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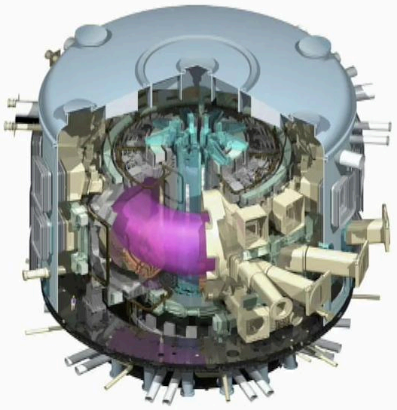
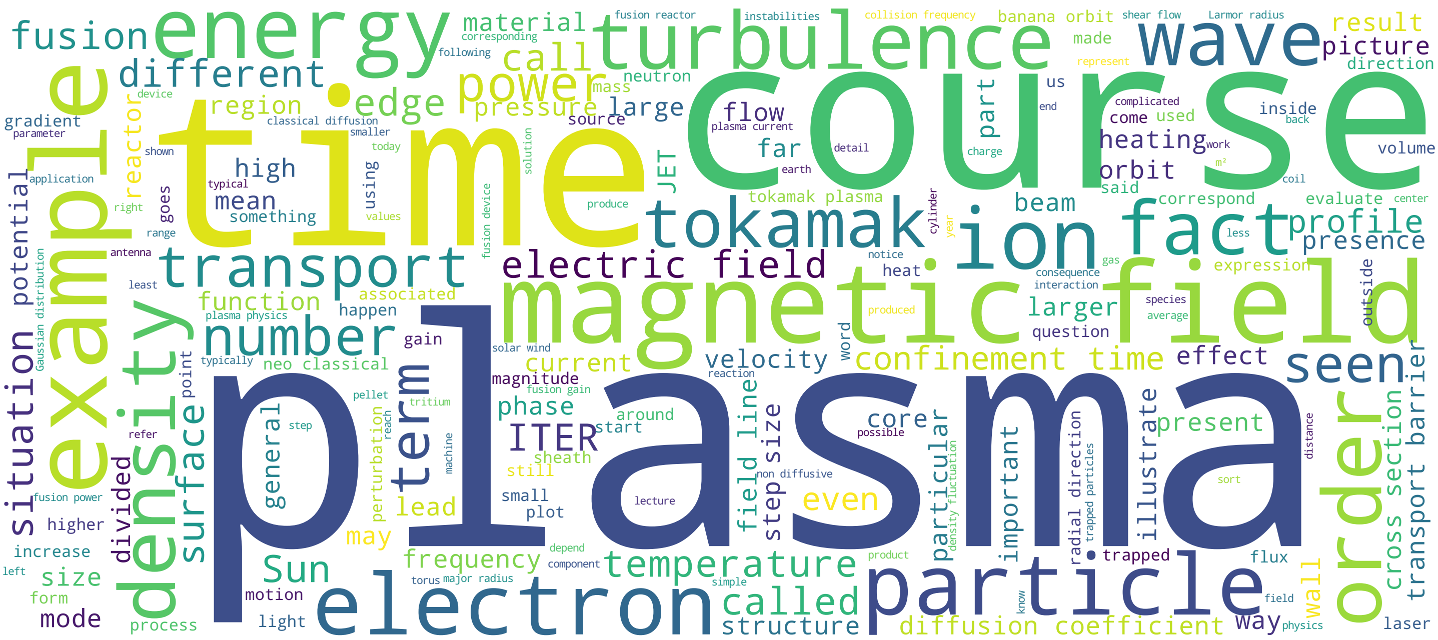


Beyond classical transport in tokamak plasmas

Plasma Physics and Application to Fusion Energy, Astrophysics and Industry

Lecture 7e

Ambrogio Fasoli



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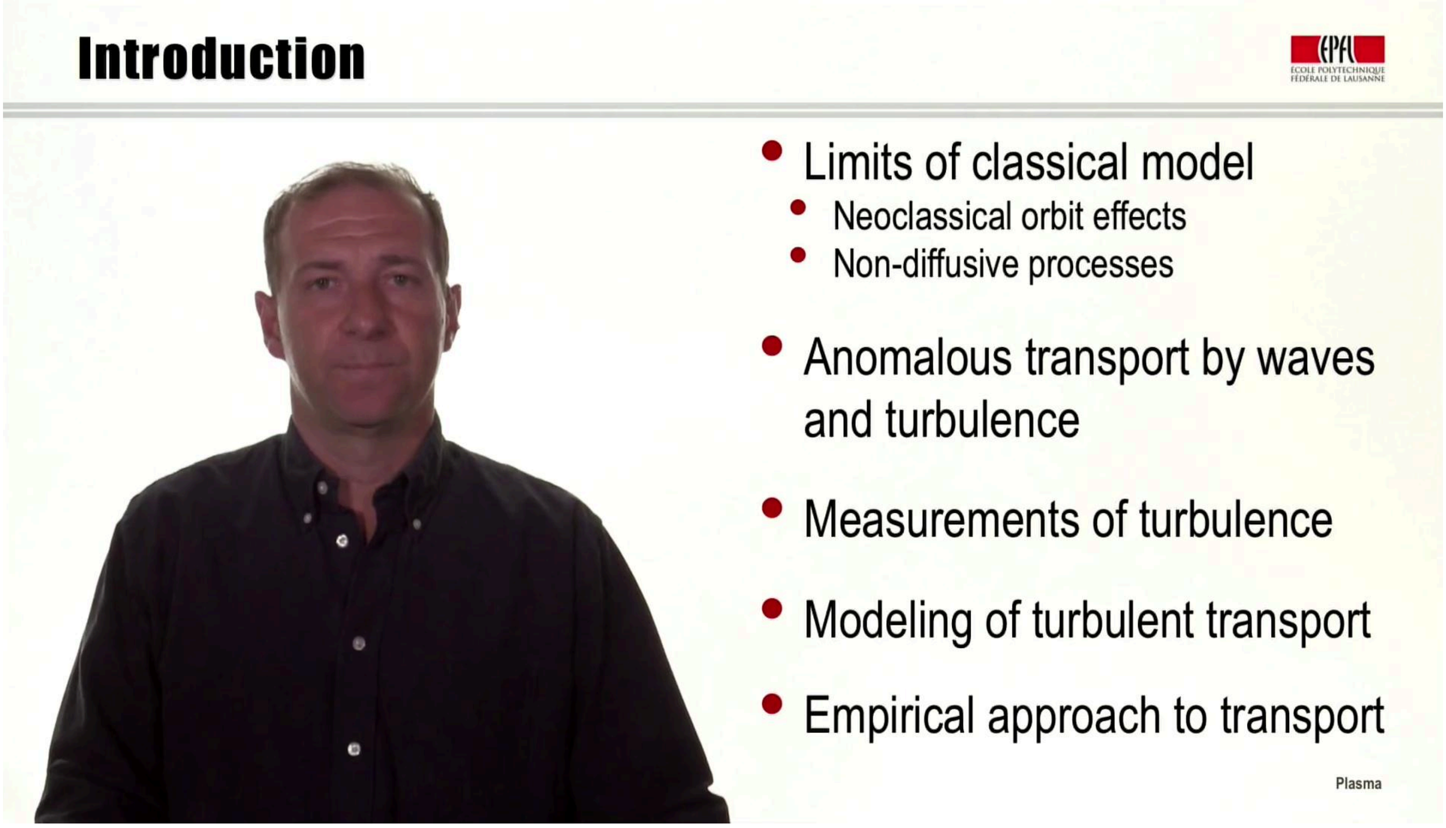


Welcome to the course on Plasma Physics and Applications. Today we will discuss transport in tokamak plasmas, going beyond the classical paradigm we illustrated last time. We will dwell on the limits of the classical model, highlighting the presence of the so-called neo-classical effects that are related to the orbits that are complex in a tokamak environment. We will also underline the fact that the processes are not always diffusive that provide transport. But that we will focus primarily on the so-called *anomalous* transport. This is the transport caused by the presence of turbulence in a plasma. Turbulence is developed from the waves and instability that are naturally occurring in fusion plasmas. We will highlight how to measure turbulence in plasmas, providing a couple of examples, and the difficulties of modeling turbulence and its consequences in a plasma. We will then focus on the empirical approach to transport and how we can make predictions based on the present experiments for the future devices.

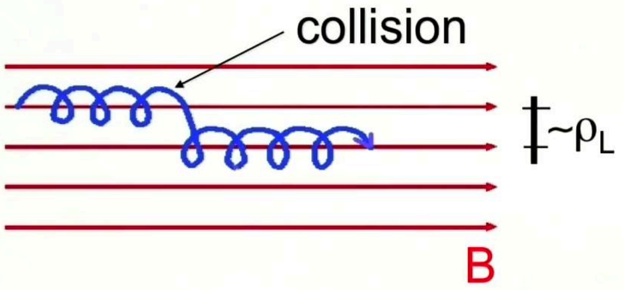
Notes

Summary

0m 05s

Reminder – the conclusion of classical theory

Random walk estimate



$$\frac{\partial n}{\partial t} = D_\perp \nabla^2 n$$

$$D_\perp \approx \rho_L^2 / \tau_{coll} \approx \rho_L^2 \langle \nu_{e/i} \rangle$$

Let us see how this can be verified, in particular how the cross-field diffusion coefficient determines a crucial parameter for fusion, the confinement time

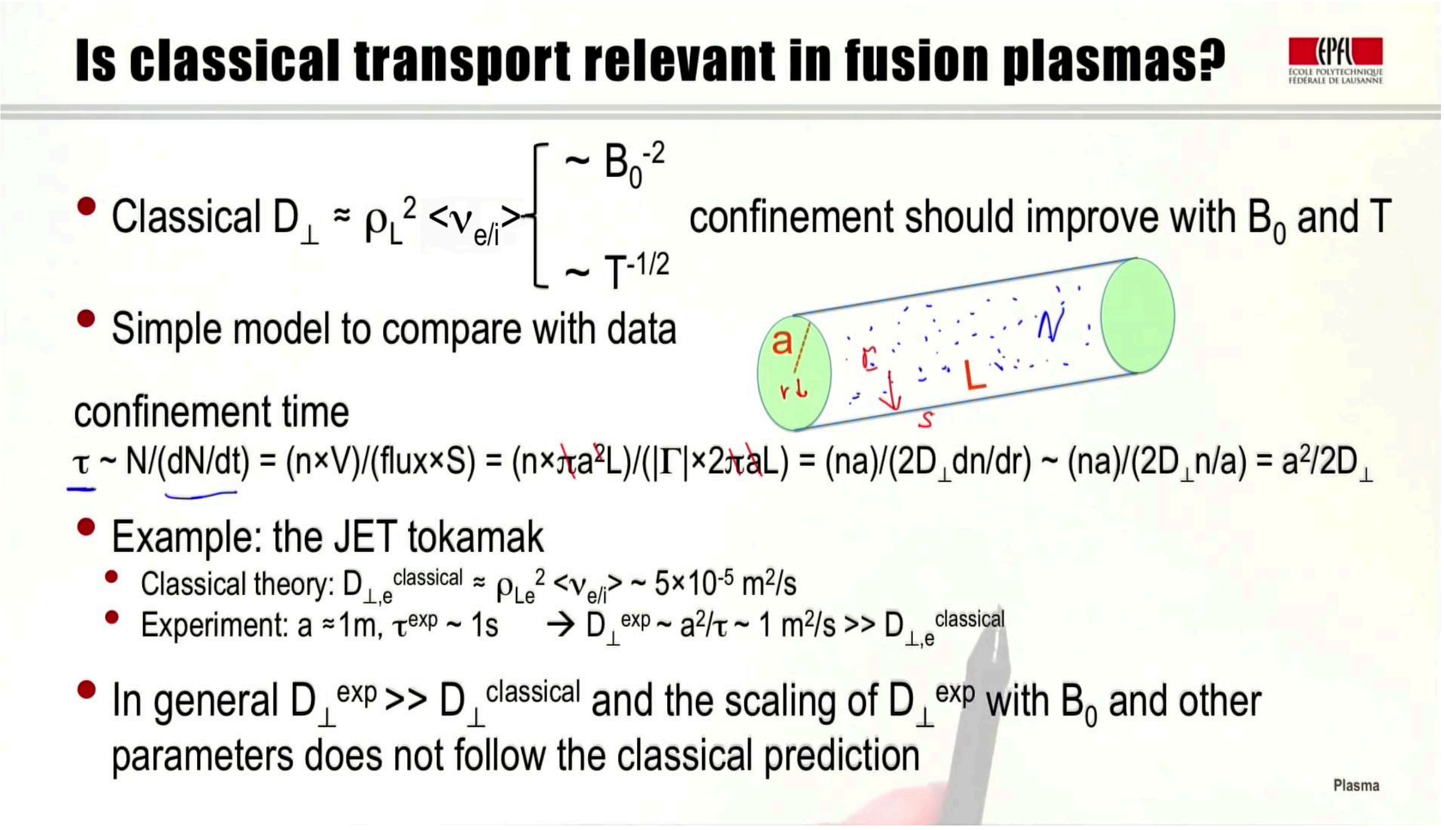
Plasma

I would like to start by reminding ourselves where we concluded from our analysis of classical theory. We have used the very simple model of *random walk*, considering that the collisions between charged particles lead to jumps in their orbits of the order of the Larmor radius of course, across the magnetic field, which leads to a diffusion equation here for the density, which has a main parameter, the perpendicular diffusion coefficient which can therefore be simply estimated on the basis of the square of the step of this diffusive process which is the Larmor radius divided by the collision time -or times the effective collision frequency- for the exchange of momentum in this case. We can now see how this can be verified in the practical situations in the experiment. In particular how the cross-field diffusion coefficient can determine a crucial parameter for fusion that is the confinement time.

Notes

Summary

1m 17s

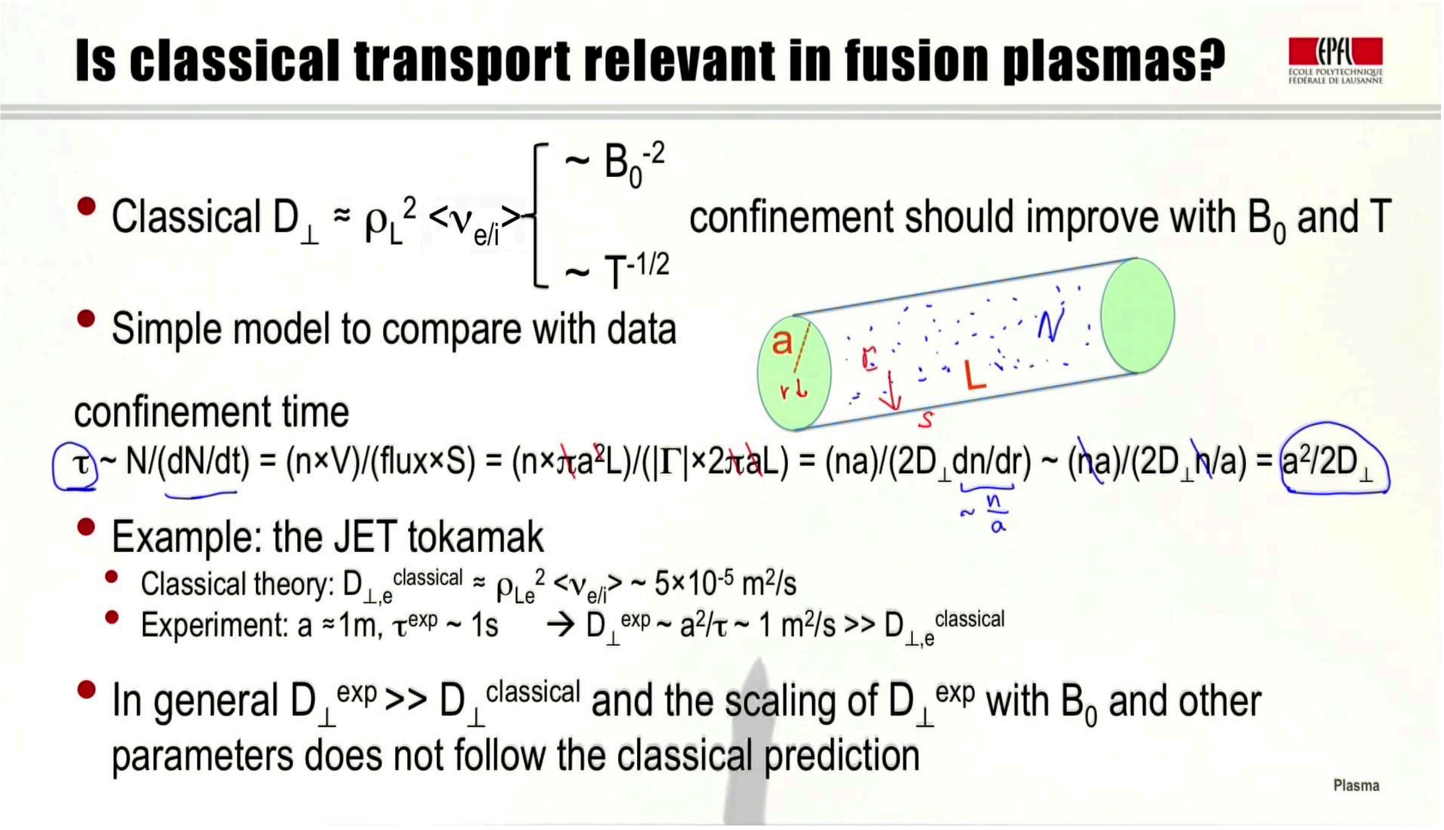


Let's take a very simple geometry: a cylindrical plasma, the cross-section of the cylinder has a radius a, the cylinder has a length L. So we can evaluate the confinement time for this situation in the following way: So τ is my confinement time, it is the ratio of the total number of particles in my plasma which will be contained in this cylinder. So these are the plasma particles in the cylinder. There are N of them. So τ will be given by N divided by the loss rate. So the number of particles lost per unit time. The number of particles N that we have will be the density times the volume. And the number of particles that are lost because of transport would be the flux say, going through the walls times the surface of the walls. So the volume is π a² L, and the surface of this cylinder around neglecting the end surfaces will be 2π a L. Of course, I put Γ here with the absolute value, not to be confused by the sign in Fick's law. Now I simplify here the different terms end up with n a / (2 D⊥) times a gradient of the density in the radial direction, [dn/dr] the radial direction is the direction from center to the edge of the cylinder.

Notes

Summary

2m 32s

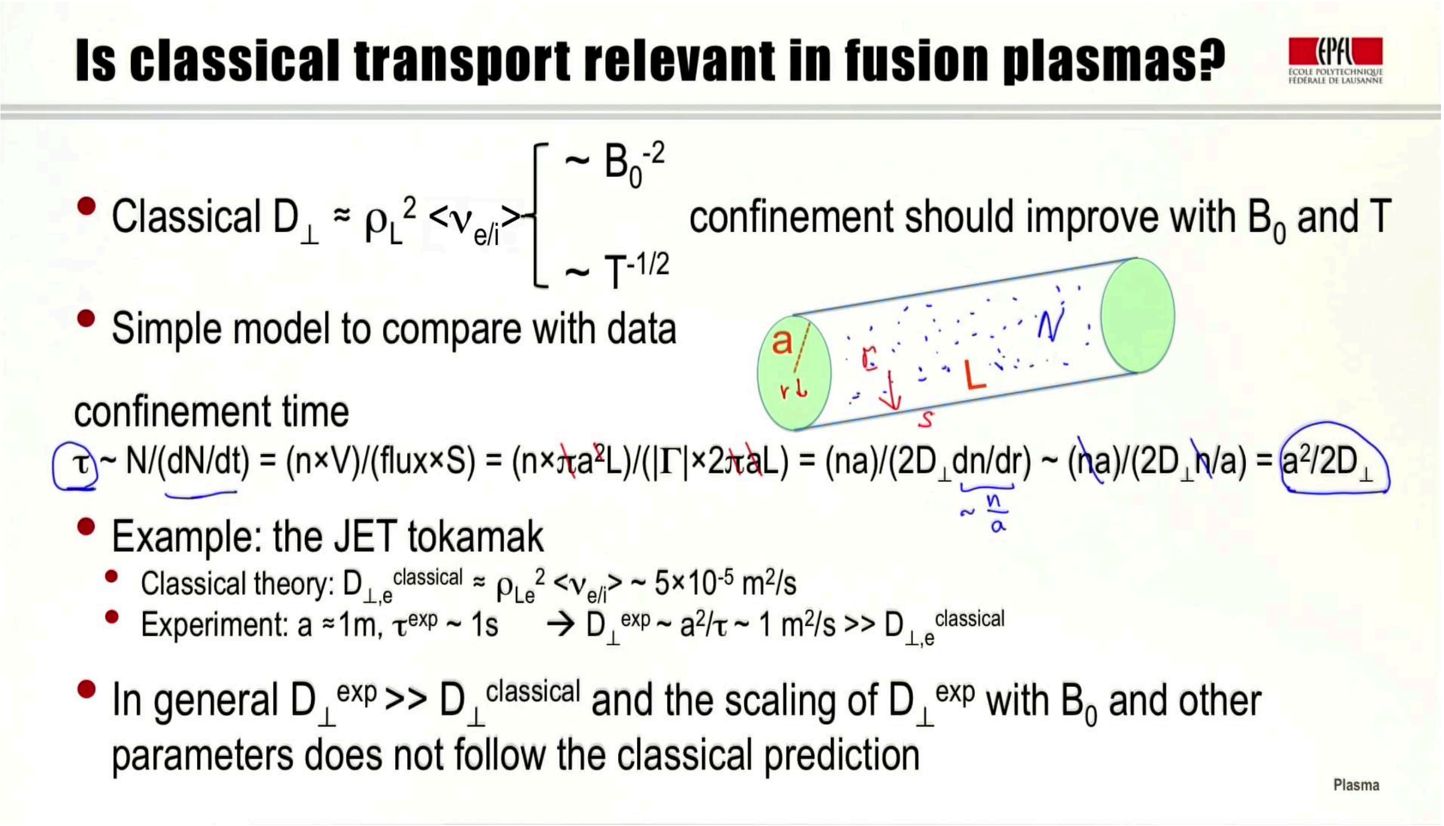


And I evaluate in a simple way this gradient in terms of order of magnitude, as just the density divided by the radius a. So that is n a / (2 D⊥) n / a. Interestingly, the density goes away, ending up just with a² / (2 D⊥). So this is one way to relate in a simple way the confinement time that one can measure experimentally to the value at least in order of magnitude of the diffusion coefficient in the perpendicular direction. a is the size of the plasma. Let's take for example the case of the JET tokamak which we know quite well. If I apply this classical theory that I developed so far, the perpendicular diffusion coefficient for electrons for example, is of the order as we say the Larmor radius squared [ρ_{Le}^2] times the collision frequency [$\langle \nu_{ei} \rangle$]. Put the numbers and that is about 5×10^{-5} m²/s What about the experimental value or the order of magnitude of the experimental value? a is of the order 1 m. The experimental confinement times of the order 1 second, so if I evaluate D⊥ from this expression we have seen together, that would be of the order of a²/τ. Here I don't even put the factor of 2 just to underline the fact that we're really only evaluating the orders of magnitude.

Notes

Summary

4m 17s

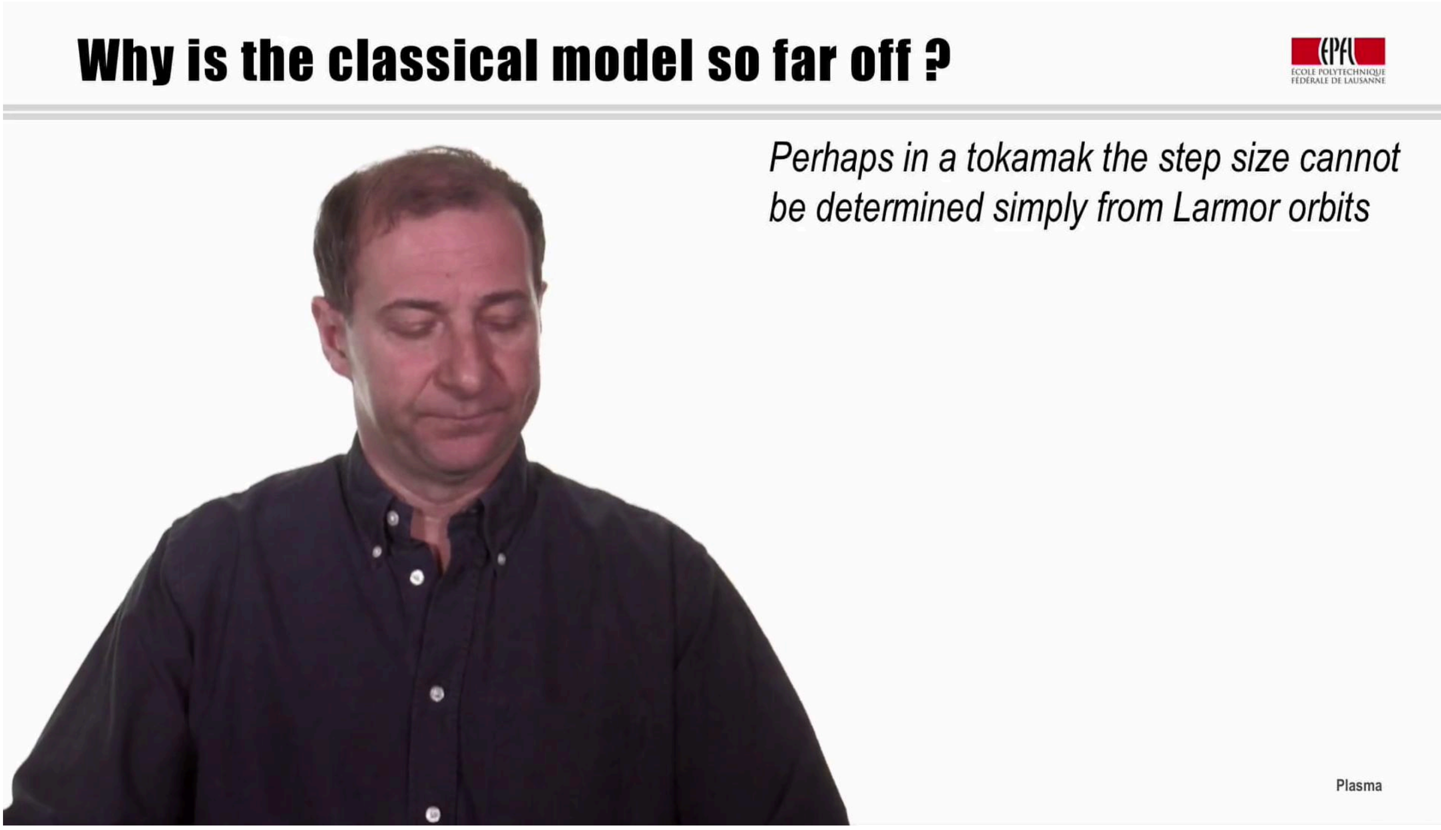


That gives me something like 1 m² /s. 1 m² /s to compare with the classical prediction of 5×10^{-5} m²/s so of course this is much larger than the classical theoretical prediction. This is quite a general observation that we have in many, many fusion devices in fact, in many magnetically confined plasmas, even at lower temperatures and lower densities. In general, the experimental diffusion coefficient is much larger than the classical value. Not only that, but also the scaling of the experimentally measured or estimated diffusion coefficient with parameters such as the magnetic field or even the temperature, etc., does not follow the classical prediction.

Notes

Summary

6m 02s



So the first question is, why is the classical model so far off, but also to evaluate D⊥ quantitatively in particular, and also in terms of the scaling of D⊥ upon the plasma parameters? What have we done wrong? First issue that comes to mind is that perhaps the step size, at least in a tokamak plasma, is not quite the Larmor radius, or it would be more complicated than that, because the orbits are more complicated than that. So let's look at that possible effect.

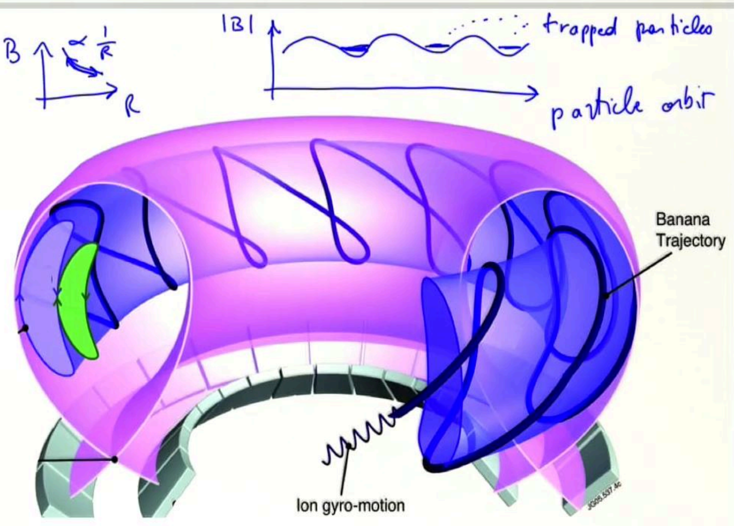
Notes

Summary

6m 50s

Neo-classical transport in tokamak plasmas

- In a tokamak particles move along helical field lines
- As B ~1/R, particles experience minima and maxima of B
- Depending on pitch angle of **v** and on a/R, a fraction of particles are trapped in effective magnetic mirror
- Projected on poloidal plane, trapped particle orbits resemble bananas



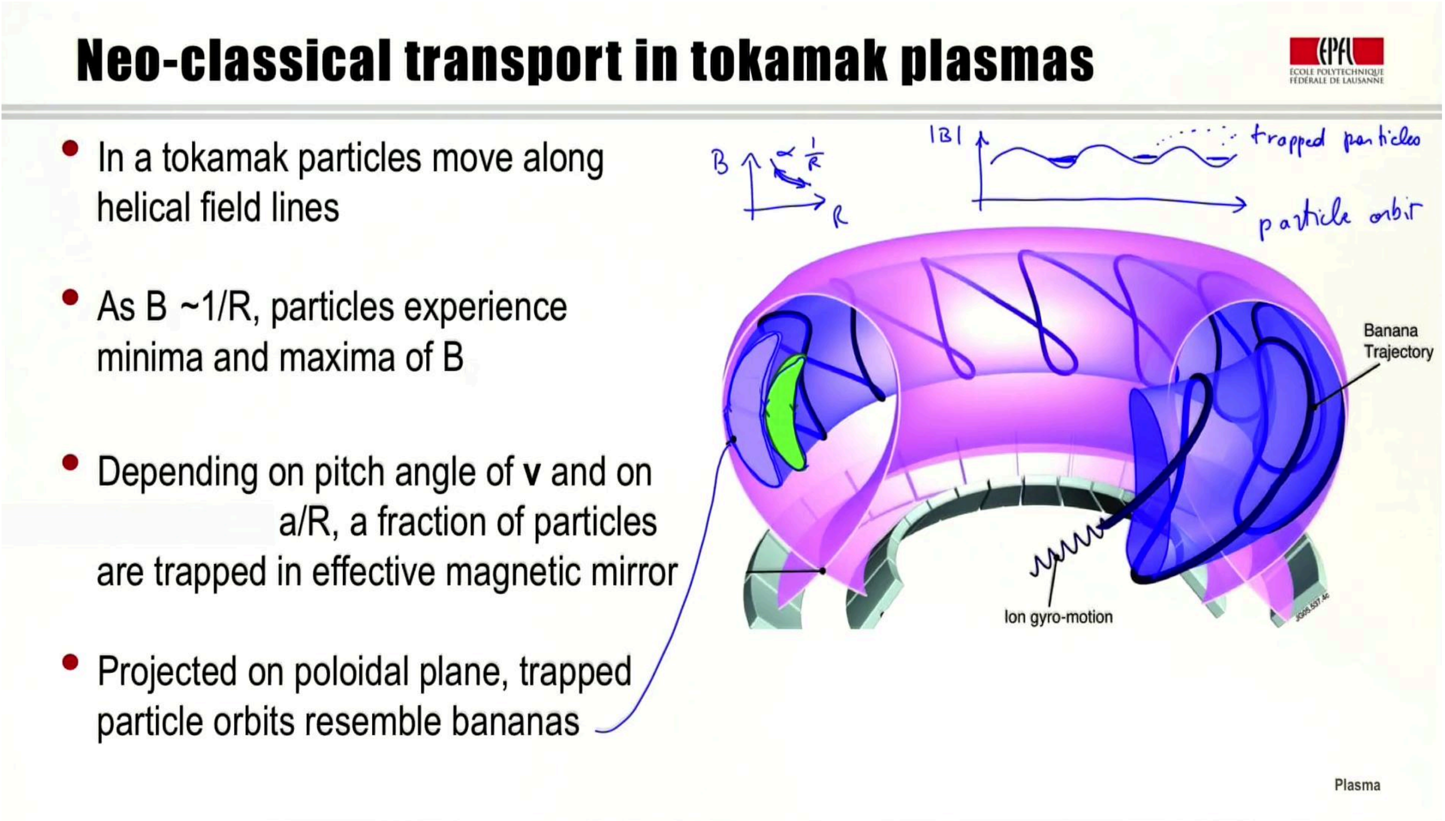
Plasma

As we have learned in previous lectures, in the tokamak, particles move along helical field lines in addition to their gyromotion, they have an orbit that goes around the helical field lines in fact, we have constructed a tokamak machine, a tokamak concept exactly to do that, so that on average its drifts are compensated and particles can be confined. But as the particles go around this helical structure, they will go in, out, in, out, in out. In general, the magnetic field is proportional to 1/R, where R is the distance from the axis of the torus. So that means that if particles go around in the way we've just seen in the picture, they will see a field that will be going up and down, up and down, up and down. Let's say this is along the particle orbit. If a particle sees a field that goes up and down, up and down, so it means it experiences minima and maxima over B because it sort of moves along this direction, back and forth. It may be trapped in the minima of B: it may be trapped by the mirror trapping effect that you have discussed in the first part of the course. Of course, not all particles are trapped.

Notes

Summary

7m 24s



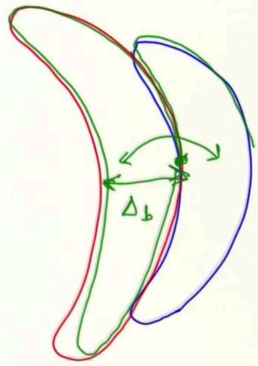
The trapping will depend on the pitch angle of their velocity and on the depth if you like, of this variation of the magnitude of B that they see along their orbit, which itself depends on inverse aspect ratio which is the minor radius a divided by the major radius [R] of the torus. But some particles will be trapped in this effective mirror. And the particles that get trapped will follow a trajectory that is not really going all the way around but it will be actually confined to some portions of the torus and if we project that trajectory on the poloidal plane-- I'm following one here for example, or a second one here, that will look like a banana. So this is why we call these *banana orbits*. These banana orbits represent the orbits of the trapped particles. Trapped particles mean particles that are actually trapped in a minima of the magnetic field as they see a variation of the field along the orbits going in and out, in and out the torus.

Notes

Summary

9m 01s

Neo-classical transport in tokamak plasmas



- The largest correction of classical estimates come from trapped particles that move quickly around *banana* orbits and, upon collisions, jump to a different orbit
- Step size: banana orbit width $\Delta_b \sim q\varepsilon^{-1/2}\rho_{Le}$
  - q=safety factor, ε=a/R inverse aspect ratio
- Effective collision frequency for *banana* orbits $\nu_{eff} \sim \underline{<\nu_{e/i}>}/\varepsilon$
- As the fraction of trapped particles is $\varepsilon^{1/2}$, the resulting *neo-classical* contribution *to* diffusion is $D_\perp^{neoclassical} \sim \varepsilon^{1/2}\Delta_b^2\,\nu_{eff} \sim \varepsilon^{1/2}(q\varepsilon^{-1/2}\rho_{Le})^2 <\nu_{e/i}>/\varepsilon = q^2/\varepsilon^{3/2} D_\perp^{classical}$
  - Ex. JET: q~3.5, ε~0.3 → $D_\perp^{neoclassical} \sim 75\, D_\perp^{classical} << D_{\perp,exp}$
- $D_\perp^{neoclassical}$ does not account for exp. values (or scalings)

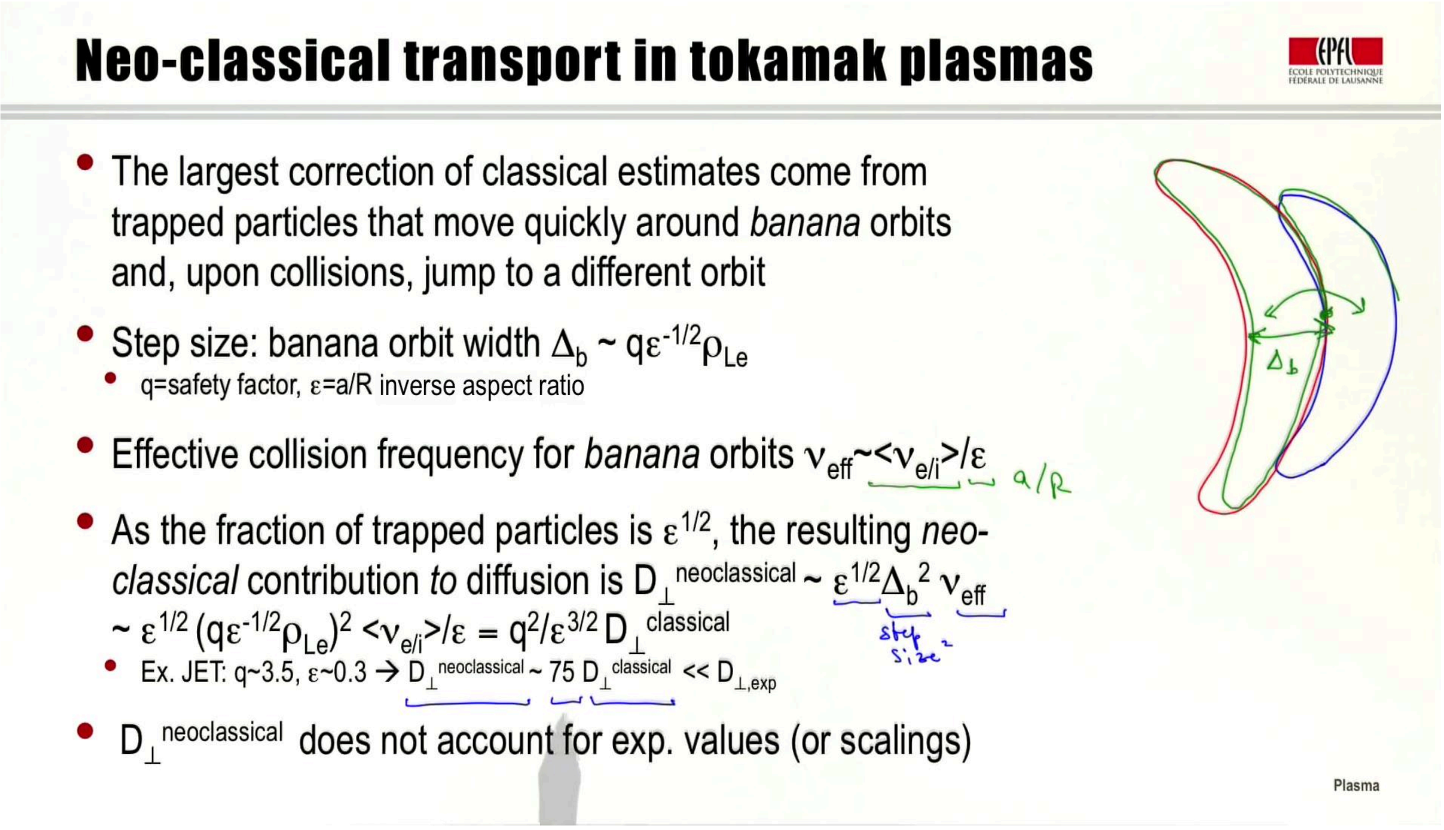
Plasma

So why is this relevant to our discussion of transport? Because if particles move quickly around banana orbits and they collide, say I represent here another banana orbit like that, as a banana orbit sort of next to it in red. Suppose a particle is moving along this blue orbit and collides with another particle at this point, they may jump to a different banana orbit and follow that agaiin. So this jump is such that the displacement of the particle on average, would not be of the size of the Larmor radius anymore, but will be of the size of the width of the banana orbit which we call Δb. So my step size in the collision process will be of the order of the banana orbit with Δb. And if I calculate that, that will be equal to the safety factor q at the location of the orbit times the Larmor radius for the particle, in this case I have taken electrons divided by the square root of the inverse aspect ratio ε, again, the ratio of the minor to the major radius. So we know now the step size, what is the effective collision frequency? Well, it will be similar to the collision frequency for the exchange of momentum that we have seen before.

Notes

Summary

10m 06s



For example, between electrons and ions but corrected by again, a factor that is the inverse aspect ratio, a/R [=ε]. Now, not all particles are trapped so we need to account for that. So we say that the fraction of trapped particles is of the order of the square root of this inverse aspect ratio, ε again, so the contribution from trapped particles will be what we call the *neoclassical diffusion* corresponding to a neoclassical diffusion coefficient, perpendicular to B would be of the order of the fractional trapped particles that are actually undergoing this process, times the step size squared, times the effective collision of frequency for the process. Now I take the numbers for JET and noticing of course, I can in fact express the terms as we have developed them before in the way of $q^2/\varepsilon^{(3/2)}$, times the classical diffusion coefficient, so I take the numbers for JET, let's say q of order 3.5, ε is about.3, so the neo-classical term, which is the neo-classical diffusion coefficient related to the fact that the orbits are not simple Larmor orbits, but they are more complicated and they are on the poloidal plane in the form of bananas, is about 75 times the classical diffusion coefficient that we have seen before.

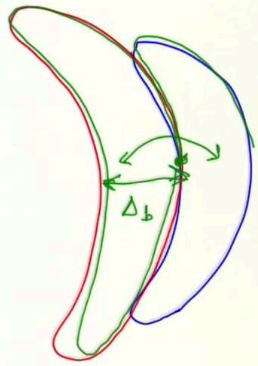
Notes

Summary

11m 43s

Neo-classical transport in tokamak plasmas

- The largest correction of classical estimates come from trapped particles that move quickly around *banana* orbits and, upon collisions, jump to a different orbit
- Step size: banana orbit width $\Delta_b \sim q\varepsilon^{-1/2}\rho_{Le}$
  - q=safety factor, ε=a/R inverse aspect ratio
- Effective collision frequency for *banana* orbits $\nu_{eff} \sim \underline{<\nu_{e/i}>}/\underline{\varepsilon} \sim a/R$
- As the fraction of trapped particles is $\varepsilon^{1/2}$, the resulting *neo-classical* contribution *to* diffusion is $D_\perp^{neoclassical} \sim \varepsilon^{1/2}\underbrace{\Delta_b^2}_{\text{step size}^2}\nu_{eff} \sim \varepsilon^{1/2}(q\varepsilon^{-1/2}\rho_{Le})^2 <\nu_{e/i}>/\varepsilon = q^2/\varepsilon^{3/2} D_\perp^{classical}$
  - Ex. JET: q~3.5, ε~0.3 → $D_\perp^{neoclassical} \sim 75\ D_\perp^{classical} << D_{\perp,exp}$
- $D_\perp^{neoclassical}$ does not account for exp. values (or scalings)



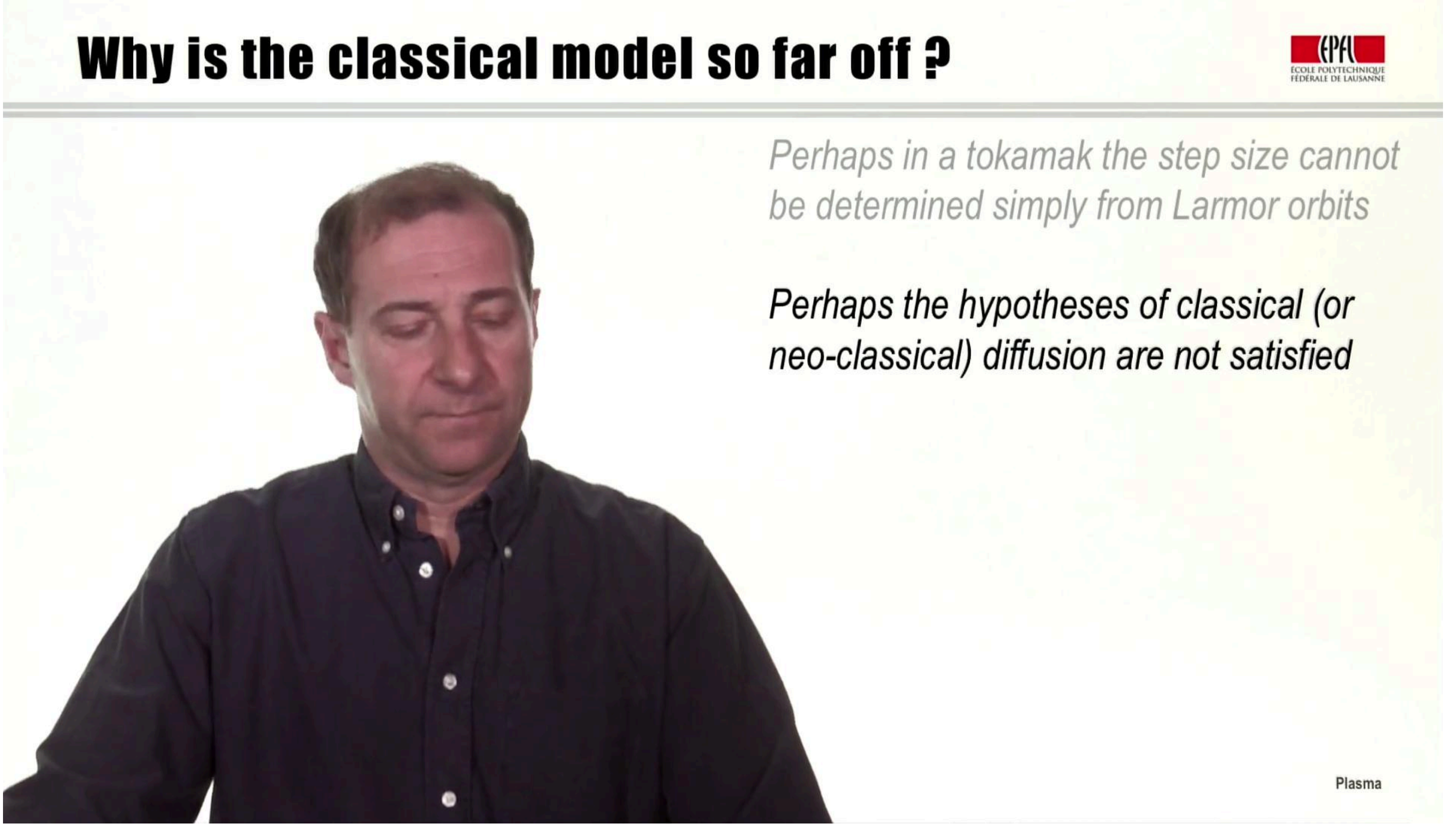
Plasma

This is of course an improvement in the sense that we are getting a little bit closer to the values that we observe experimentally but remember that we were orders of magnitude off and we are still much, much lower than the experimentally measured or estimated data. So even this correction which is in fact necessary, leading to this neo-classical term, neo-classical diffusion coefficient for neo-classical transport does not account really for experimental measures and in fact, does not even account for scalings in many cases.

Notes

Summary

13m 16s

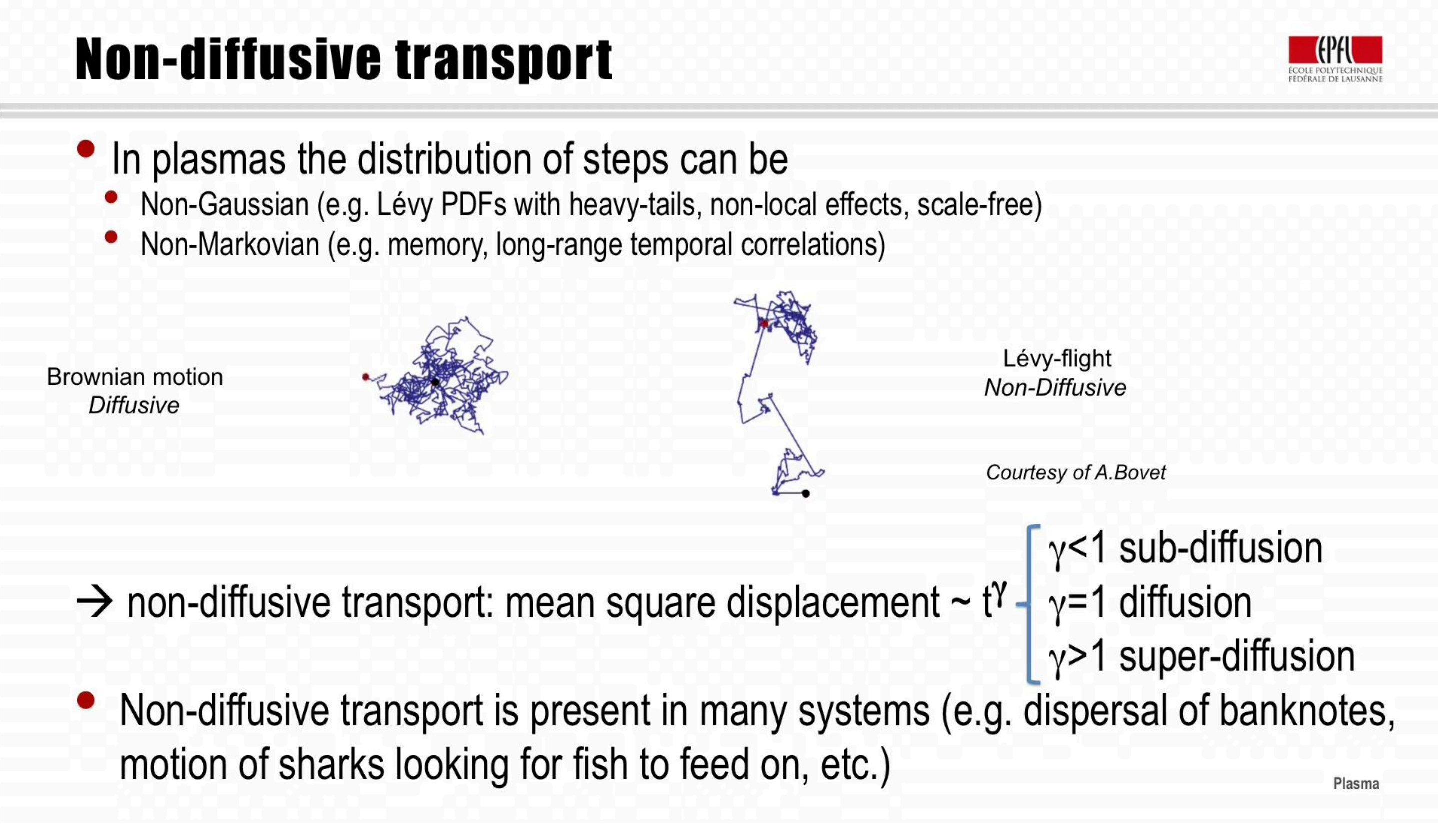


So we have to ask ourselves another question. We have sort of corrected the step size with the proper orbit. we have considered a rather standard collision frequency or even correcting that with the appropriate term for this neo-classical effect. But that's not sufficient, so what else can we do? Perhaps we can even question the hypothesis of classical or even neo-classical diffusion. Are they really satisfied?

Notes

Summary

13m 49s



This is a little diversion, but it's important, at least conceptually. What we have assumed is that the classical diffusion was characterized by a Gaussian distribution of step sizes. In fact, we have taken even the same step size for all particles of the same species. This may not always be the case. We can have a non-Gaussian distribution. For example, the probability distribution functions that have heavy tails or in other words that have a non-negligible probability of having very, very large steps. This is a typical situation of what's called *Levy-flight*. Effects that are non-local between different parts of the plasma, effects that are not really described well by a single scale, so effects that are so called *scale free*. So that's for the step size, that may not be distributed according to Gaussian distributions. But also, we may have situations that are non-Markovian. In other words each step is not necessarily independent of the previous step. So there may be memory in the system. So there may be long-range correlation also in terms of time. These are situations that are not described by the very simple classical model we have seen so far.

Notes

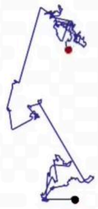
Summary

14m 22s

Non-diffusive transport

- In plasmas the distribution of steps can be
  - Non-Gaussian (e.g. Lévy PDFs with heavy-tails, non-local effects, scale-free)
  - Non-Markovian (e.g. memory, long-range temporal correlations)

Brownian motion
Diffusive



Lévy-flight
Non-Diffusive

Courtesy of A.Bovet

→ non-diffusive transport: mean square displacement ~ t^γ $\begin{cases} \gamma<1 \text{ sub-diffusion} \\ \gamma=1 \text{ diffusion} \\ \gamma>1 \text{ super-diffusion} \end{cases}$

- Non-diffusive transport is present in many systems (e.g. dispersal of banknotes, motion of sharks looking for fish to feed on, etc.)

Plasma

These two movies illustrate the difference between two situations. On the left is a situation we have seen so far, it's the *Brownian motion*. So it's a particle undergoing uncorrelated steps of the same size, or a size distributor according to a very simple Gaussian distribution. On the right we have a simulation of a so-called *Levy-flight*. So it's a non-diffusive transport in which there's a finite probability for having very large jumps as opposed to an exponentially small probability of having very large jumps which would be the case of the classical Brownian motion, which will lead to diffusion. The consequence of this kind of-- non-classical behavior is that the diffusive transport model does not work. So we have a situation which is non-diffusive in which the mean square displacement is no longer necessarily proportional to the time simply, but is proportional to the time to an exponent γ which may be smaller than 1, and that's the case of *sub-diffusion*, or larger than one and that's the case of *super-diffusion*. I notice that non-diffusive transport in fact is very, very common in physical systems so we have examples here. The dispersal of banknotes for example.

Notes

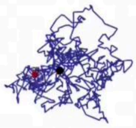
Summary

15m 50s

Non-diffusive transport

- In plasmas the distribution of steps can be
  - Non-Gaussian (e.g. Lévy PDFs with heavy-tails, non-local effects, scale-free)
  - Non-Markovian (e.g. memory, long-range temporal correlations)

Brownian motion
Diffusive



Lévy-flight
Non-Diffusive

Courtesy of A.Bovet

→ non-diffusive transport: mean square displacement ~ t^{γ}
- $\gamma<1$ sub-diffusion
- $\gamma=1$ diffusion
- $\gamma>1$ super-diffusion

- Non-diffusive transport is present in many systems (e.g. dispersal of banknotes, motion of sharks looking for fish to feed on, etc.)

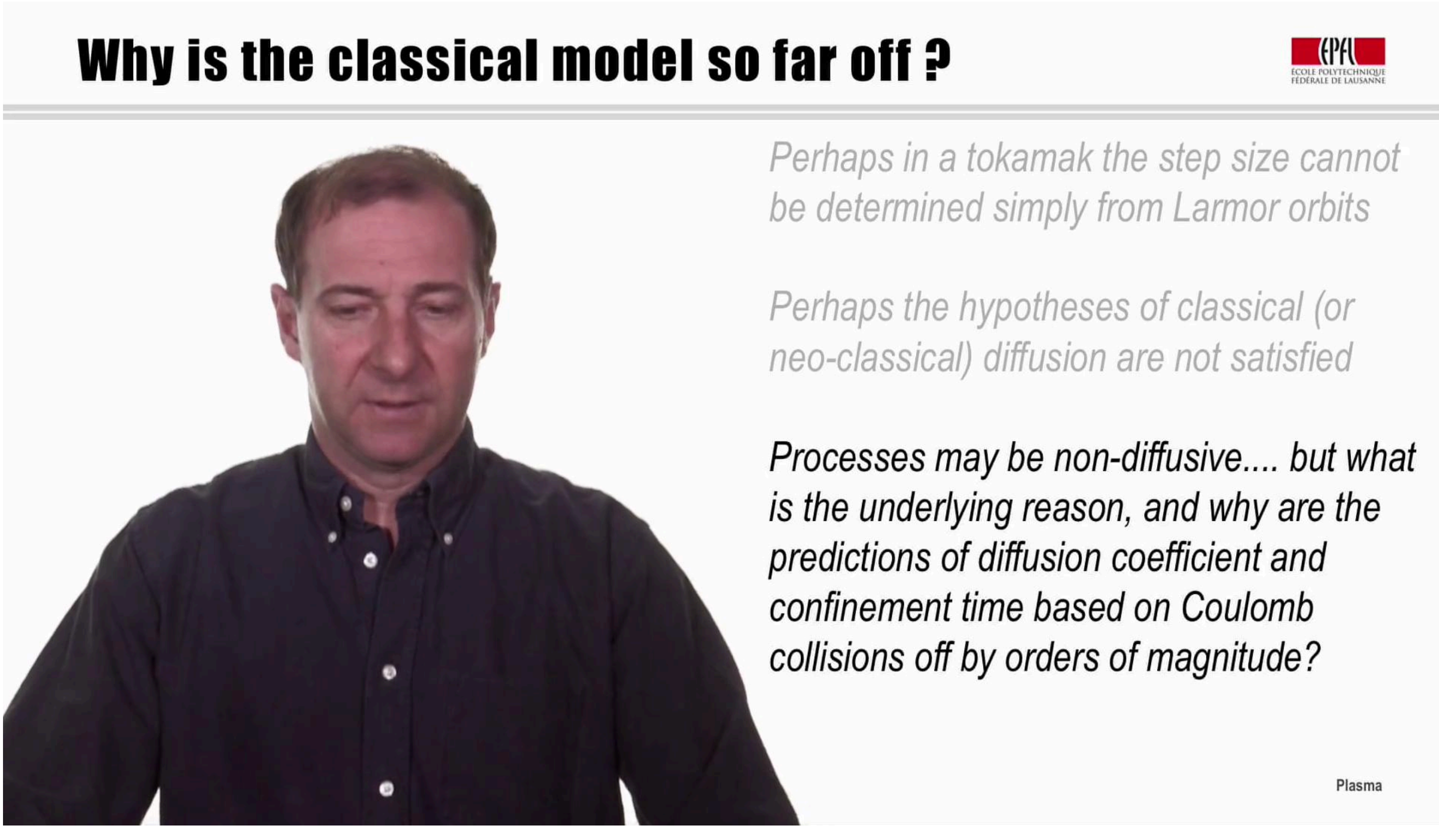
Plasma

You live in your village or in your town, using banknotes and the transport of these banknotes may be described by a Gaussian distribution, relatively a simple sort of classical and random walk. But suddenly you take the plane and you go to a different country and a different location and you use banknotes there and so you have a sudden big jump that's not accounted at all by a Gaussian distribution, therefore by a classical motion. Other examples in nature include the motion of sharks that are looking for fish to eat, to feed on. They explore and utilize the local reservoir of fish and then suddenly, there are no fish anymore for them to eat and they have a very long jump in their motion which is a Levy-flight to go to a different location, maybe thousands of kilometers away, and start feeding on new reservoirs of fish. So this non-diffusive transport is pretty common in many physical systems.

Notes

Summary

17m 15s



However, even considering that the process may be non-diffusive, we still need to understand what is the underlying reason for that and also we need to understand why the predictions of diffusion coefficients and the corresponding confinement times are so far off compared to the experiment, orders of magnitude off. So Coulomb Collisions do not necessarily explain what we observe in the plasmas in terms of transport and even sort of correcting or generalizing the classical approach may not help at all in explaining what we measure in the experimental situation.

Notes

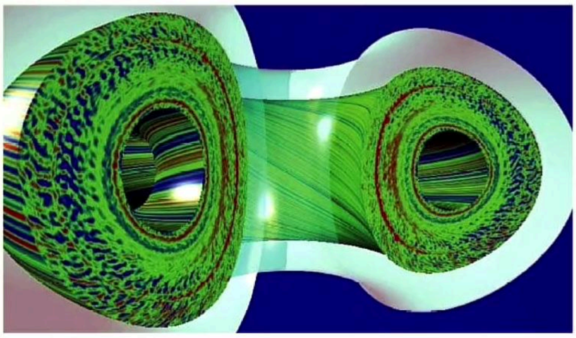
Summary

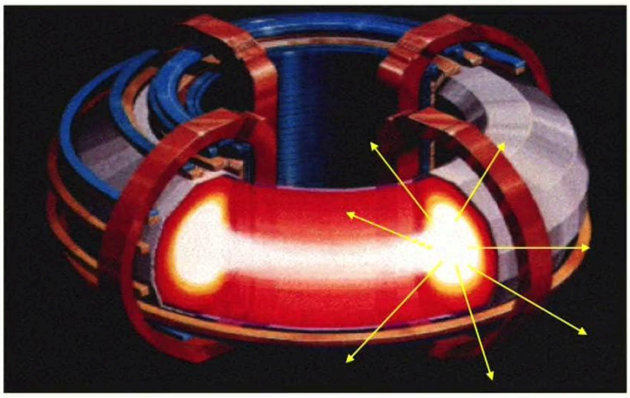
18m 21s

Anomalous or turbulent transport

The *anomalous* transport generated by the interaction of plasma particles with small scale collective instabilities (turbulence) is by far the dominant factor in plasma confinement in magnetic fusion

Free energy → Small-scale instabilities → Plasma turbulence





Plasma

The answer to the question of what is the underlying mechanism that makes diffusion transport so much more effective than that Coulomb collisions would make is turbulence. The transport that results from turbulence is referred to as *anomalous* transport to indicate that it's not a collisional effect. It is in fact generated by the interaction of plasma particles with small-scale collective instabilities which is what turbulence is, and in fact is by far the dominant factor in the confinement of a plasma for magnetic fusion. Turbulence is generated by the instabilities that tap the free energy present in the plasma gradients. This free energy is the source for small-scale instabilities that combine nonlinearly to give rise to turbulence. This is a picture of a simulation showing the structure that forms in a fairly complex manner inside a tokamak and the turbulence that characterizes the tokamak. And in this simple sketch we see that particles and even heat are kicked out by this turbulence from the confinement region to the outside.

Notes

Summary

19m 03s

Turbulence: an open fundamental science question

- Turbulence is a spontaneous way of releasing free energy associated with flows or gradients, in the presence of nonlinearities and dissipation
- Turbulence is ubiquitous and acts over a variety of scales

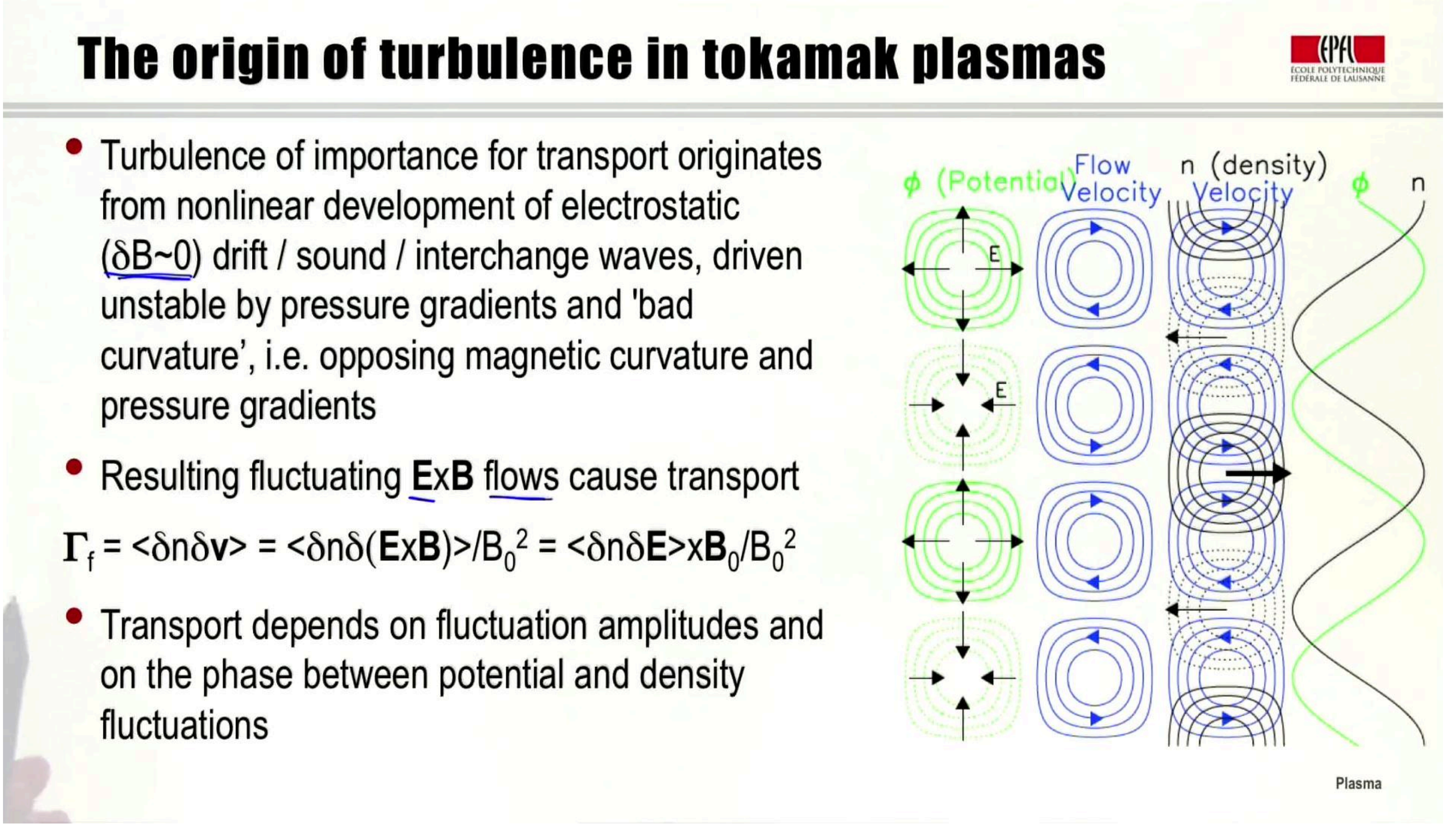
Plasma

In fact, turbulence in general is a fundamental science question that remains at least partly open. Again, turbulence is a spontaneous way of releasing free energy associated with flows or gradients in the presence of nonlinearities and of dissipation. Turbulence doesn't just happen in plasmas of course, it's present in many physical systems and it acts over a large variety of scales, both spatial and temporal. The pictures here illustrate such a variety. Here we see a picture of the turbulence present in the global atmosphere of our planet. Turbulence is present for example, in the flow of the wind, in this case behind wind turbines. Turbulence is present in the mixing of fluids, like water in this glass. And turbulence is even present in the systems that are man-made like the stock exchange.

Notes

Summary

20m 28s



Let's focus on the origins of turbulence in tokamak plasmas and on its consequence on transport. Turbulence that's important for transport in plasmas originates from the nonlinear development of electrostatic waves typically. Electrostatic waves mean that in the wave itself, there is practically no perturbation to the magnetic field. So we can neglect the magnetic part of the wave. There are several kinds of electrostatic waves of importance for turbulence. Typically they are relatively low frequency compared to the gyrofrequencies of both the electrons and the ions. These are waves that are referred to as drift waves or sound waves or interchange waves that are driven unstable by pressure gradients and what we call *bad curvature*, that is, opposing magnetic curvature and pressure gradients. What are the consequences of the turbulence on transport and what is the cause of transport? Well, the turbulence results in the fluctuation of electric fields primarily, as we said we mostly deal with electrostatic waves, and when we have a fluctuating electric field, we have a fluctuating flow that's associated with ExB, related to that field. This flow can cause transport.

Notes

Summary

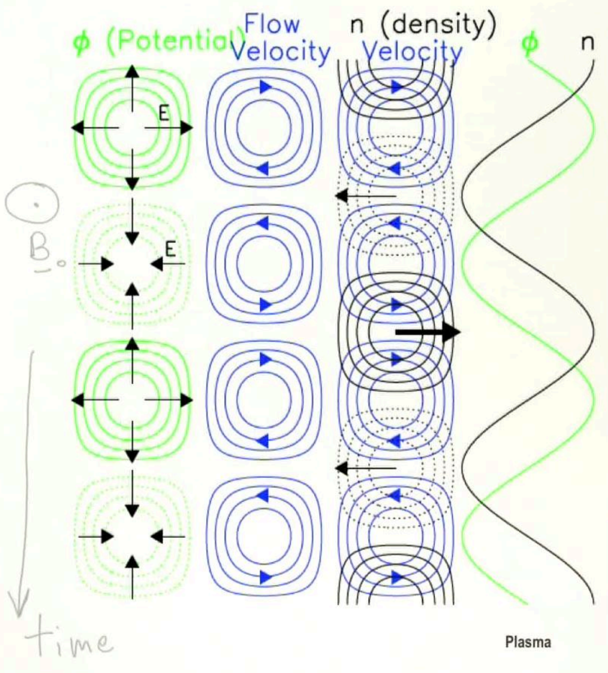
21m 37s

The origin of turbulence in tokamak plasmas

- Turbulence of importance for transport originates from nonlinear development of electrostatic ($\delta B \sim 0$) drift / sound / interchange waves, driven unstable by pressure gradients and 'bad curvature', i.e. opposing magnetic curvature and pressure gradients
- Resulting fluctuating **E**x**B** flows cause transport

$$\Gamma_f = \langle \delta n \delta \mathbf{v} \rangle = \langle \delta n \delta (\mathbf{E}\mathrm{x}\mathbf{B}) \rangle / B_0^2 = \langle \delta n \delta \mathbf{E} \rangle \mathrm{x} \mathbf{B}_0 / B_0^2$$

- Transport depends on fluctuation amplitudes and on the phase between potential and density fluctuations



So if we represent the flux here, Γf, that is associated with these perturbations. This is the time average of the product of the perturbation in the density and the perturbation in the velocity. The perturbation in the velocity comes from the ExB term in which B can be considered as the background magnetic field because as we said, the wave this primarily electrostatic while E of course is the perturbed field associated with the wave and needs nonlinear development. So at the end we have the product between density and field between density and potential, if you like. That has to be time averaged,...×B_0, where B_0 is the ambient magnetic field, and divided by B_0^2. $< \delta n\ \delta E > \times B_0 / B_0^2$ So of course, transport depends on the fluctuation amplitude that we have. But it also depends on the phase between the potential and the density fluctuation, and let's look at that in a slightly more in-depth way. To do that, we have a picture here that illustrates the case for a single mode in which we have the potential fluctuations or the potential oscillations if you like. Say it's a function of time going down. We assumed as a magnetic field, B_0 coming out from the board.

Notes

Summary

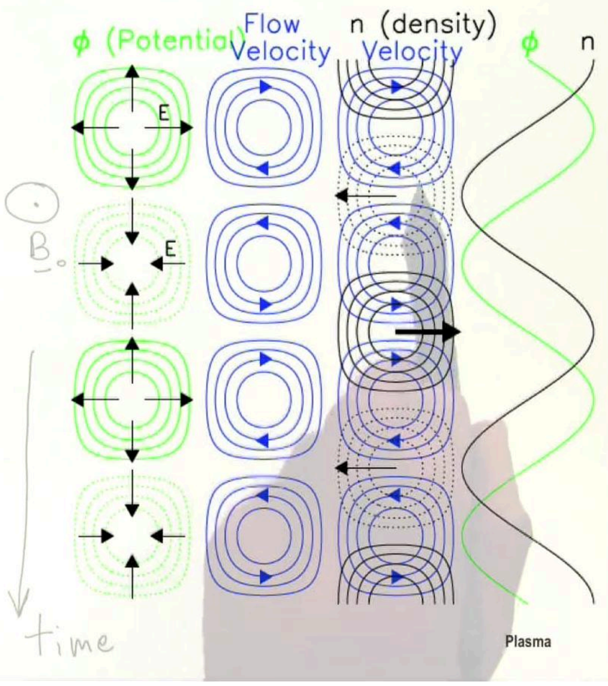
23m 12s

The origin of turbulence in tokamak plasmas

- Turbulence of importance for transport originates from nonlinear development of electrostatic ($\delta B \sim 0$) drift / sound / interchange waves, driven unstable by pressure gradients and 'bad curvature', i.e. opposing magnetic curvature and pressure gradients
- Resulting fluctuating **E**x**B** flows cause transport

$$\Gamma_f = \langle \delta n \delta \mathbf{v} \rangle = \langle \delta n \delta(\mathbf{E}\mathrm{x}\mathbf{B}) \rangle / B_0^2 = \langle \delta n \delta \mathbf{E} \rangle \mathrm{x} \mathbf{B}_0 / B_0^2$$

- Transport depends on fluctuation amplitudes and on the phase between potential and density fluctuations



We see that the potential or the electric field of course will cause a perturbation in the velocity which we call *flow velocity* here, which would be going around in eddies if you like, which are associated with these potential wave structures. Now the point is that you also have density fluctuations and these are represented by the black lines in this third column but a key point is where are these density fluctuations with respect to the flow velocity fluctuations and if they are perfectly aligned, so if they are in phase with each other which is not the case of the picture, of course there would be no transport, everything will oscillate up and down together, but there would be no net transport. When density and potential are in phase, we call the situation adiabatic situations, so this is a typical condition we have assumed in the first part of the course to make simple estimates like the evaluation of the screening of the charges and the Debye length. Now when adiabaticity is present, no transport is induced by the fluctuations. But when it is not present, in other words, when the density and the flow velocity issued by the potential fluctuation are not in phase, then you can have transport.

Notes

Summary

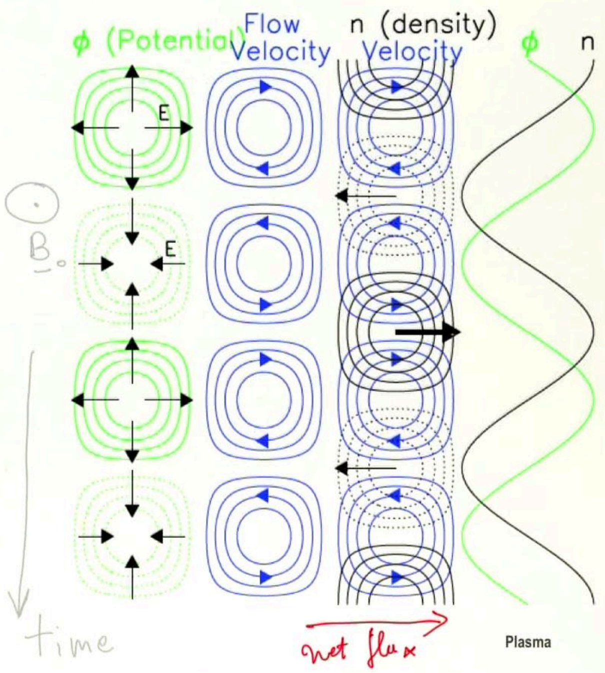
24m 54s

The origin of turbulence in tokamak plasmas

- Turbulence of importance for transport originates from nonlinear development of electrostatic ($\delta B \sim 0$) drift / sound / interchange waves, driven unstable by pressure gradients and 'bad curvature', i.e. opposing magnetic curvature and pressure gradients
- Resulting fluctuating **E**x**B** flows cause transport

$$\Gamma_f = \langle \delta n \delta \mathbf{v} \rangle = \langle \delta n \delta (\mathbf{E} \times \mathbf{B}) \rangle / B_0^2 = \langle \delta n \delta \mathbf{E} \rangle \times \mathbf{B}_0 / B_0^2$$

- Transport depends on fluctuation amplitudes and on the phase between potential and density fluctuations

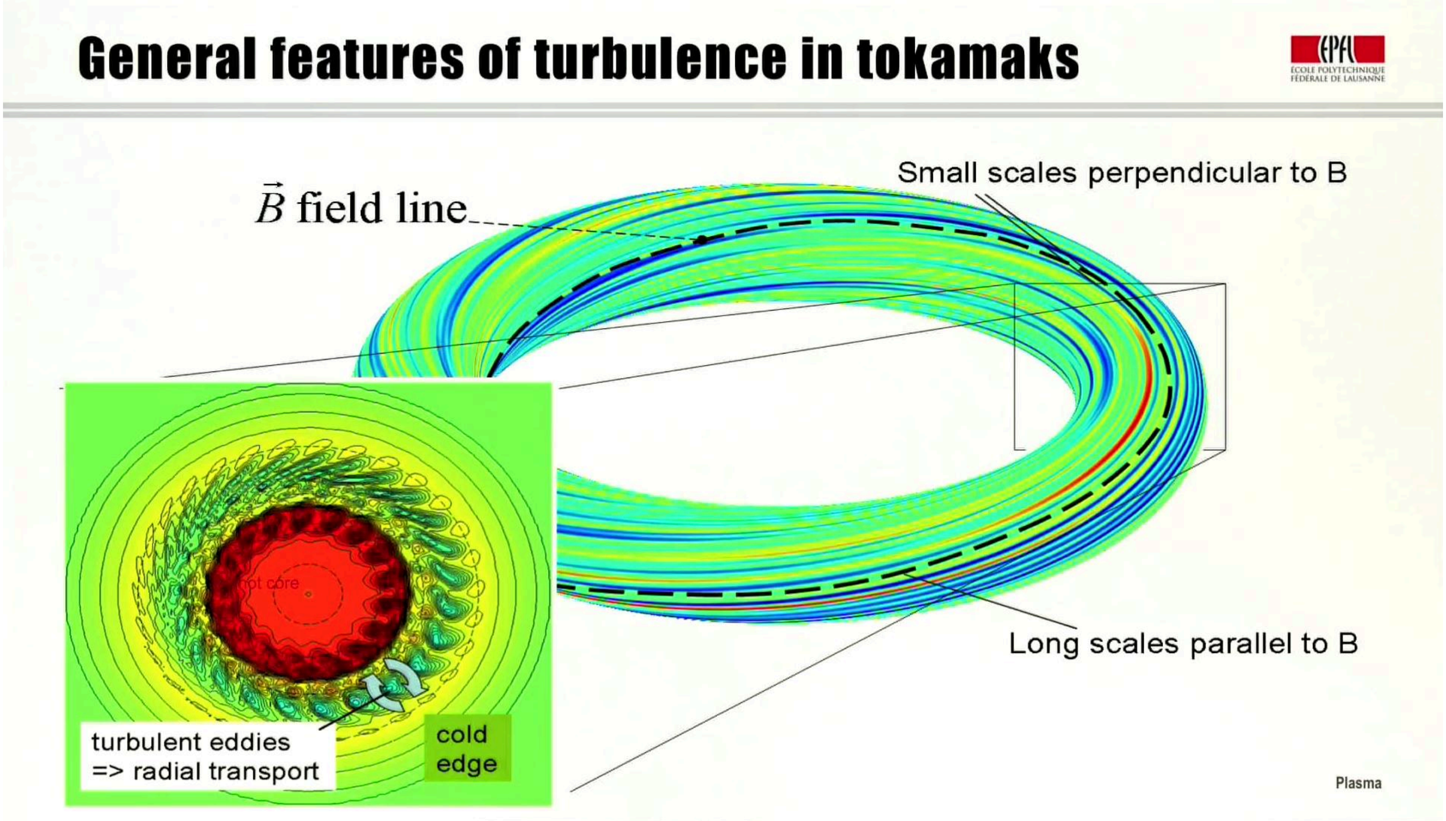


The reason for that is that you can have of course, parts of the oscillations that lead to a net flow in one direction, and parts of the oscillations that lead to a net flow in the opposite direction but if the flow in the opposite direction characterizes a large number of particles, then you have a bigger effect for the outflow than you have for the inflow, where you have a small number of particles. In other words, when you have a flow that goes one direction and the other, but associated with a different number of particles, you can have a net, overall transport of the plasma in one particular direction. In this case, to the right-hand side. So in this case, we would have a net flux to the outside, to the right-hand side of this board. So once again, the transport that is caused by the fluctuations depends on their amplitude, --which is very intuitive of course, but also on the phase between the potential and density fluctuations.

Notes

Summary

26m 26s

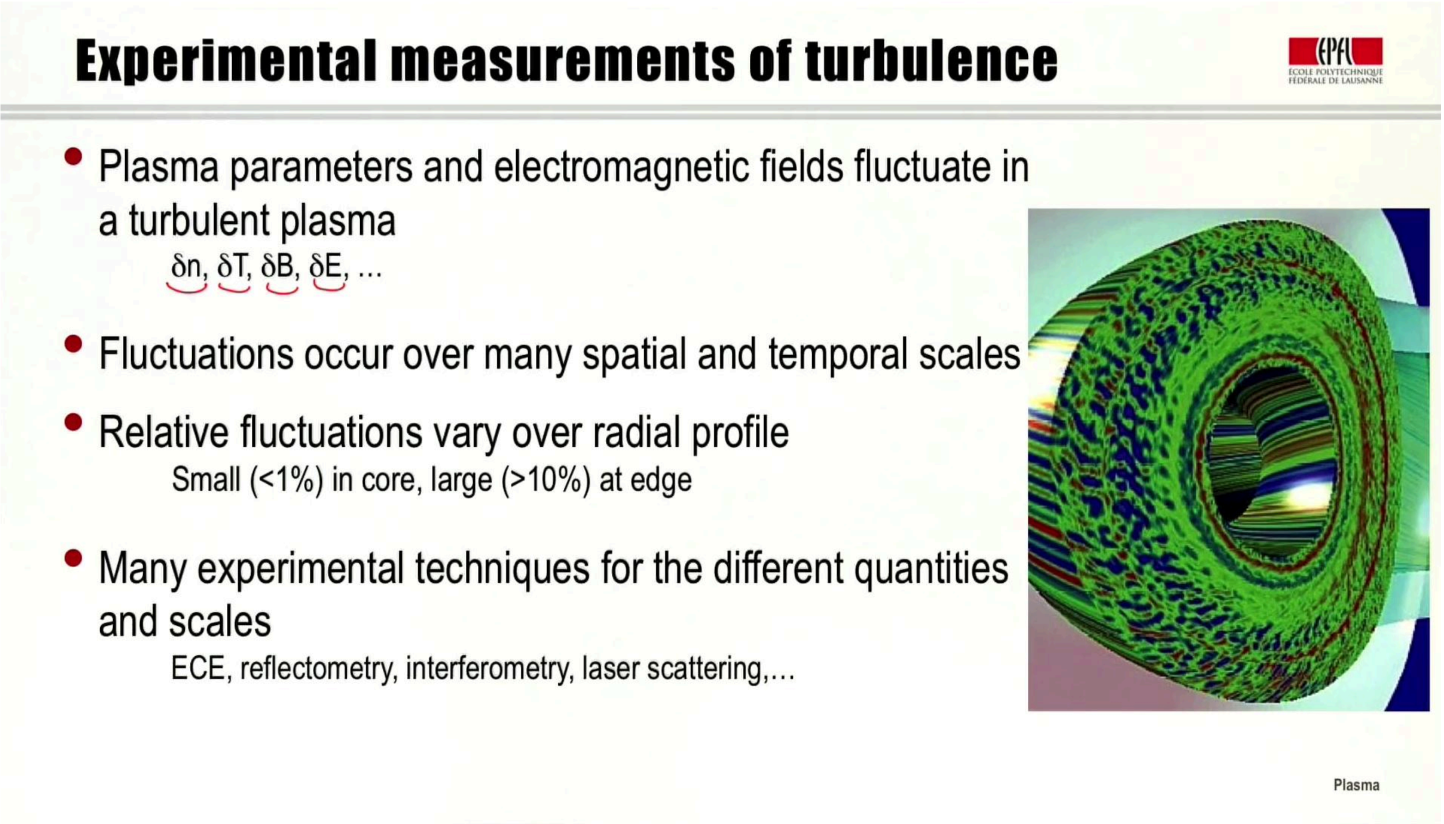


Let's just comment on a few general features of turbulence in tokamaks. Typically we have scales that are very long. Parallel to B, this is typically, mostly the toroidal direction of the tokamak, and scales that are small, perpendicular to B. So the eddies that cause transport are therefore illustrated here in the cross-section, and they mix if you like, the hot core with a cold edge and that's exactly what we do not want if you want to confine the plasma to make it fuse in the core.

Notes

Summary

27m 39s

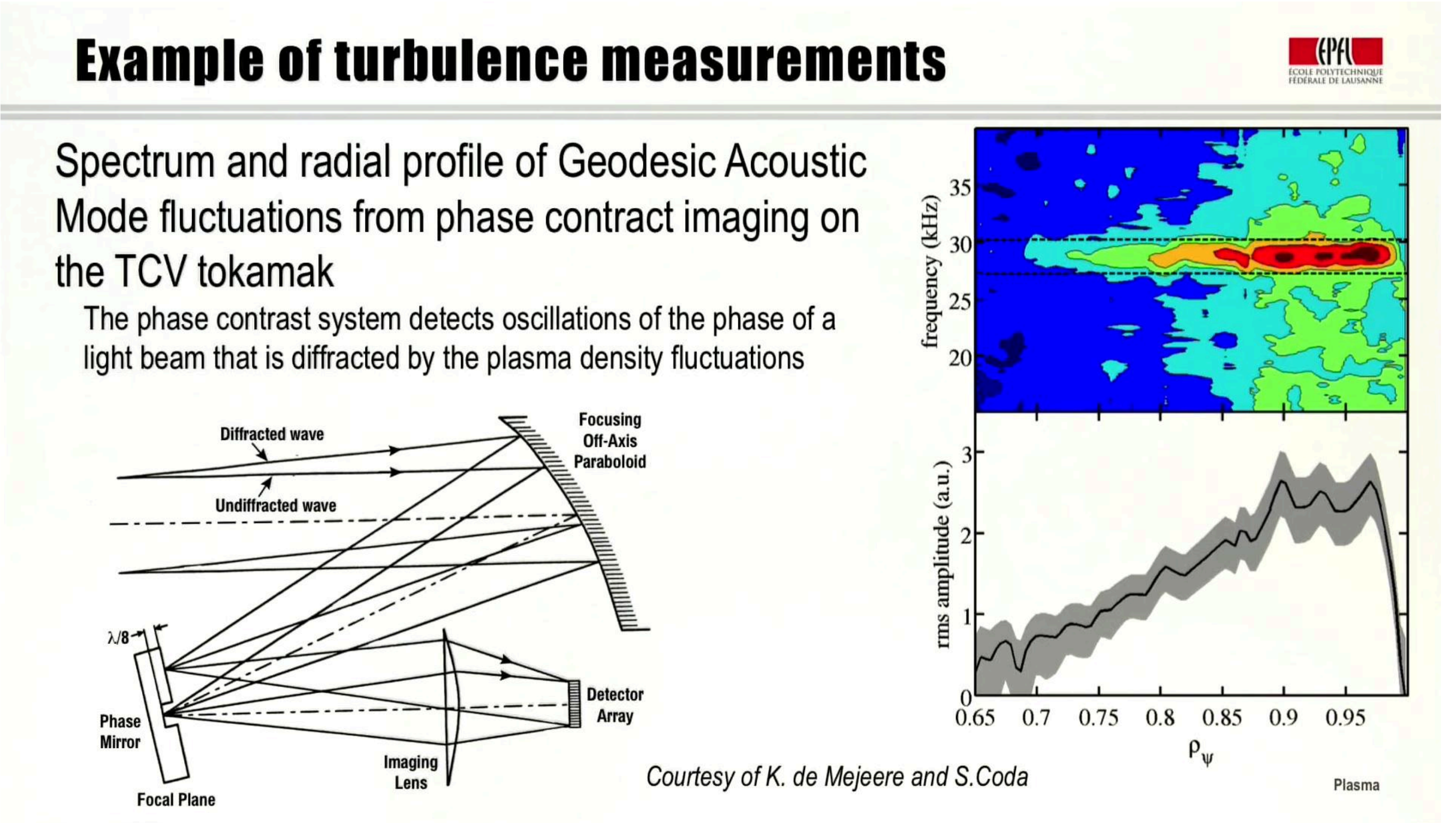


How do we characterize turbulence experimentally? In general, we have plasma waves and even if they develop nonlinearly into turbulence, you have several plasma parameters and electromagnetic fields that fluctuate together. For example, you have the density that fluctuates, the temperature that fluctuates, the magnetic field in case of electromagnetic perturbations (this can be neglected if we have electrostatic perturbations as we said) and the electric field and so on. So you have to measure in principle, several parameters. You also have to measure over many spatial and temporal scales because fluctuations cover several scales. Depending on where you are in the plasma profile, you also have a relative fluctuation amplitude that's very different. Typically, they are relatively small in the core say, less than 1%, and relatively large towards the edge and the very edge can reach much more than 10% typically. We do have a number of experimental techniques that are dedicated to measuring the different quantities and scales that characterize turbulence in fusion plasmas, particularly in tokamaks. For example, *ECE* that is, Electron Cyclotron Emission, reflectometry, interferometry, scattering of laser light and so on.

Notes

Summary

28m 16s



Just take one example to illustrate typical measurement of turbulence in a tokamak, and this is the measurement of the frequency spectrum and of the RMS amplitude [Root Mean Square amplitude], as a function of essentially, the radial position in the plasma of what we call a *Geodesic Acoustic Mode* [GAM] and the fluctuations that are associated with it. We don't need to go into details of the physics of this mode. This is done on the TCV tokamak plasma in Lausanne. This is just to illustrate that you have in this case, a mode that has a main frequency component going across the profile but an amplitude that does vary cross a profile. It also illustrates a particular technique. In this case, we use the so-called *Phase Contrast System* [PCS] which is built to detect oscillations of the phase of a beam of light that this injected into the plasma and is diffracted by the plasma density fluctuations. The fluctuations are then transformed to phase fluctuations and then detected over a range of frequencies that can go as high as hundreds of KHz.

Notes

Summary

29m 48s

Macroscopic turbulence structures and transport

- Effective $D_\perp \sim$ (size of wave structure)^2/(correlation time)
- Small radial wavelength modes would give very small transport, but turbulence can develop nonlinear macroscopic structures – many nonlinear systems create large-scale organized structures
- Radially elongated structures give large radial transport
- Coherent shear flows can break these structures, steal energy from turbulence and reduce radial correlations, restoring a small radial transport

Courtesy of NASA

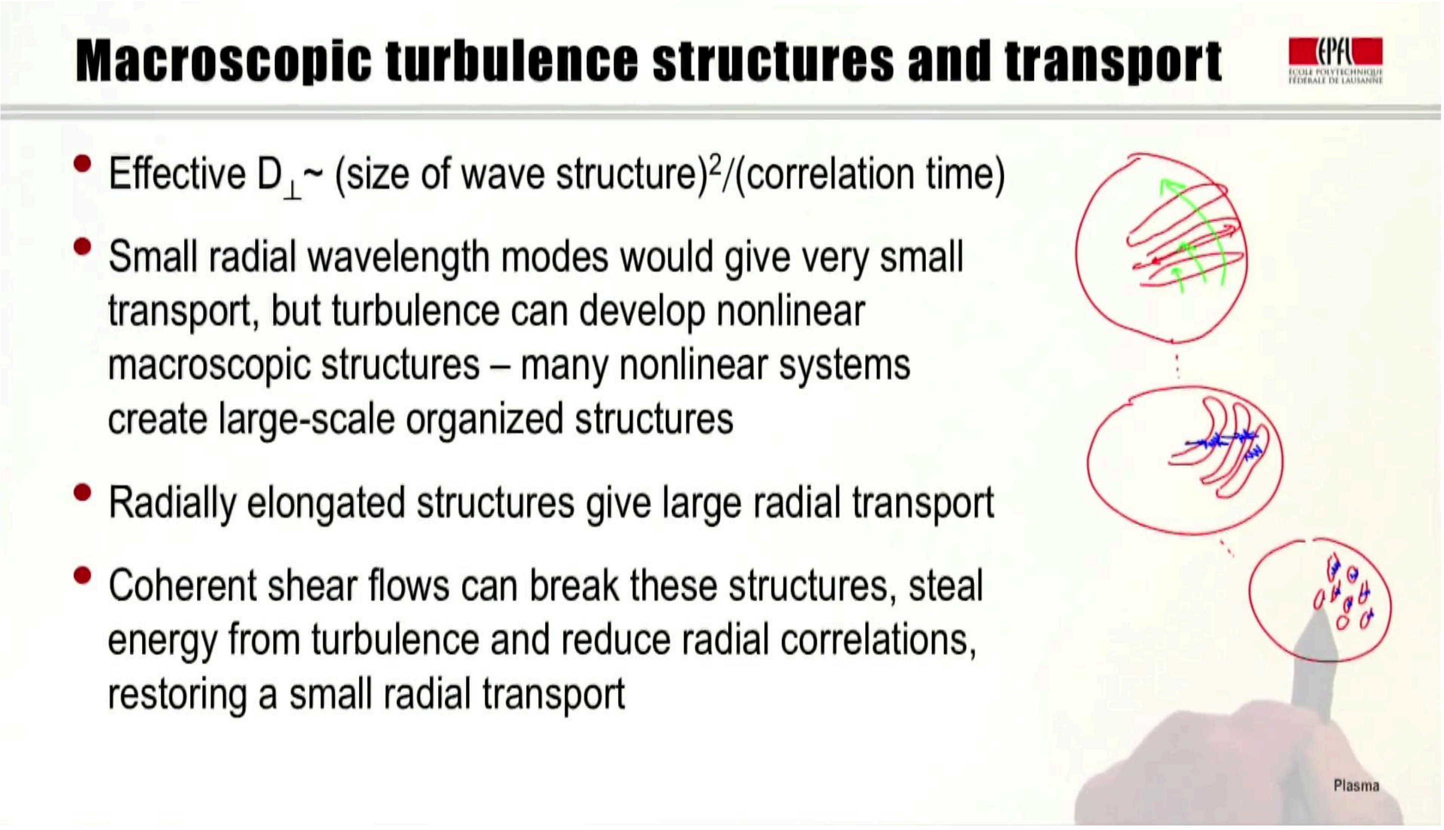
Plasma

Let us go back to a few general considerations on the effect of turbulence on transport, in particular via the development of macroscopic structures. What we can say in simple terms is that the effective diffusive coefficient in our case, perpendicular to the magnetic field, can be simply estimated by taking the size of the wave structure or the turbulence structure squared of course, as this would be the typical step-size divided by the correlation time. Now of course, small radial wavelength modes would give small steps that is, small transport. But turbulence can develop nonlinear macroscopic structures and in fact, it does in many, many, many systems in which large-scale organized structures are present. The example here is that of a hurricane in the southern United States.

Notes

Summary

31m 02s

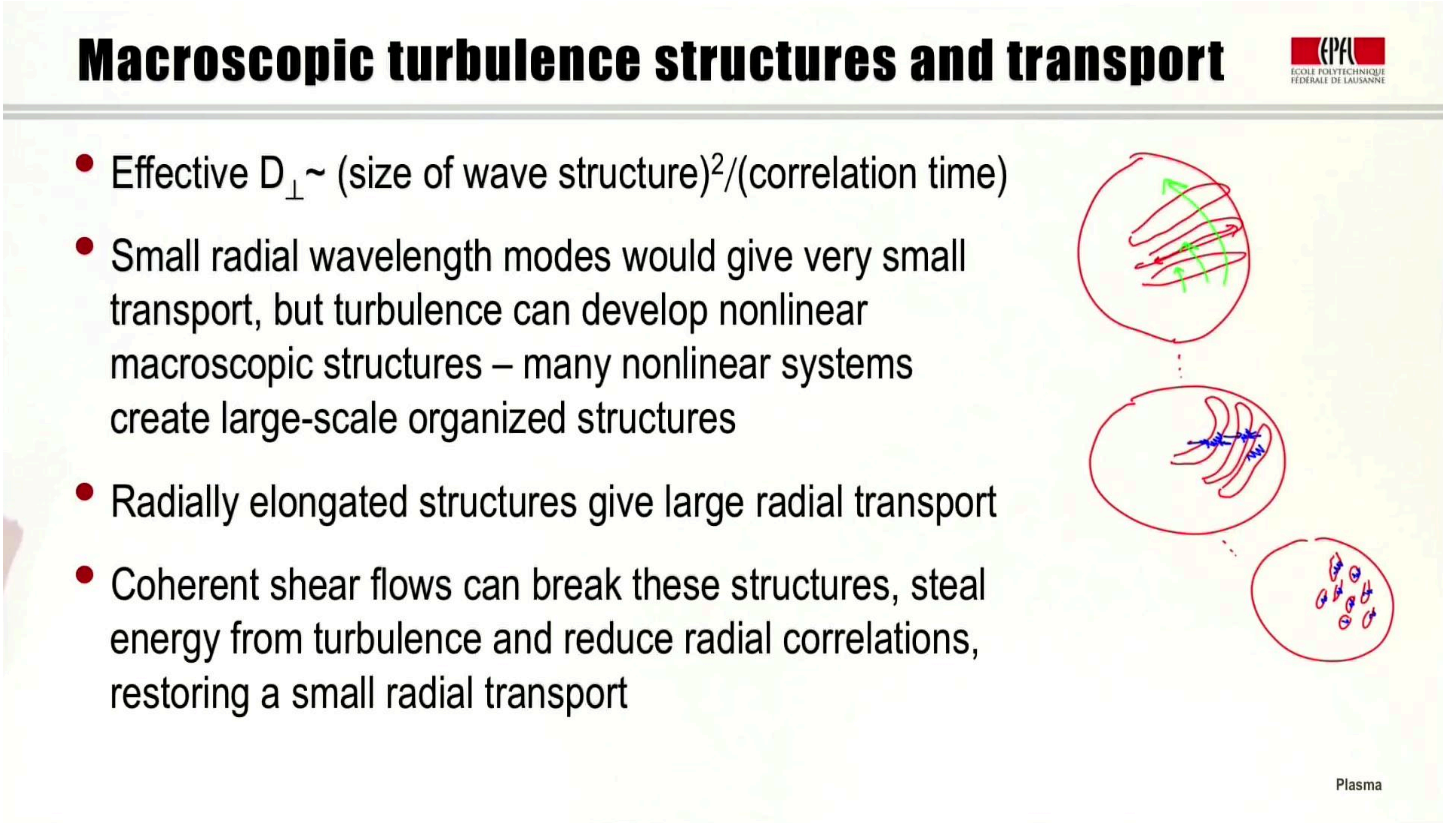


So, in plasmas you can have radially elongated structures and that would be bad. Let me just draw them, for example here. it would be bad-- this is a cross-section of our tokamak for example. It would be bad because the step-size would be large, say of the order of the size of the structure itself and therefore the effective diffusion would be fast. However, you could have flows that are also generated by the turbulence itself that could be sheared, that is non-uniform in the radial direction for example they could be larger on the outside than the inside. The result of these flows would be that the structures would be distorted or even broken. Let me just try to illustrate what would happen say, in the presence of these flows, the structures would be distorted or even broken apart. This would actually be very good for a transport because the radial size of the step would be significant and shortened, both when they are distorted and in fact, when they are completely broken apart.

Notes

Summary

32m 06s

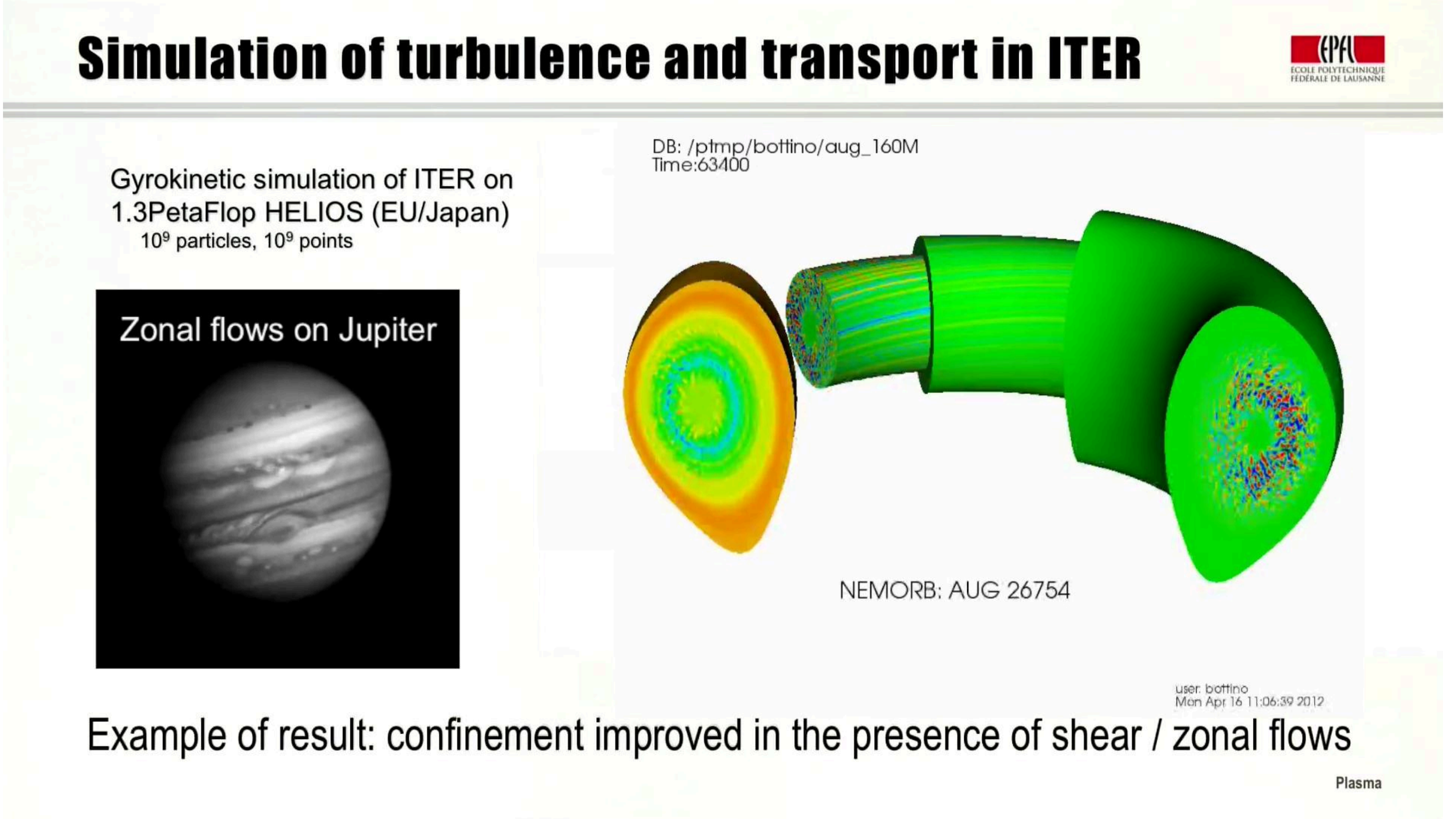


So, turbulence could do both things, it could generate large-scale structures in the radial direction, that is bad because it would facilitate radial transport, and at the same time it could also provide shear flows that would break or distort these structures and then restore something that would be relatively beneficial that is a level of transport that could be relatively small because again, the step-sizes corresponding to the sizes or the structures associated with the waves and the turbulence would be small again.

Notes

Summary

33m 33s



Let's just say a word about the possibility of simulating turbulence and transport in the tokamak plasma particularly, in this case, in ITER. As you will see, in the evolution of the movie that's being shown on the right, you see that the instabilities are being generated by the gradients in the tokamak, but are also is evolving nonlinearly into turbulence and then evolving into structures that first seem to be elongated radially and then seem to be, at least in some regions, sheared apart by flows that are non-uniform in the radial direction, these are the famous shear flows, or *zonal flows*. This is a simulation of the ITER plasma on one of the highest performance computers used for fusion, it's a 1.3 petaflop computer in this case, there were a billion particles and a billion points in the grid to simulate the ITER core plasma. On the left you also see an image of the zonal flows of Jupiter indicating that this question and this development of turbulence into regions of reduced transport because of the presence of macroscopic self-organized structures is not unique to tokamak plasmas.

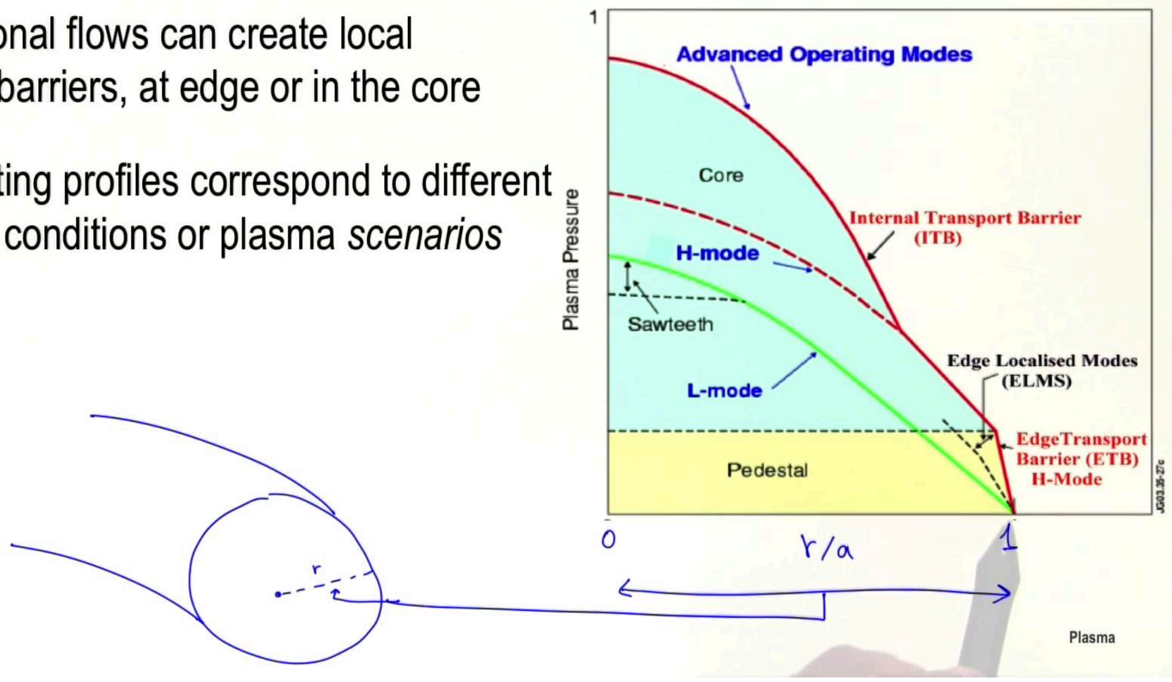
Notes

Summary

34m 10s

Transport barriers and plasma scenarios

- Shear / zonal flows can create local transport barriers, at edge or in the core
- The resulting profiles correspond to different operating conditions or plasma *scenarios*



These shear and zonal flows we have seen in tokamak plasmas but also in other situations can in fact, create *local transport barriers* that is, local regions where the transport is very, very small. This is very beneficial for fusion. These regions can be at the edge or in the core and they have been observed experimentally. So the profiles that result from the presence of these region in fact, correspond to different operating conditions of a tokamak plasma typically and to what we refer to as *plasma scenarios*. So let me just illustrate them. This is the radial profile say, the radial coordinate normalized to the minor radius of our tokamak, say between zero and one, so this would be a region corresponding to-- the section of our tokamak device and you can have transport barriers at the edge we said or in the core, or in some cases you don't have them at all of course. When you don't have them at all, we have a situation referred to as the *low confinement mode*, We're not helped, if you like, by the beneficial turbulent structures that set these transport barriers in this case.

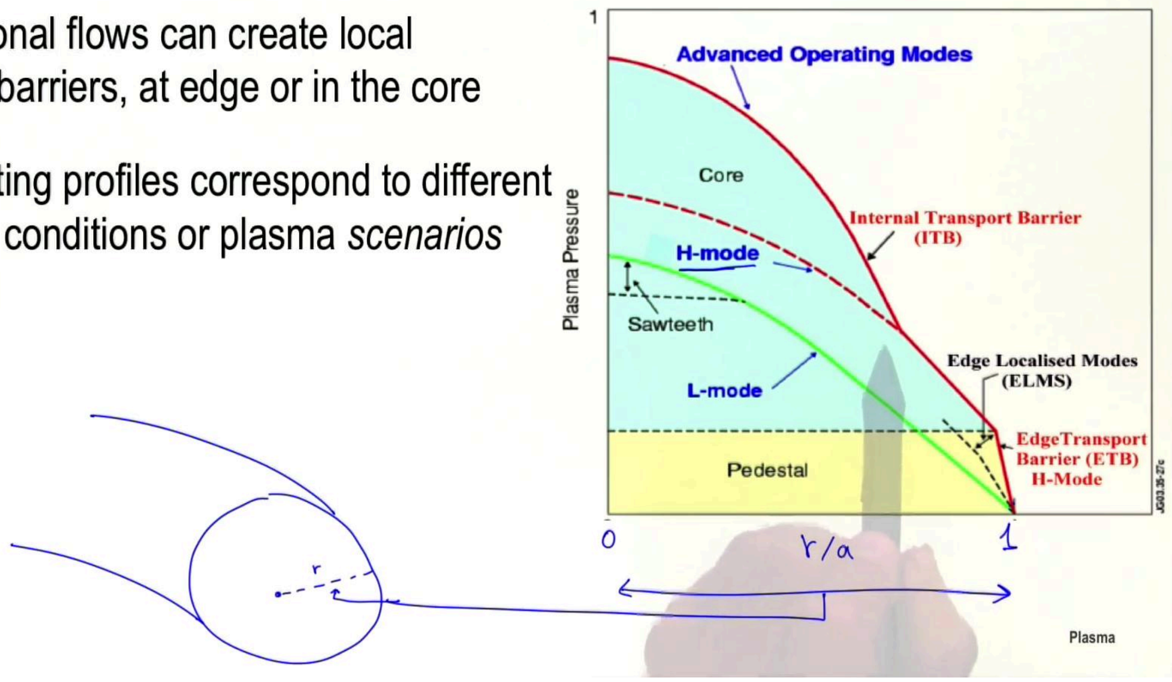
Notes

Summary

35m 45s

Transport barriers and plasma scenarios

- Shear / zonal flows can create local transport barriers, at edge or in the core
- The resulting profiles correspond to different operating conditions or plasma *scenarios*



The low confinement mode or *L-mode* has a profile that's relatively simple but also relatively low and the profile here is represented in terms of the plasma pressure, and the low plasma pressure of course implies a relatively low fusion performance. You can also have a situation in which you develop a transport barrier at the edge. So a very steep gradient in a relatively narrow region but even just the relatively narrow region will help a lot for the performance of the whole plasma, in particular of the plasma core, because it is as if we had the pedestal on which the whole profile was sitting and so the rest of the profile would be similar to what we have in L-mode but it would be sitting on a pedestal created by this transport barrier at the edge and so it would be much higher in terms of pressure and therefore much higher in terms of potential fusion performance, This is is what we would refer to as the *high confinement* or *H-mode*. It's one of the modes we actually foresee for the possible operation of a fusion reactor. You could also have a transport barrier more to the inside, what we call the *internal transport barrier*.

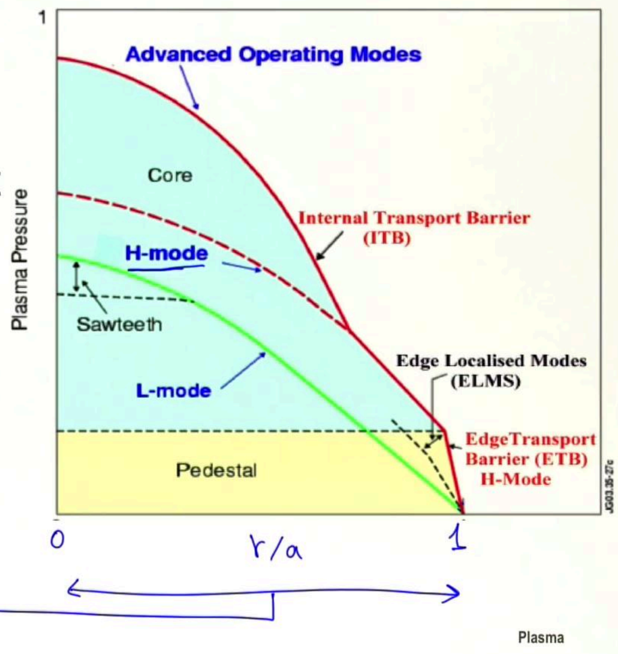
Notes

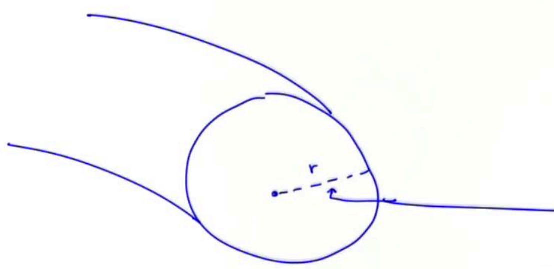
Summary

37m 14s

Transport barriers and plasma scenarios

- Shear / zonal flows can create local transport barriers, at edge or in the core
- The resulting profiles correspond to different operating conditions or plasma *scenarios*





This would be a shear flow generated transport barrier in some region not too close to the edge of the plasma. This would also generate a boost in a pressure again which will increase further the performance of the core in terms of fusion. This is what we refer to as *internal transport barrier scenario* or *advanced modes of operation of tokamaks*; they have been discovered relatively recently.

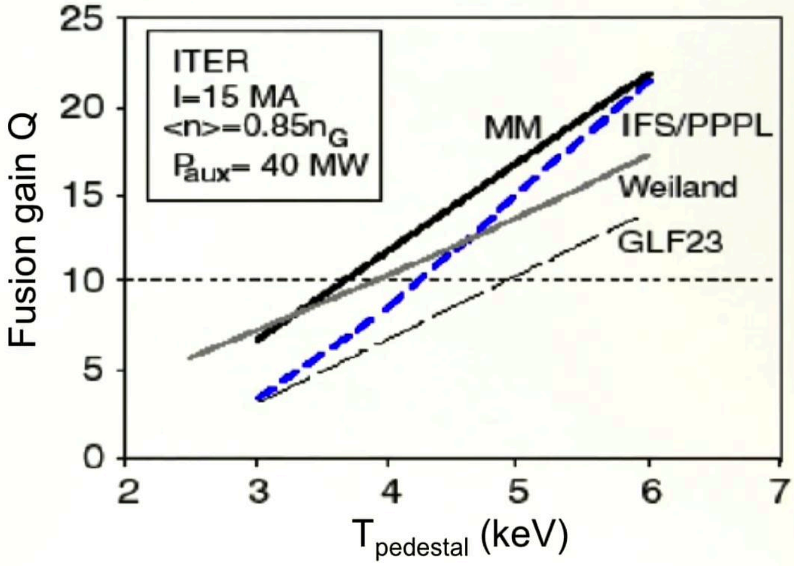
Notes

Summary

38m 33s

Turbulence couples edge and core performance

Different theoretical and numerical models predict influence of edge (pedestal) temperature on core temperature, hence fusion gain

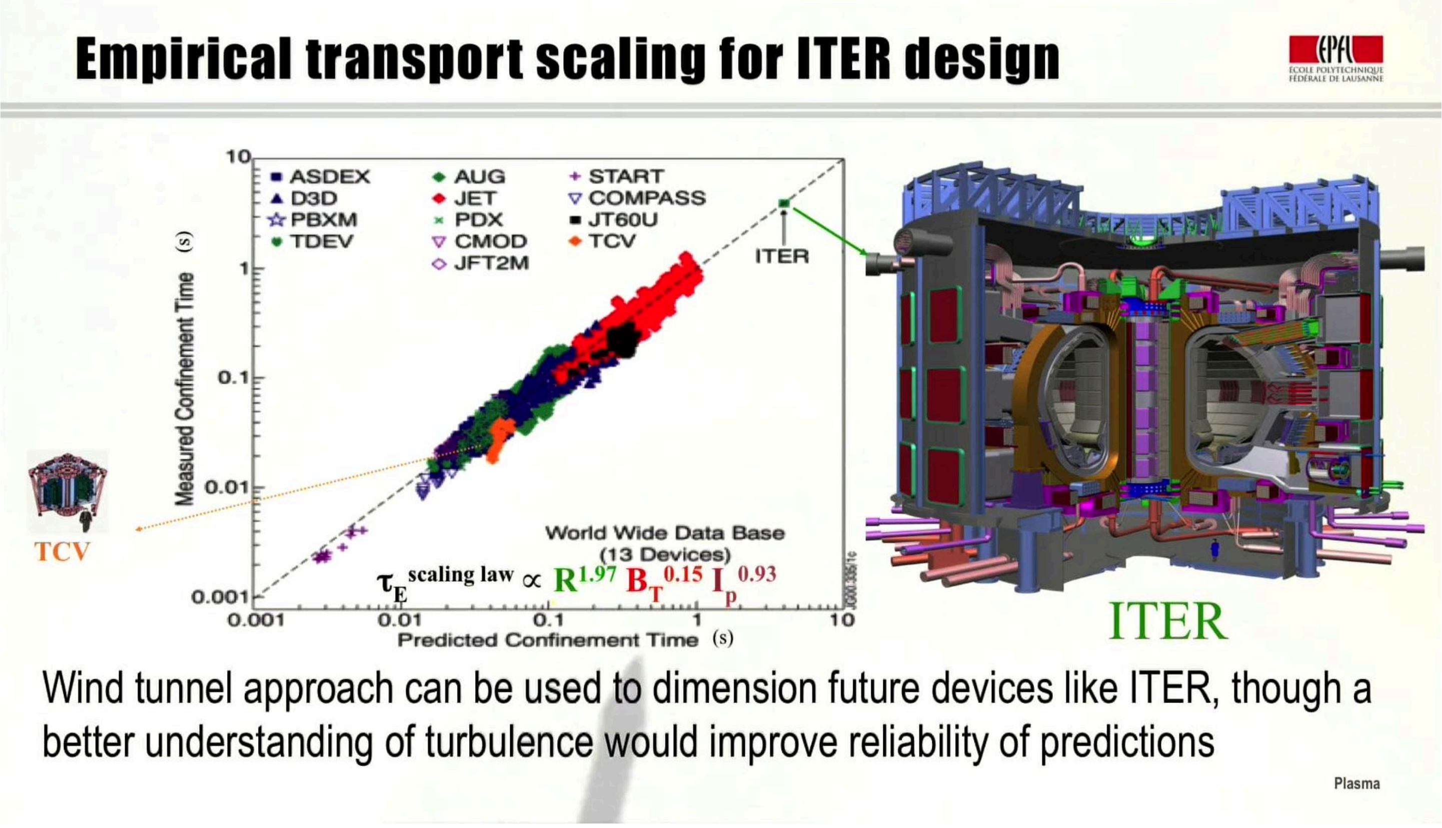


Now we have seen that in the sketches of the profiles we can gain a lot even having a transport barrier only at the very edge of the plasma because the turbulence actually couples the edge and the core so the profile of the core of the plasma is relatively similar to this situation in which you don't have a transport barrier. And In fact to-- highlight this coupling between the edge and the core performance, I illustrate here the findings of different turbulent models -- into which we'll not go, in terms of the fusion gain versus the temperature of the pedestal, that is the region that's made at higher pressure by the presence of the edge transport barrier. Although the details or the different models are different and even the details of the exact values are different, in all cases, we see that by increasing the pedestal temperature, the fusion gain, Q, which we can call a fusion performance actually goes up in all cases. So it is very important to have a pedestal good performance in order to have good fusion gain in the plasma core.

Notes

Summary

39m 03s

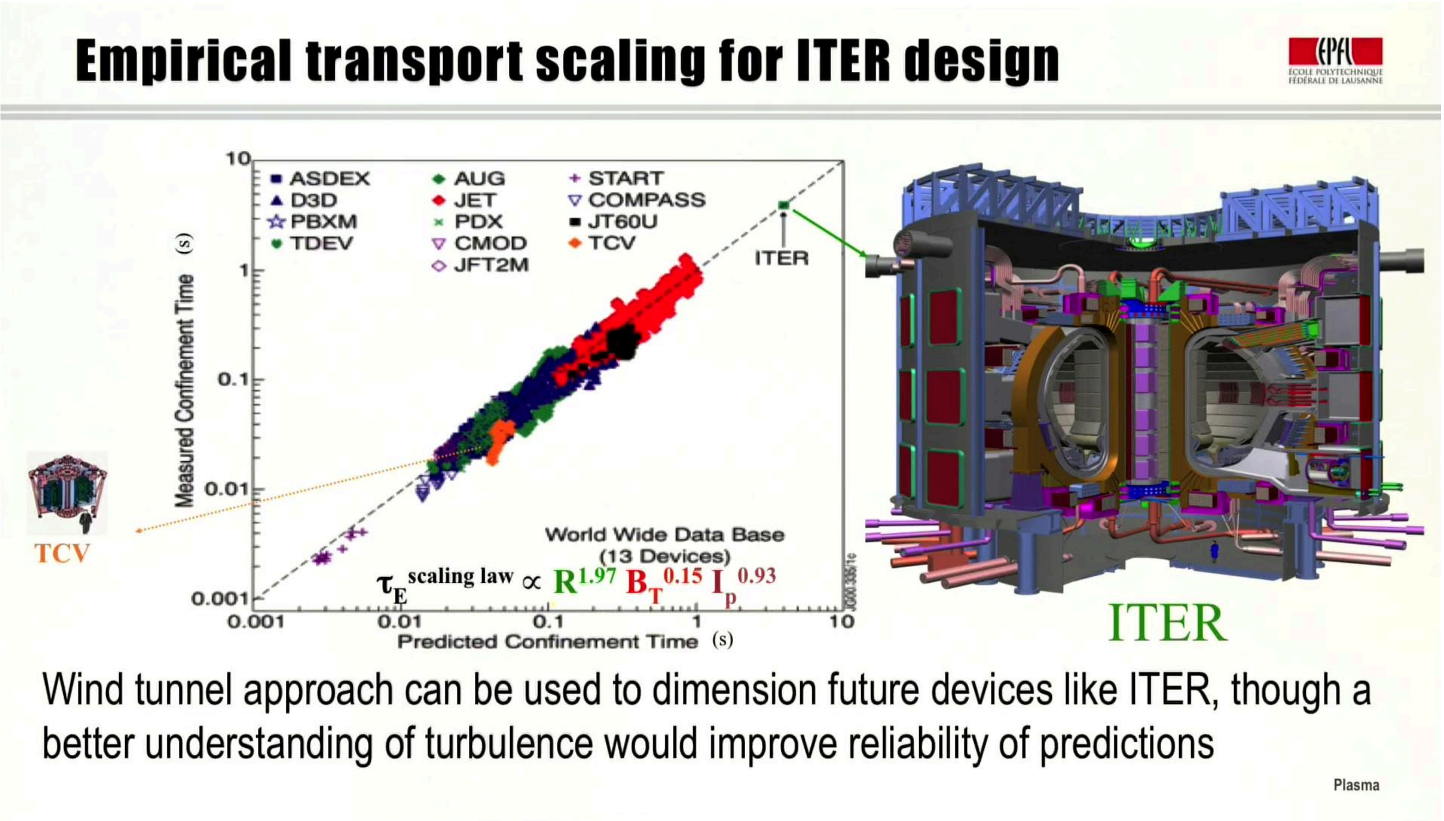


Now we have of course played experimentally with several devices, in particular several tokamaks, we have measured transport, we have measured confinement time and we have varied all the possible parameters to explore the dependance of the confinement time upon these parameters. In the absence of a complete ab initio theory, because of this complexity in the turbulence, what we can do is to plot the different results from the different experiments worldwide in an empirical transport scaling kind of plot. In particular this is something we can use to design future devices and this is something that has been used to design the ITER machine that's being built in a moment. This is the plot that summarizes these findings, representing the confinement time, measured experimentally in seconds as opposed to the predicted confinement time predicted here on a basis of a scaling law, which includes the main parameters of the machines and of the plasmas. Here I put the three main parameters that play a major role that is the size of the plasma, the major radius which appears as power 1.97, say about 2, so of course we gain in the confinement as we increase the size.

Notes

Summary

40m 32s

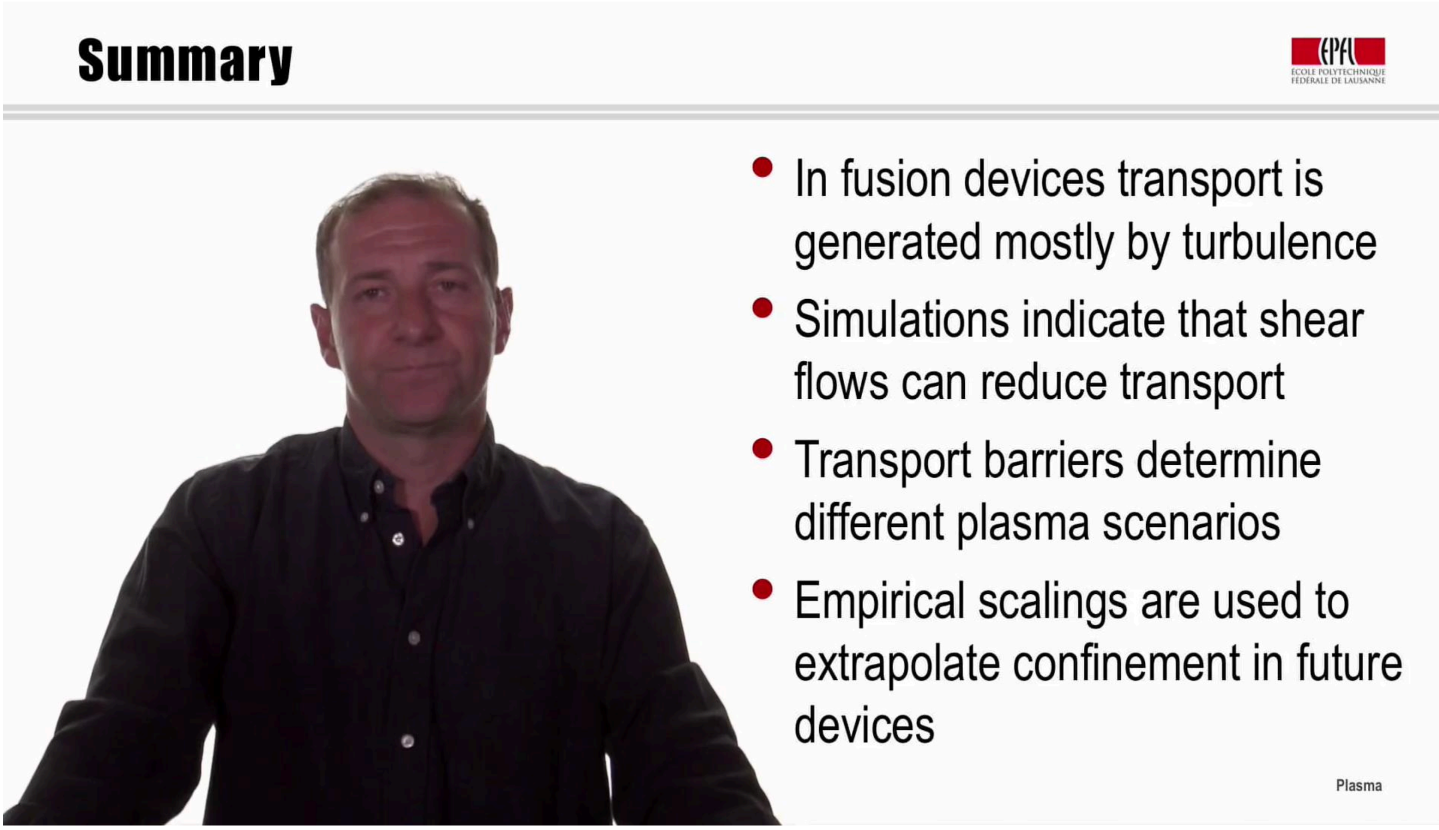


We gain also some if we increase the toroidal magnetic field, we don't gain much because the dependency is only to the power.15, and we gain by increasing the plasma current which of course reduces the size of the orbits of the particles inside the tokamak. The different machines are represented by different colors here, and you can see that we cover quite a range as the two axes are logarithmic. I highlight our own machine the TCV tokamak here but of course there are many machines and in particular as we go towards larger confinement times, that means we're also going towards larger and larger machines, the JET device here is the one providing all of the red points and therefore is the one that is closest to the extrapolation we need to make for ITER which needs a few seconds of confinement time. Therefore based on this scaling we can devise it's size. This is sort of a wind tunnel approach that we use to dimension the fusion devices like ITER, but of course we also like to further our understanding of turbulence because that would improve the reliability of the prediction and it would also make suggestions for the ways to go to optimize a tokamak concept in general.

Notes

Summary

42m 07s



So in summary we have seen that in fusion devices, transport is generated mostly by turbulence. Simulations and indeed experiments indicate that shear flows, that is, flows that are not uniform in the radial direction of the device can very significantly reduce transport. The transport barriers that are associated with these shear flows, in fact determine different plasma scenarios or different operating conditions for our future reactor. At the moment we don't have a complete understanding of turbulence and therefore we use empirical scalings to extrapolate confinement in fusion devices and to design the size in particular and the main parameters for the future experiments.

Notes

Summary

43m 33s