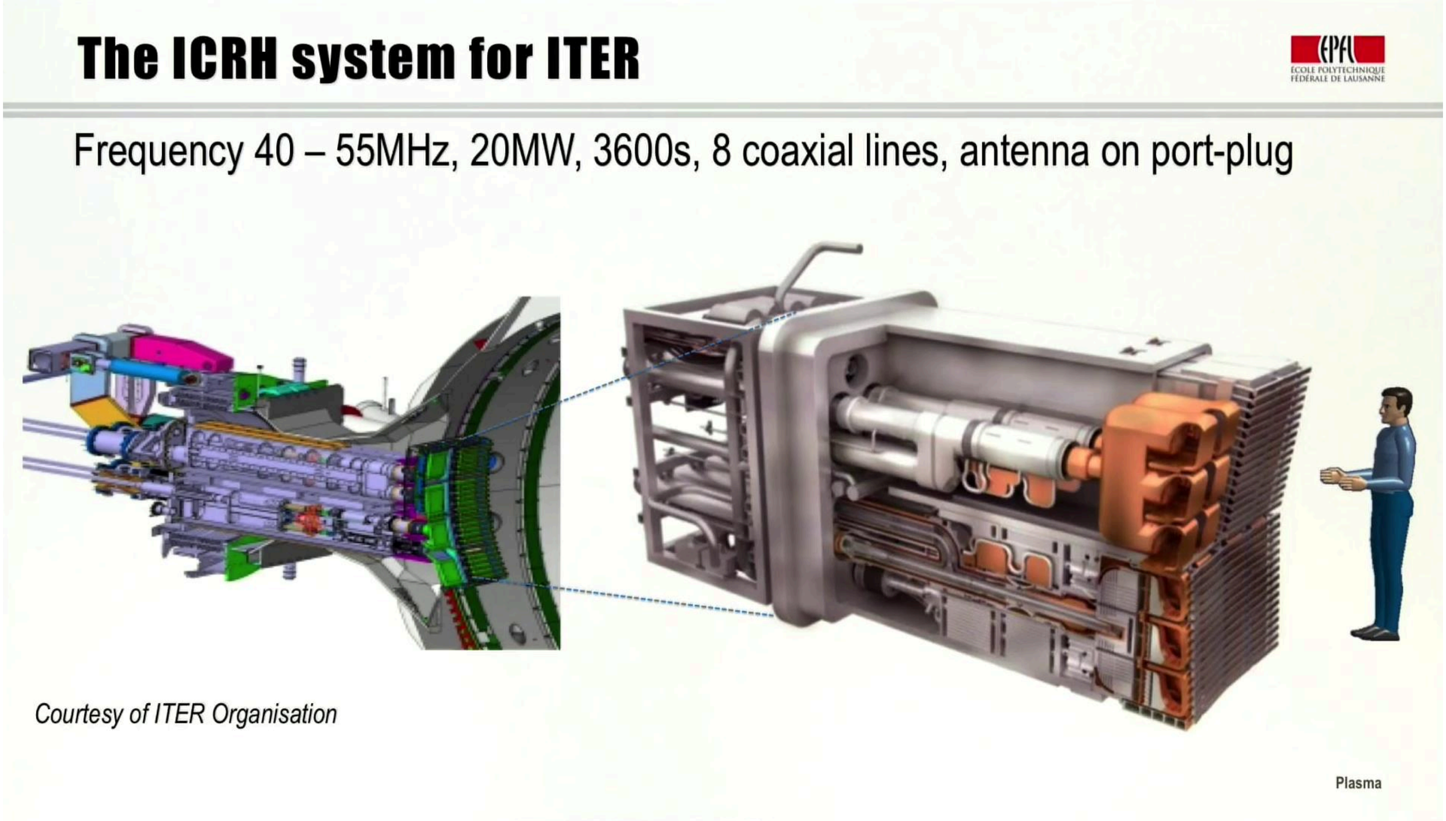




We have mentioned before that ICRH works by generating energetic ions because they are the ones that resonate with the waves and it's interesting to see how these ions are actually measured and how we verify that they are in fact generated by the ICRH mechanism. The example shown in this slide is an experiment done at JET in which the frequency of the ICRH system is chosen to be the third harmonic of the cyclotron frequency of alpha particles, i.e. $^4$He ions And how do we observe them? We observe them by measuring the emission profiles in the tomographic way, gamma rays that that produced by nuclear reactions between the α-particles and the beryllium impurities that are present in the plasma and the point is that these nuclear reactions have a threshold for the energy of the α-particles, in other words, they occur only if the energy of the α's is larger than about 2MeV. So if we see a signature of this reaction in the form of emission of γ-rays, we are sure that we have energized these α-particles using ICRH at least to levels of about 2MeV. And this is in fact the profile of these γ-rays emissions.

Notes

Summary

24m 43s




We can briefly take a look at the system for ICRH that's foreseen for ITER. The frequency is actually very similar to that in JET between 40 and 55 MHz, power up to 20 MW, and for a duration of 3600 seconds. There are eight coaxial lines and one of the features that characterizes the ITER system and that's one of the pictures that have been tested in JET using this so-called ITER-like antenna, is that the antenna has to come on a port plug, in other words, it has to be inserted as sort of a part of an arm that comes into a port, into an opening of the vessel.. Here we see a picture of the antenna as it's been drawn now. You can also see how big that is. It's quite a sizable object and you can also see that it has several straps. It's the same concept as the ones we have described before, but he has an even larger number of straps to try to reduce the strong electric fields in proximity of the antenna. It has also the Faraday screens we have described before.

Notes

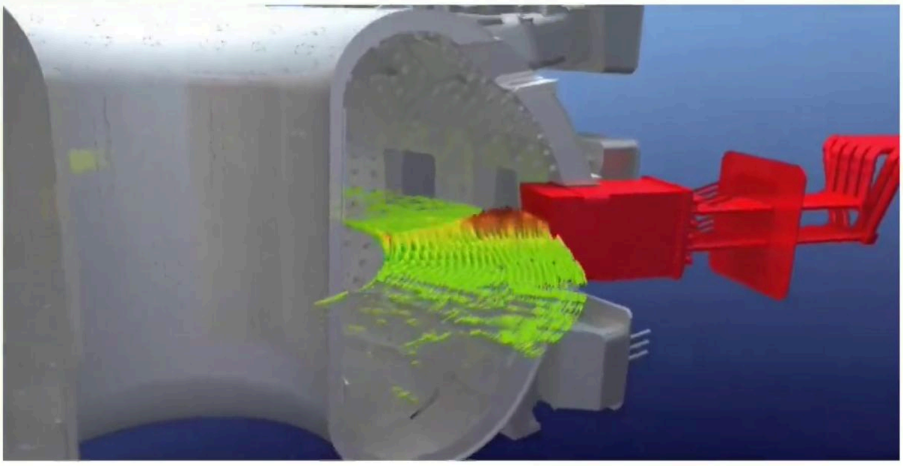
Summary

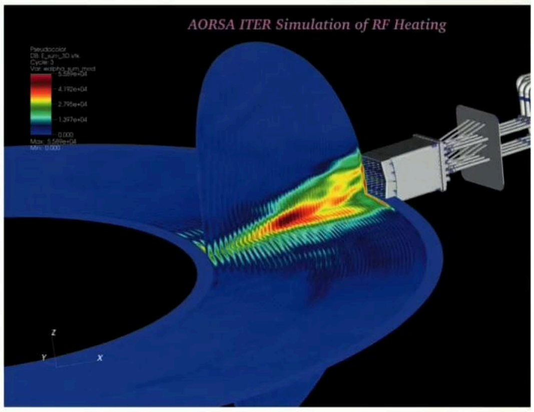
26m 12s

# ICRH modeling

Fast wave has large vacuum λ – cannot be described in simple Fourier formalism

Ex. of wave field from full wave calculation of $2^{nd}$ harmonic T ICRH in ITER (53MHz, 20MW)






*Courtesy of P.Bonoli, E.F.Jaeger et al., PoP 15, 072513 (2008)*

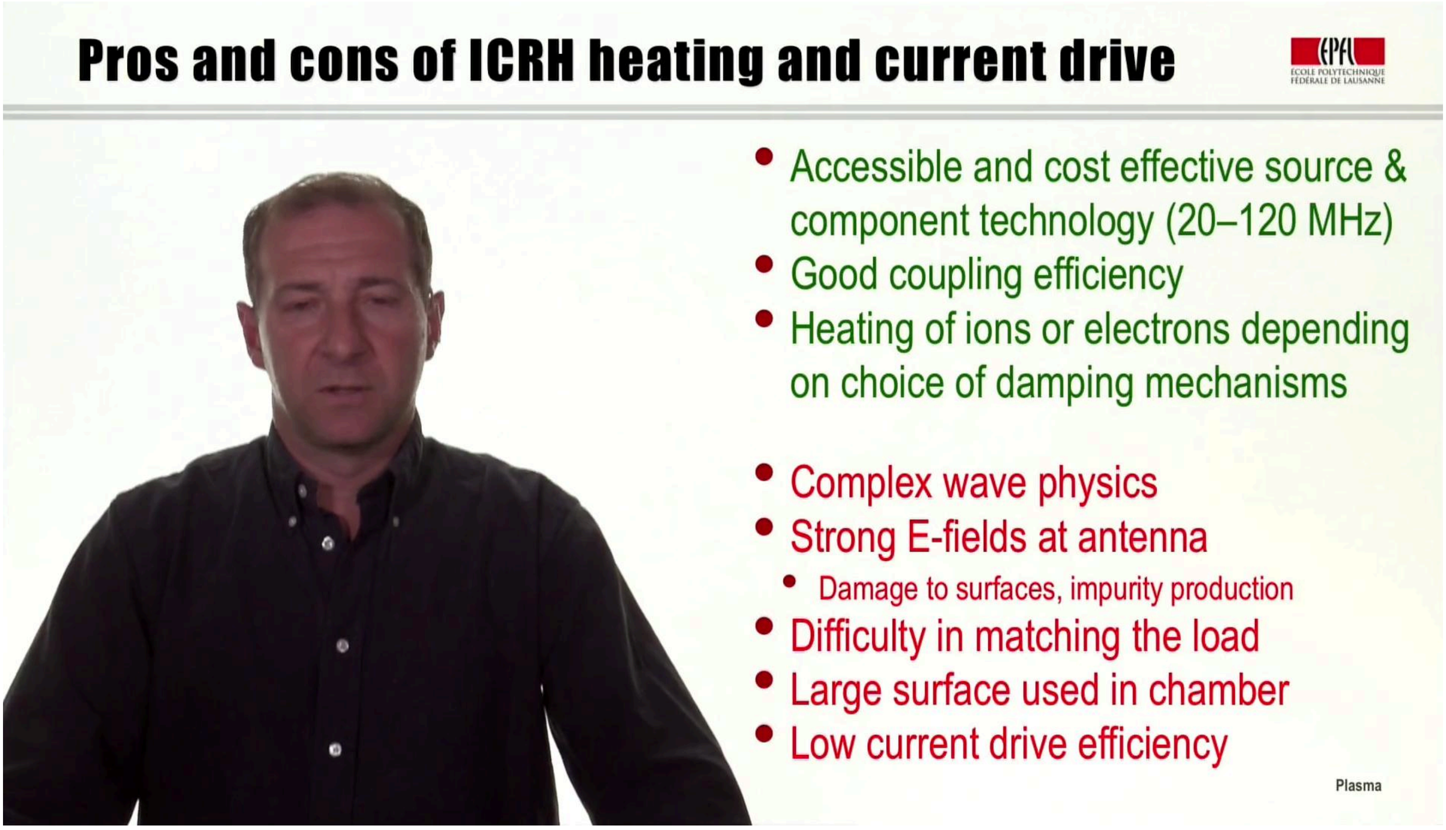
Plasma

To model the propagation and the absorption of ICRH waves is a non-trivial exercise. We have seen the dispersion relations in terms of, of course, ω versus k that means in Fourier space assuming that everything is of infinite size and uniform, which is of course not the case in tokamaks. The fast wave we'd like to use to carry the energy to the plasma core has a relatively large vacuum wavelength. That means it cannot be properly described in a simple Fourier formalism. A full-wave calculation needs to be done. And this is an example of such a calculation. On the right here you see just a still picture of the field produced by the antenna in ITER, in front of the antenna of ITER and on the left you can see a movie that models the propagation and the evolution of the electric field in the ICRH heating of the ITER plasma.

Notes

Summary

27m 24s

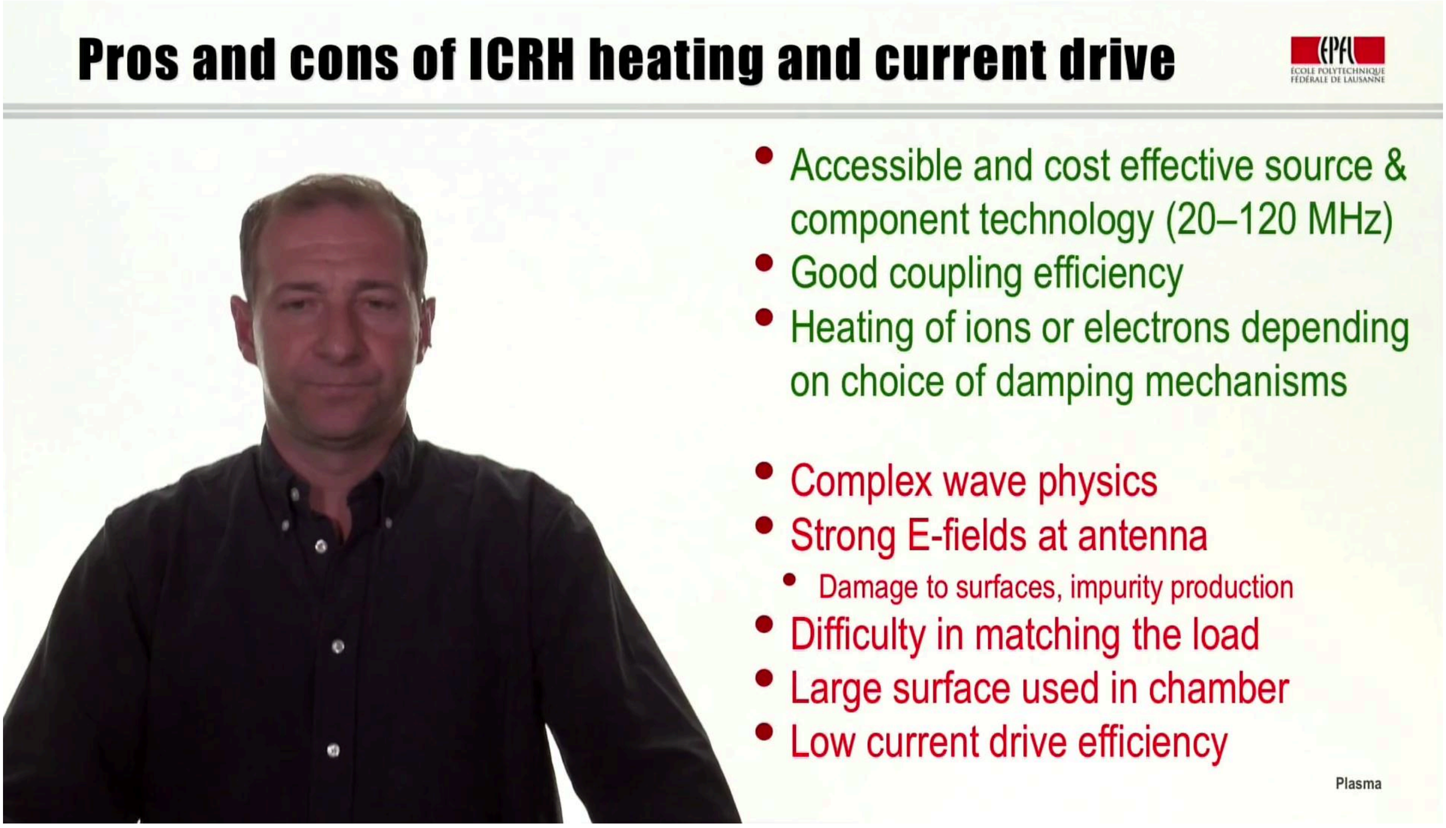



We're now ready to briefly discuss in a qualitative and somewhat personal way, the pros and cons of the ICRH. As an advantage we have an accessible and a relatively cost effective source and component technology. We are in a frequency range between say 20 and 120 MHZ, that is fairly easy to work with. We can have a very good coupling efficiency and we can choose a mechanism for the absorption that preferentially heats the ions or the electrons, which can be an advantage as it gives us quite a flexibility in the operation of the system. On the other hand, among the disadvantages that I can think of, we have a fairly complex wave physics: the absorption mechanism is not straightforward and we have, even more dramatically, a problem with the strong electric fields at the antenna. The strong electric fields, especially when rectified by nonlinear phenomena such as at the rf-shield can damage surfaces, can produce impurity influx and therefore can really reduce the lifetime of the antenna itself and of the components around it. It is also quite difficult to match the load, particularly in the presence of variations of the edge conditions such as caused by instabilities at the edge of the plasma.

Notes

Summary

28m 30s




The antenna itself requires quite a large surface in the chamber, a surface that, of course cannot be used for purposes such as breeding tritium in a blanket. And in terms of the current drive, the efficiency is relatively low, so there's not a large amount of current driven by a given amount of power in the ICRH.

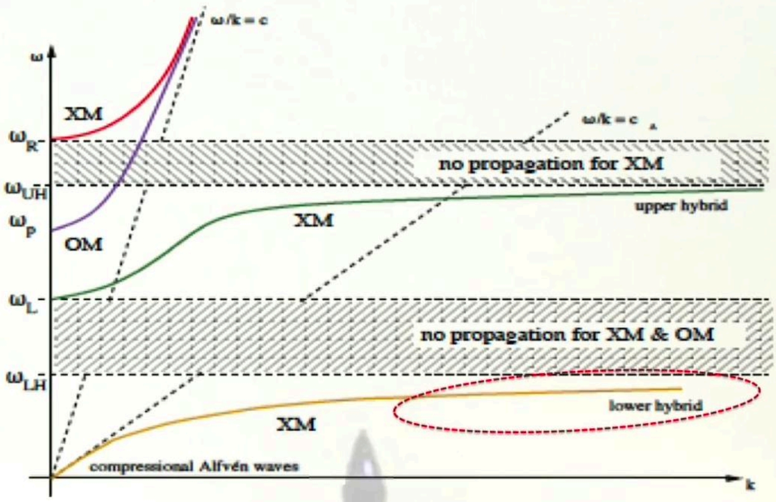
Notes

Summary

29m 54s

# Lower Hybrid wave for heating and current drive

- Wave-particle resonance
  $f = f_{LH} = \mathbf{k} \cdot \mathbf{v}/2\pi$
  $\sim 1.3 T_e^{1/2}{}_{[keV]} / \lambda_{||\,[cm]}$ [GHz]
- Electrostatic waves ($\delta B \sim 0$)
- Minimum density required to launch wave, antenna needs to be in contact with plasma




Plasma

In order to drive current more efficiently, in fact we normally think of using a different kind of wave. That's the lower hybrid wave. Considered for heating and current drive, but we should say nowadays primarily only for current drive, the concept of lower hybrid interaction is based on the wave-particle resonance. So this is the resonance for which, say, the n in front of the cyclotron frequency is equal to zero. So we're really going-- if you like with a wave that propagates at the same speed as a group of particles, which are therefore referred to as resonant particles. And if we take that as sort of in an optimization process for the electron population, we can evaluate the frequency at which that occurs to be about 1.3 times the square root of the temperature, the temperature is expressed as *keV* divided by the parallel wavelength of the wave expressing in centimeters and frequency would be expressed in GHz. So if we take a 16 keV plasma, a few centimeters of a parallel wavelength we have something of the order of a few GHz for this wave particle resonance that corresponds to one portion of this lower hybrid branch in the dispersion relation for the fluid wave in a plasma.

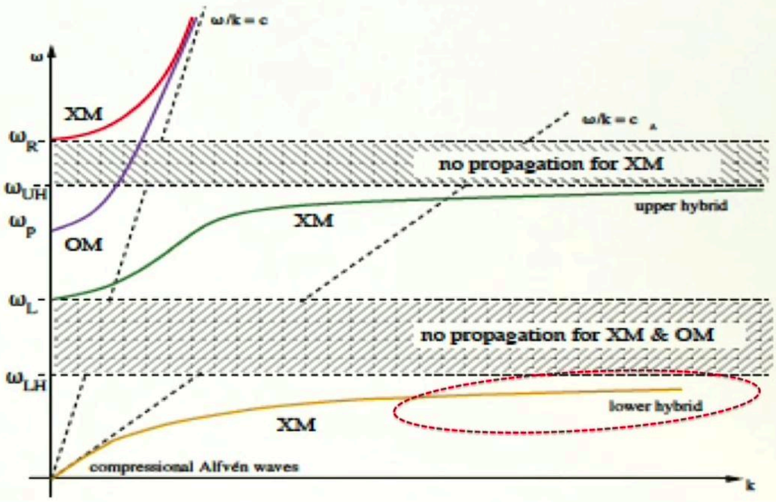
Notes

Summary

30m 16s

# Lower Hybrid wave for heating and current drive

- Wave-particle resonance
  $f = f_{LH} = \mathbf{k} \cdot \mathbf{v}/2\pi$
  $\sim 1.3 T_e^{1/2}{}_{[keV]} / \lambda_{||\,[cm]}$ [GHz]
- Electrostatic waves ($\delta B \sim 0$)
- Minimum density required to launch wave, antenna needs to be in contact with plasma



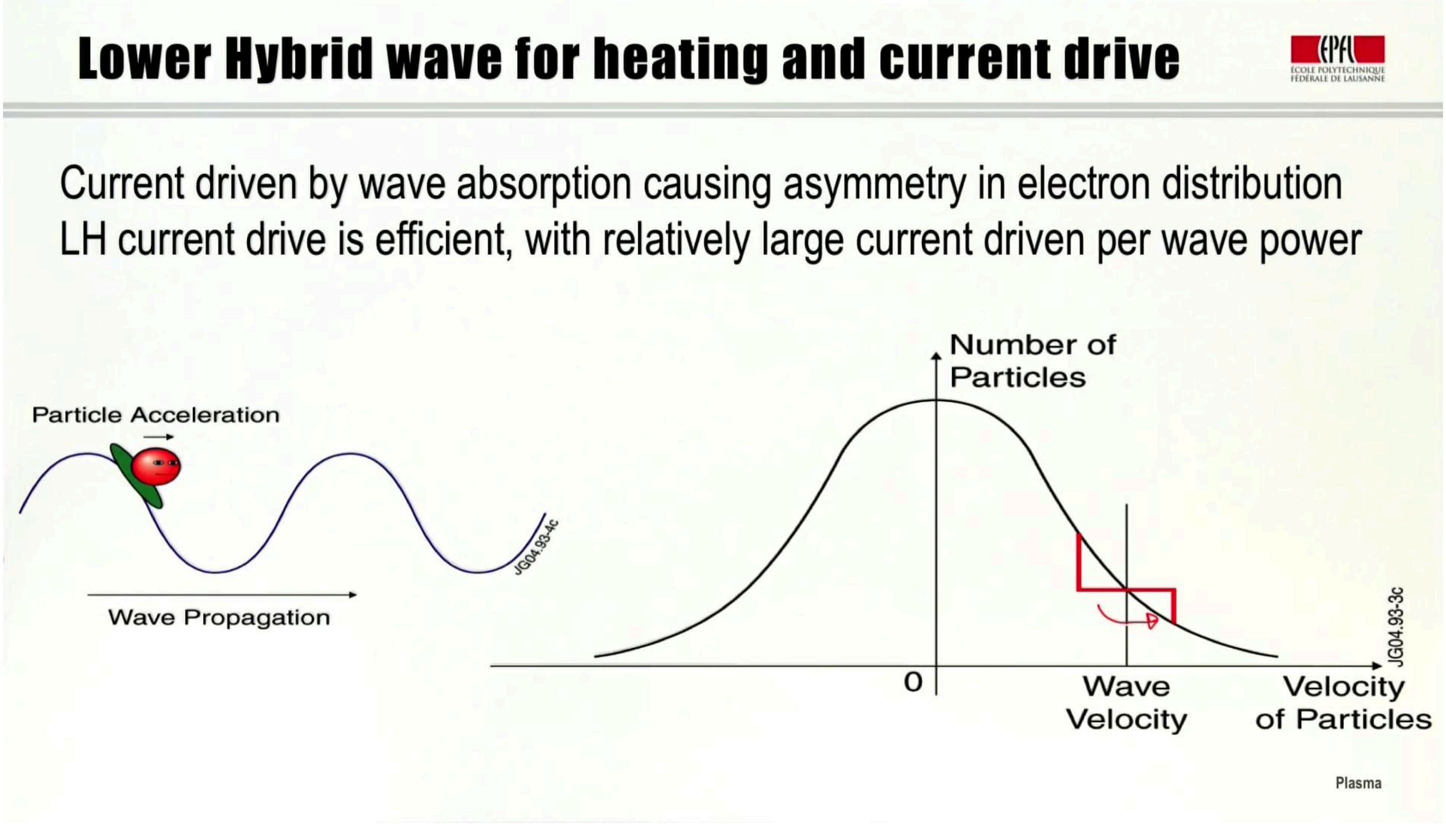

Plasma

Again, it's the extraordinary mode that we're dealing with. Now we are already quite to the right of this plot, which means that ω/k is pretty small, we are in a regime that can be represented well by the electrostatic wave approximation. So we have a wave that's primarily electrostatic, meaning that the perturbed magnetic field associated with the wave is generally negligible. Typically for electrostatic waves we have the need to have an antenna in the plasma. There's a minimum density that's required to launch such a wave and so we need to be pretty much in contact with the plasma, which we've seen is not necessarily an easy condition to satisfy.

Notes

Summary

31m 41s




What is the fundamental mechanism for driving the current using this wave? Say we have a wave particle resonance, so there is an acceleration of a class of particles, the class of particles that resonate with the waves and that has a smaller energy than the wave to begin with, on average would be accelerated. The class of particles that resonate with the wave but that start with velocity that's slightly larger than that corresponding to the wave phase velocity, on average will in fact lose energy to the wave. So the distribution function that we're representing here in a 1-D plot in a very simple way would be modified. Again, we will push particles that are going a little slower than the wave to the right so we accelerate them. That means that if we look at the overall structure of the distribution function we have made that asymmetric. Say these are electrons, that means on average we have changed the average velocity of the population, that means that we are driving current and the lower hybrid interaction because of this resonant feature is quite efficient in doing that. That means we can have a relatively large current driven in the plasma, per unit wave power.

Notes

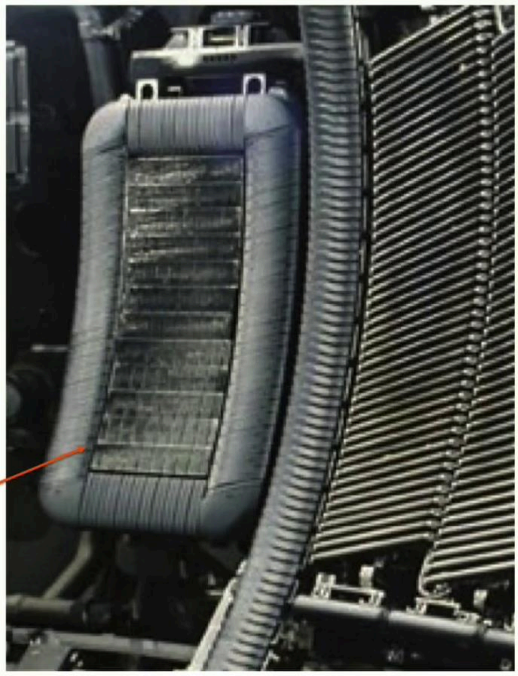
Summary

32m 26s

## Lower Hybrid wave for heating and current drive

Antenna needs to provide directivity with defined spectrum

Many phased waveguides (‘grill’)




Plasma

Let's see how an antenna looks like that can launch lower hybrid waves of use for current drive. To do that we need to provide a certain directivity of the wave with a well defined spectrum. To do that we have decided to go in general for the idea of what we call a *grill*, that's an antenna made up by several, many phased wave guides. So the phasing of the wave guides allows the good definition of the spectrum of the wave number of the wave and therefore to direct the propagation of the wave in one particular direction. So this is an example of a lower hybrid antenna with, again we call it lower hybrid grid, installed in the JET tokamak plasma.

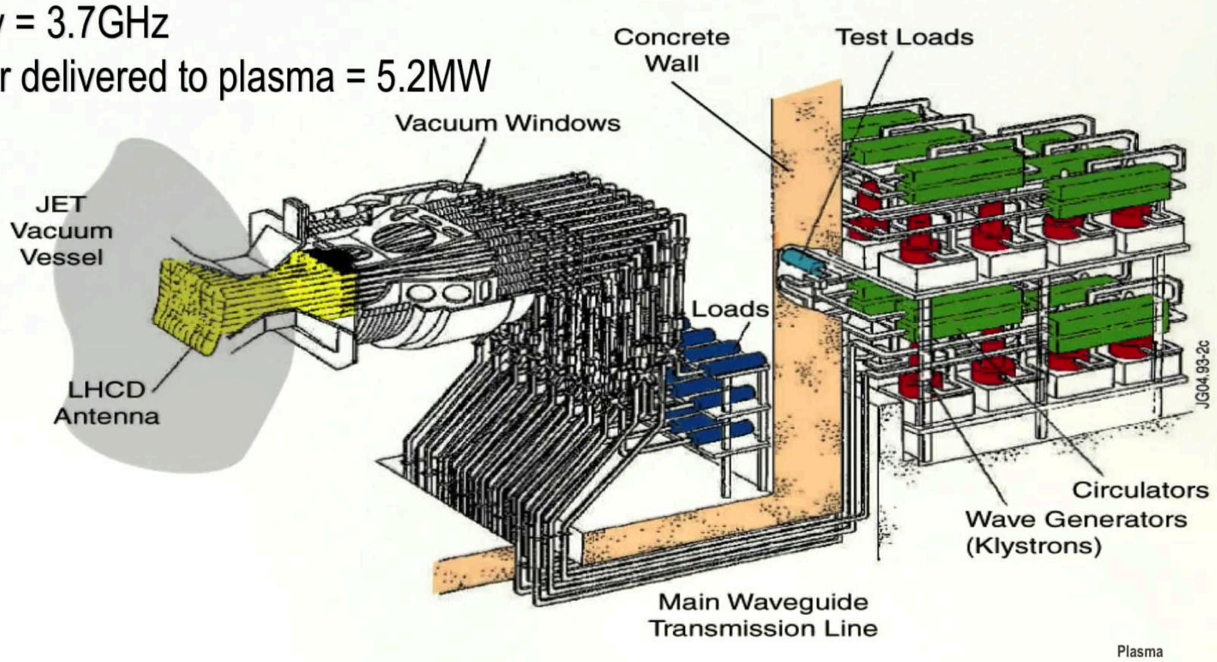
Notes

Summary

33m 48s

# Example of present LH system: JET

Frequency = 3.7GHz
Max power delivered to plasma = 5.2MW




And as an example of a complete lower hybrid system I also use that of JET. The frequency is 3.7 GHZ and so far the maximum power that we have delivered to the plasma is slightly about 5 MW. And as in the other system we go back from the plasma from the antenna we have seen in the form of a grill there's s set of a feed-throughs here and then there are transmission lines and they pass through the concrete wall of the torus hall and then of course they are connected to the generators, which are klystrons.

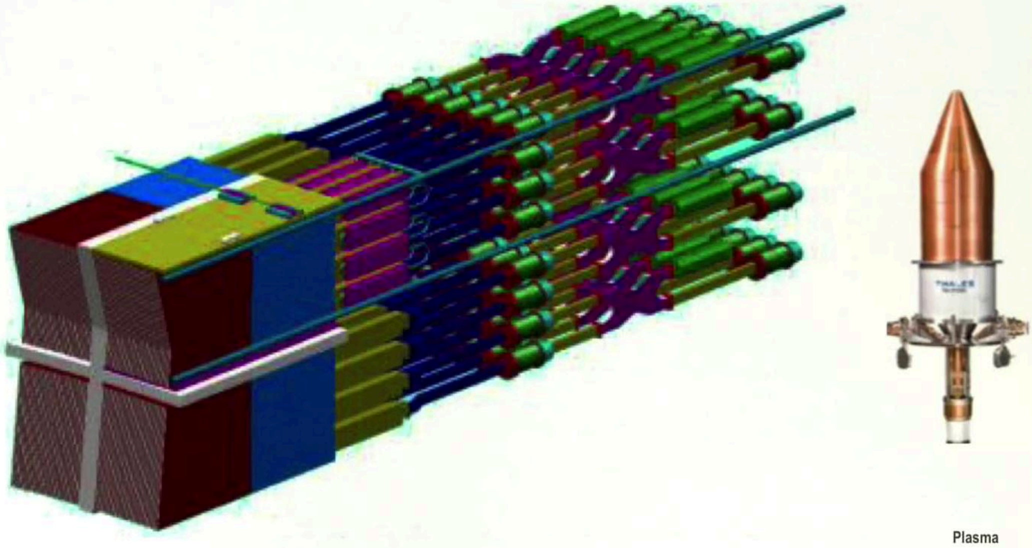
Notes

Summary

34m 37s

## The LH system for ITER

Frequency 5GHz, 20MW will be installed for second stage of heating upgrades
Mostly for off-axis current drive



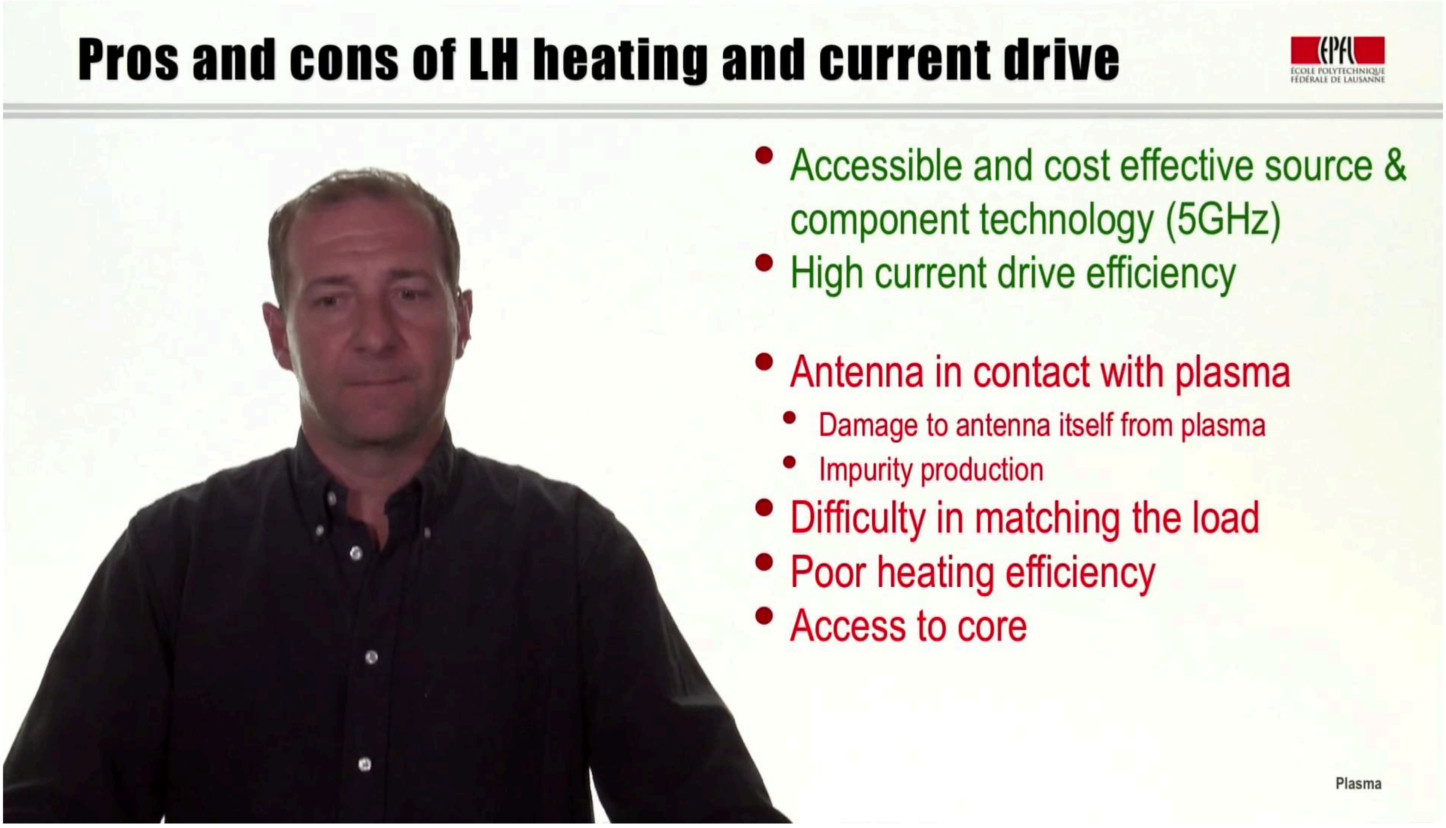

*Courtesy of ITER Organisation*

A lower hybrid system is also foreseen for ITER with a frequency of 5 GHZ and a power up to 20 MW. Although it's foreseen only for the second stage of installation of heating upgrades, not for the first stage of operation. The idea is to use this primarily for driving current in a plasma non-inductively but because of the plasma density in ITER, it will only be possible to drive current off-axis. Nevertheless that will be of interest to control the current profile and control the regime of operation of the plasma.

Notes

Summary

35m 18s

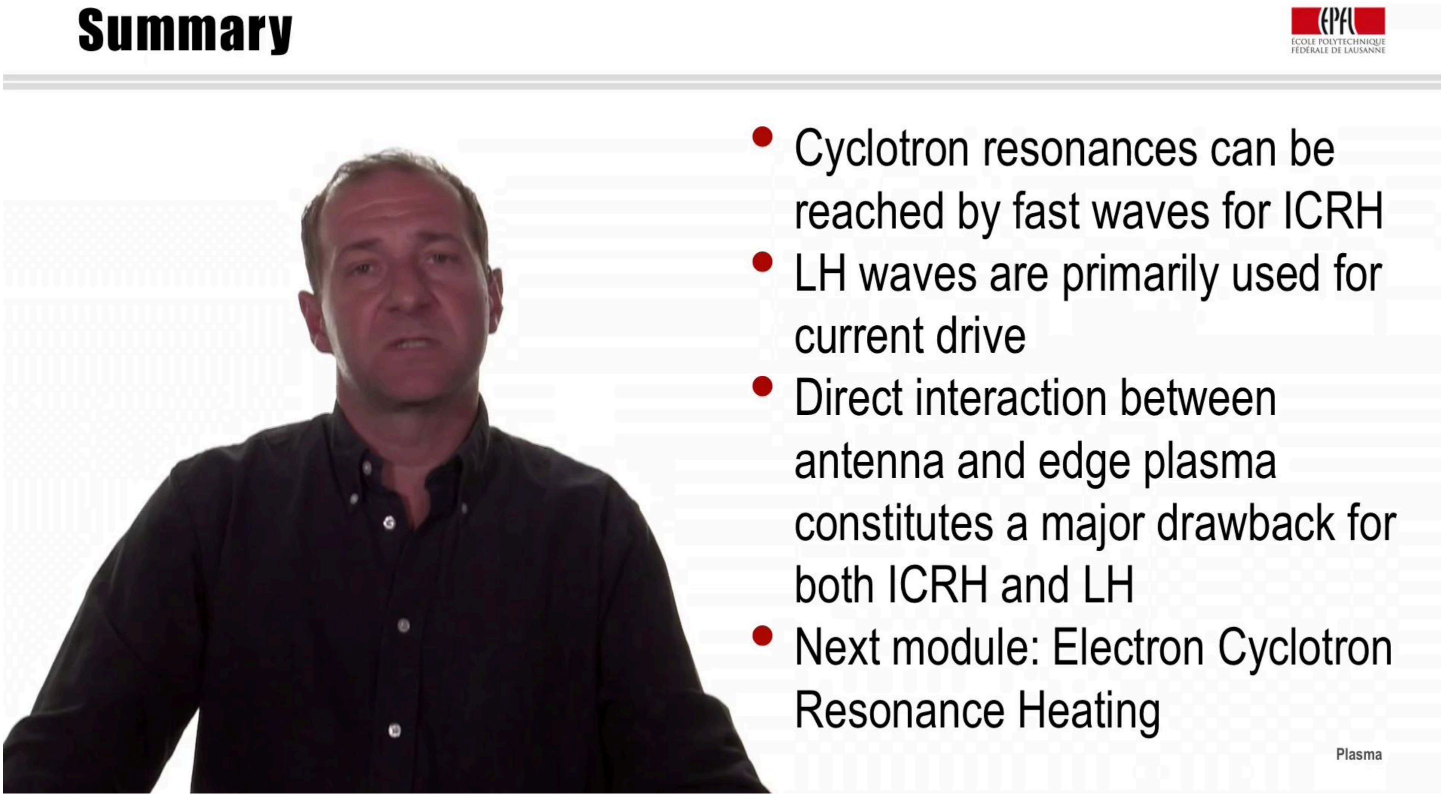



We are now ready to discuss very briefly and qualitatively advantages and disadvantages of lower hybrid current drive. First of all, as was the case for ICRH there is a technology for the source and for the components that's relatively easily accessible and cost effective. We are in the few GHz range of frequencies where several applications in different domains exist. However, the main advantage that we foresee for lower hybrid is the ability of driving current in the plasma in a very efficient way, at least in some ranges of the density values in the plasma. On the disadvantage line, there's also the same kind of problematic that we have for ICRH, having an antenna that needs to be in direct contact with the plasma, which can lead to damages of the antenna itself from the plasma and to the impurity production by antenna itself or by the surrounding surfaces. It's also difficult to match the load, the load that's constituted by the antenna and the plasma together that's therefore varying with time and the heating efficiency is generally quite poor as is difficult to access the core of the plasma if we go to higher and higher densities.

Notes

Summary

35m 53s




In summary, we have seen that cyclotron resonances can be reached by fast waves for ICRH. We have seen that lower hybrid waves are primarily used for current drive in addition of course, to the ohmic current drive by the transformer action. We have seen that both for ICRH and lower hybrid the direct interaction between the antenna and the edge plasma constitutes a major drawback. In the next module, we'll discuss the electron cyclotron resonance heating. It's physics basics and some of the technology aspects of it.

Notes

Summary

37m 16s