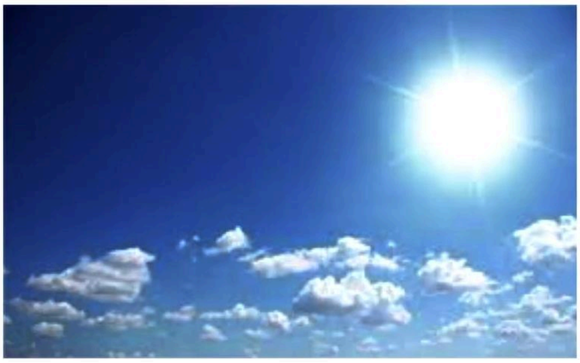

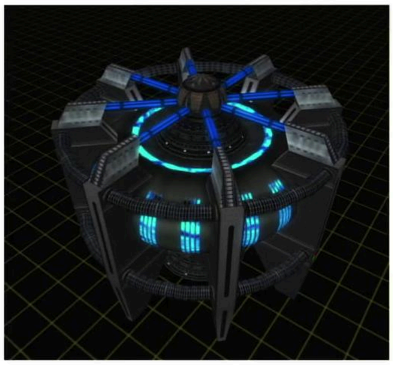

Thermonuclear fusion: power balance in reactors

Plasma Physics and Application to Fusion Energy, Astrophysics and Industry

Lecture 6b

Ambrogio Fasoli

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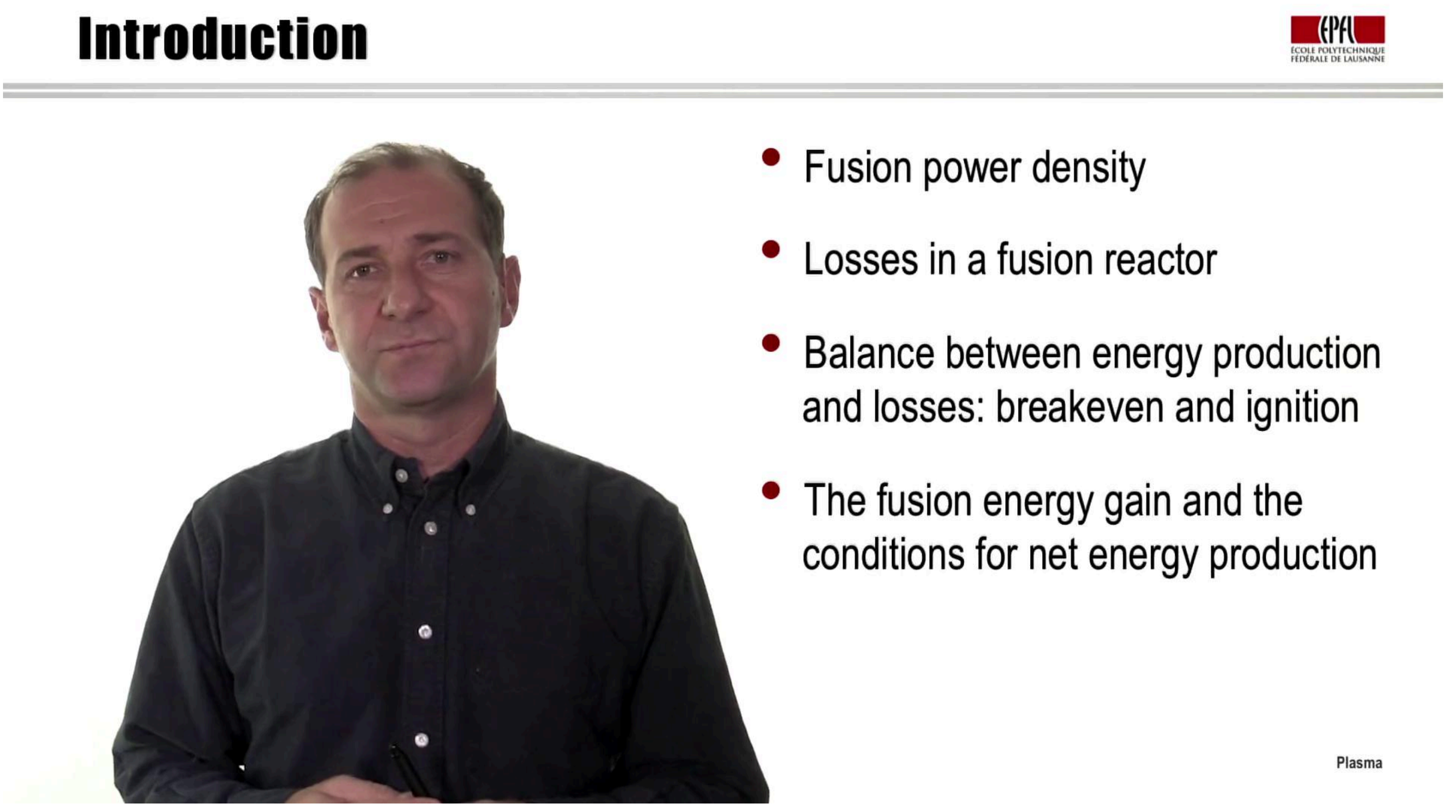


Welcome to the course on Plasma Physics and Applications. Today, we will explore thermonuclear fusion a little bit more by looking at the power balance in a reactor and the conditions for the reactor to operate. In particular, we will explore how to calculate the fusion power density, the losses in a fusion reactor, and the balance between energy production and losses. We'll derive the conditions from breakeven and ignition. And finally we will define the fusion energy gain and we'll really clarify the conditions under which the energy production can be obtained for a fusion reactor.

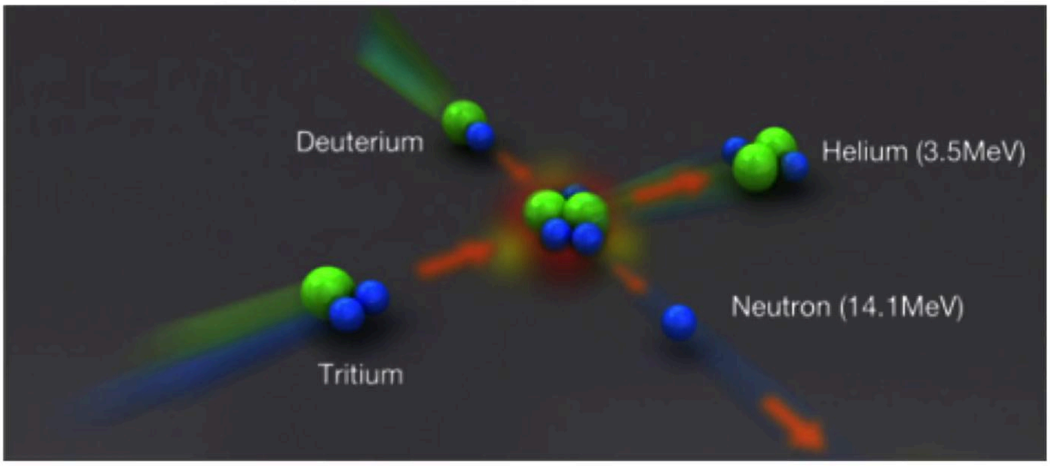
Notes

Summary

0m 07s

Reminder – the D-T reaction

The D-T reaction has the largest cross-section at not-too-large temperatures, hence is chosen for the first generation of reactors



Each reaction gives energy $\Delta E_f = \Delta E_\alpha + \Delta E_n = 3.5\text{MeV} + 14.1\text{MeV} = 17.6\text{MeV}$

Plasma

As a reminder of what we have discussed in a previous course, here I have reported the same picture we have shown with a D-T reaction. A D-T reaction has the largest cross section at not too large temperatures, which means that's the one we chose for operating the first generation of fusion reactor. Each reaction gives an energy that's the sum of the alpha particle energy of 3.5MeV and that of the neutron at 14MeV for a total of 17.6MeV.

Notes

Summary

0m 42s

Fusion power density

- Fusion power density for a particular relative velocity v (i.e. energy) of the D-T nuclei

$$R_{DT}(v)\Delta E_f = \overbrace{(n_D n_T \sigma_{DT}(v) v)}^{\#\text{ of reactions/s/volume}} \times \underbrace{(\Delta E_f)}_{\text{energy of one reaction}} \quad \left(\frac{\mathrm{W}}{\mathrm{m}^3}\right)$$

- To get the fusion power density in the whole plasma, we integrate over the distributions of velocities of D and T
  - We assume that the plasma is neutral: $n_D = n_T = n_e/2 = n/2$, and neglect impurities and n_α

$$\text{Fusion power density} = n_D n_T \langle \sigma v \rangle_{DT} \Delta E_f = \frac{1}{4} n^2 \langle \sigma v \rangle_{DT} \Delta E_f$$

Plasma

We can look at the fusion power density from such reaction. If we take a particular relative velocity, v, that is a particular energy in the collision between the deuterium and tritium nuclei, we can evaluate the number of reactions per second per volume and multiply that times the energy for one reaction to get the power density that comes from the D-T reactions. This is the expression in here where we underline the fact that we have a dependence upon the velocity in the different terms and therefore the overall result is still a function of velocity or energy. To get the fusion power density in the whole plasma we need to integrate over the distribution of velocities of Deuterium and Tritium. We do that by assuming that the plasma is neutral, that is, the density of the Deuterium and Tritium nuclei correspond each to half of the electron density, which we will refer to as just *n*. We also neglect impurities and we neglect the effect of the alpha particle density. The density that is of the alpha particles that are produced by the fusion reactions themselves. We neglect that effect on the overall charge balance in the plasma.

Notes

Summary

1m 13s

Fusion power density

- Fusion power density for a particular relative velocity v (i.e. energy) of the D-T nuclei

$$R_{DT}(v)\Delta E_f = \overbrace{(n_D n_T \sigma_{DT}(v) v)}^{\#\text{ of reactions/s/volume}} \times \underbrace{(\Delta E_f)}_{\text{energy of one reaction}} \quad \left(\frac{\mathrm{W}}{\mathrm{m}^3}\right)$$

- To get the fusion power density in the whole plasma, we integrate over the distributions of velocities of D and T
  - We assume that the plasma is neutral: $n_D = n_T = n_e/2 = n/2$, and neglect impurities and n_α

$$\text{Fusion power density} = n_D n_T \langle \sigma v \rangle_{DT} \Delta E_f = \frac{1}{4} n^2 \langle \sigma v \rangle_{DT} \Delta E_f$$

Plasma

We therefore come up with an expression which gives us the fusion power density, now not a function of velocity or energy anymore but it's an overall property of the plasma, which is then given by the reactivity integrated over velocity. The integration, again, is given by this symbol that we see here and we replace the electron density we come up with a general expression that contains just the electron density *n* squared, the fusion reactivity for of course the D-T fusion reaction that we consider throughout the course and the energy provided by a single reaction, which is ΔEf.

Notes

Summary

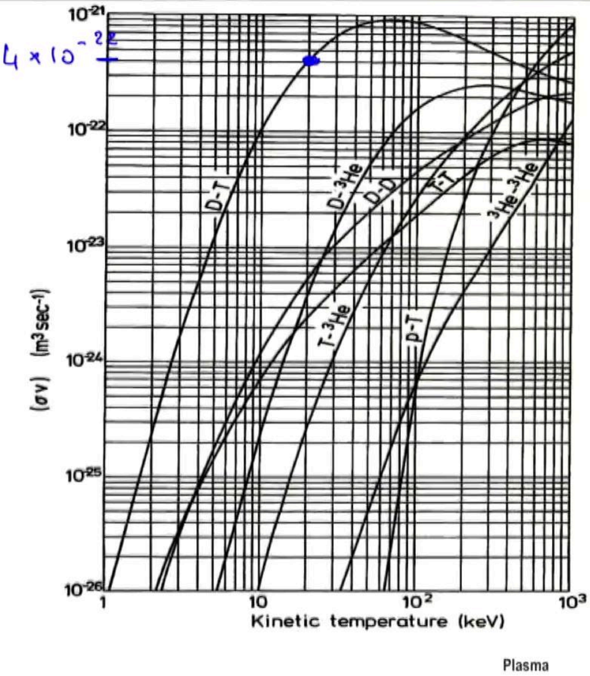
2m 32s

Fusion power density – a numerical exercise

- Consider the curve for $<\sigma v>_{DT}$, calculated for Maxwellian distributions
- Take T ~ 20keV, n ~ $5{\times}10^{20}$m^{-3}
- Volume to produce 1GW of fusion power?

$<\sigma v>_{DT} \, (T = 20 \, \mathrm{keV}) \simeq 4 \times 10^{-22} \, m^3/s$

$$\text{Volume} = \frac{\text{Fusion power}}{\text{Fusion power density}} \simeq$$



Before proceeding to more complicated power balance exercises, I'd like to just do a brief numerical exercise. Here we consider the curve for the reaction rate calculated for a maxwellian distribution, in fact for two maxwellian distributions for both Deuterium and Tritium. This curve is given here and it's expressed as a function of temperature of the plasma. We suppose to have plasma at 20keV and the density of 5 times 10 ^{20} per cubic meter. So we look up the curve that's plotted here for 20keV. It's this line, and we consider the value that corresponds to that temperature for <σv>. That value is about 4 times 10^{-22} in terms of meters to the third power per second. So the question we want to address in this simple numerical exercise is how much of a plasma or in other words, how big a volume do we need to produce 1GW of fusion power? To calculate that we take this value that we have just identified graphically, for the <σv> for D-T at 20keV of temperature. We have said that is about 4 times 10^{-22} meter to the third per second and we can then evaluate the volume, which is the fusion power divided by the fusion power density. We have chosen a reactor that produces 1GW of fusion power.

Notes

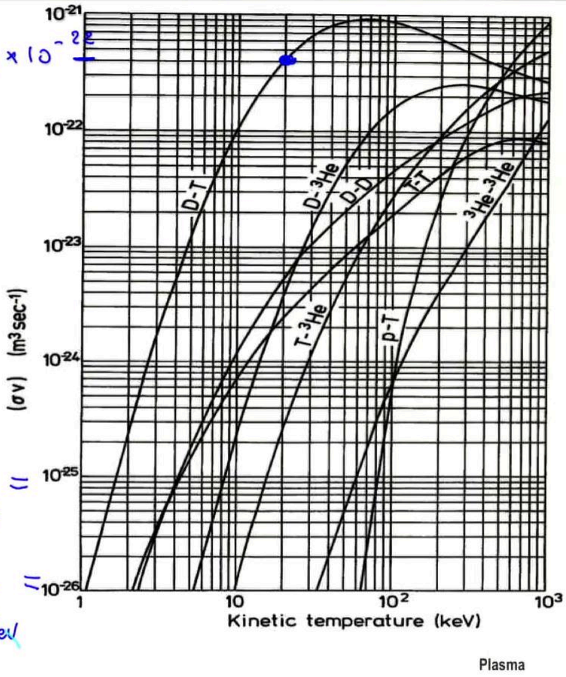
Summary

3m 19s

Fusion power density – a numerical exercise

- Consider the curve for $<\sigma v>_{DT}$, calculated for Maxwellian distributions
- Take T ~ 20keV, n ~ 5×10^{20}m^{-3}
- Volume to produce 1GW of fusion power?

4×10^{-22}



$$\langle\sigma v\rangle_{DT}(T=20\,\mathrm{keV}) \simeq 4\times10^{-22}\,\mathrm{m}^3/\mathrm{s}$$

$$\text{Volume} = \frac{\text{Fusion power}}{\text{Fusion power density}} \simeq \frac{10^9\,\mathrm{J/s}}{\frac{1}{4}n^2\langle\sigma v\rangle_{DT}\Delta E_F} =$$

$$= \frac{10^9\,\cancel{\mathrm{J}}/\cancel{\mathrm{s}}}{\frac{1}{4}(5\times10^{20})^2\,\mathrm{m}^{-\cancel{6}\,3}\times4\times10^{-22}\,\frac{\cancel{\mathrm{m}^3}}{\cancel{\mathrm{s}}}\times17.6\times10^6\,\cancel{\mathrm{eV}}\times1.6\times10^{-19}\,\cancel{\mathrm{J}}/\cancel{\mathrm{eV}}} \simeq 14\,\mathrm{m}^3$$

So that's 10⁹ joules per second. And of course we have to divide that by the fusion power density that's given by the expression we have considered before. We can proceed in this numerical evaluation and put the numbers for our example. So I have replaced all the values for the expression for the fusion power density. We can now simplify the expression at least in terms of the measurement units. And we find our final result which is about 14 cubic meters. So to produce 1GW of fusion power in a plasma of about 20keV with 5 times 10^{20} per cubic meter of density we need about 14 cubic meters of plasma. That's an absolute reasonable volume. It's not gigantic, nor is it microscopic. So this is giving us confidence that we can proceed in our balance between the power production by fusion and the losses can come up with a condition for a fusion reactor to operate.

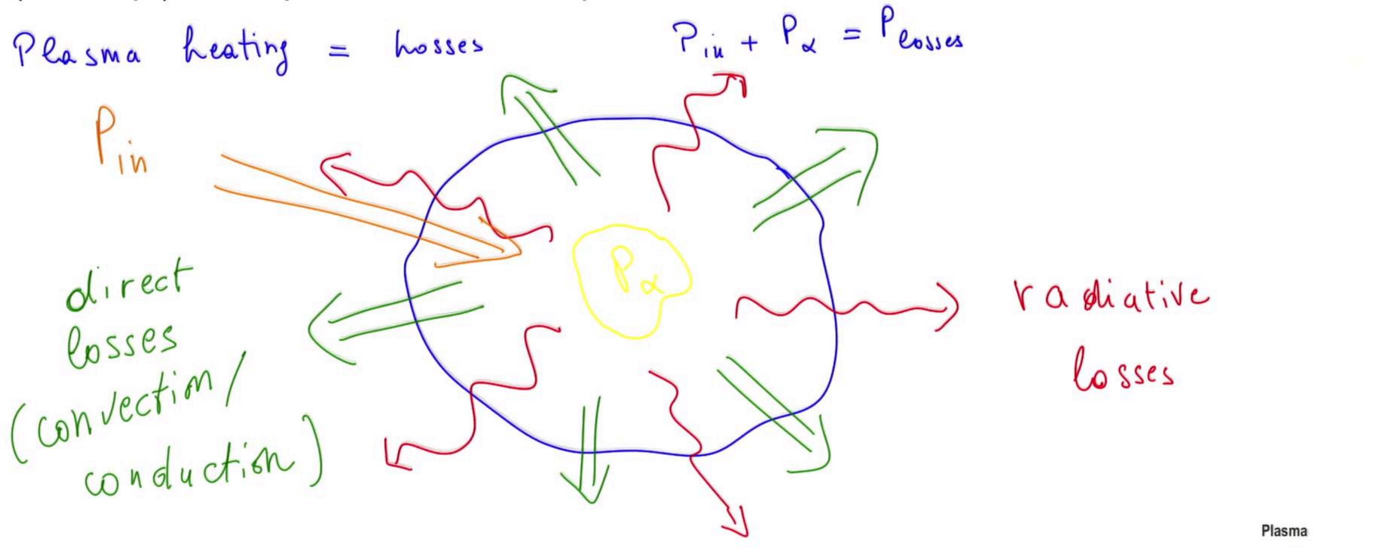
Notes

Summary

5m 02s

Power balance in a fusion reactor - generalities

- In steady-state, the sum of the power injected into the plasma and that produced (and kept) in the plasma must be equal to the losses



Let's start with some general considerations. In steady state, the sum of the power that we inject into the plasma from outside and that is produced and kept in the plasma must be equal to the losses. So that means that the heating of the plasma is equal to the losses from the plasma. The heating from the plasma comes from what we inject from outside and what the fusion reactions give in terms of by-products that are kept inside the plasma and that is the alpha particles. What kind of losses do we have? We have two kinds of losses. We can consider that the plasma is made of charged particles that are subject to acceleration. So there are radiative losses. But the plasma is also a fluid that's subject to direct losses, like convection and conduction. So if I want to complete my little picture here with the overall balance, I need to consider that in the core of the plasma we have the alpha heating, Pα, and that, coming from outside, we also have the input power heating that we produce from outside and inject into the plasma. So this is now the power balance with two kinds of losses, radiative and direct and the two sources of heating for the plasma. Again, in power from outside and the alpha particle power from the fusion reaction themselves.

Notes

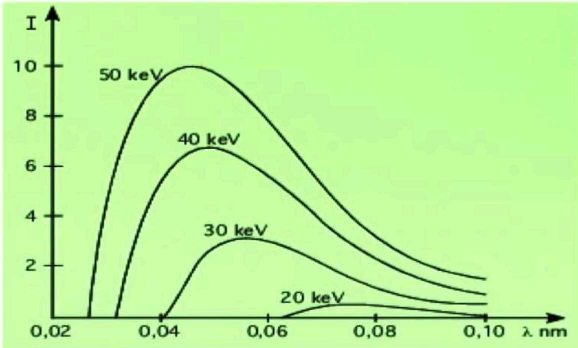
Summary

6m 19s

Radiative losses in a fusion reactor

- Radiative losses
  - Bremsstrahlung (acceleration of electrons in electric field created by ions) $\frac{P_b}{\text{volume}} \simeq A n^2 Z_{\text{eff}} T_e^{1/2}$

    where A = $5\times10^{-37}\,\text{Wm}^{-3}$ (T_e is in keV) and we define $Z_{\text{eff}} = \frac{\sum_j n_j Z_j^2}{n}$
  - For thermonuclear temperatures, bremsstrahlung is in X-ray range, to which the plasma and the containment vessel are mostly transparent



Plasma

Let's look a little bit more in detail at the radiative losses. Radiative losses are in the form of bremsstrahlung, this is the radiation that is produced by the acceleration of electrons in the field created by ions or by other electrons. The radiative power by bremsstrahlung can be expressed or at least it's density, that is the power by the volume, can be expressed in terms of a simple expression proportional to the square of the density to the square root of the temperature and to a parameter called *Zeff* which is defined here, which basically describes the average charge state of the ions in the plasma. For thermonuclear temperatures, the bremsstrahlung radiation is in a range of X-rays to which the plasma and the vessel that contains the plasma are mostly transparent and that's why we consider this as a net loss. The spectrum of the radiation by bremsstrahlung is indicated here and we see that for example for 30keV, it is in the range of X-rays.

Notes

Summary

8m 02s

Direct losses in a fusion reactor

- Direct (conductive and convective) losses
  - Described by a single parameter, the *energy confinement time* τ_E, i.e. the characteristic time over which energy is transported outside the plasma
  - We assume equipartition of energy between ion and electron species, which have an energy of *3/2T* each

$$\underbrace{\frac{P_{dl}}{\text{volume}}} = \underbrace{\frac{\text{energy/volume}}{\tau_E}} = \frac{3n\ T}{\tau_E}$$

Plasma

Having seen what the radiative losses are, we can look now at the direct losses in the fusion reactor. These are the conductive and convective losses. In fact, we can describe them in a very simple way using a single parameter called "energy confinement time", τE, which is the characteristic time over which the energy is transported outside the plasma. If we assume equipartition of energy between the ion and electron species, meaning that each species has an average energy of 3/2T the volume is at the denominator in order to calculate the power density for the losses and the expression is therefore simply given by the energy content of the plasma [divided] by the volume, divided by this confinement time, τE, which is actually defined through this equality. The energy density of the plasma is simply the product of density and temperature times 3 and so it is 3n T / τE as an overall estimate for the direct losses from the plasma.

Notes

Summary

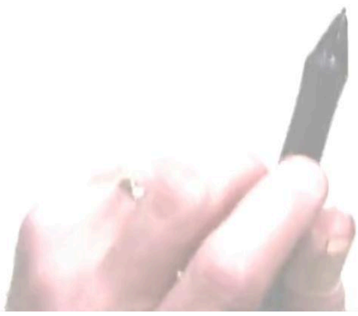
9m 17s

Power balance in a fusion reactor - calculation

Define physics fusion gain $Q = \dfrac{\text{Fusion power}}{\text{Input power}} = \dfrac{P_f}{P_{in}}$ Reactor: $Q > 1$

$Q = 1$ breakeven: $P_f = P_{in}$

$$Q = \frac{P_f}{P_{in}} = \left(\text{as } P_{in} + P_\alpha = P_{losses}\right) = \frac{P_f}{P_{de} + P_b - P_\alpha} = \frac{\frac{1}{4} n^2 \langle \sigma v \rangle_{DT} \Delta E_f}{\frac{3nT}{\tau_E} + A n^2 Z_{eff} T^{1/2} - \frac{1}{4} n^2 \langle \sigma v \rangle_{DT} \Delta E_\alpha} \gtrsim 1$$



Plasma

We are now ready to calculate the power balance in a fusion reactor. Let's do that by defining first a physics fusion gain. We refer to that as capital Q. That's the ratio between the fusion power and the input power. Naturally a reactor can only work if Q is larger than one. That is if we gain power from the system. The frontier that is the value of Q equal to one is called the *breakeven*. So that's the situation in which fusion power and input power are identical. Let's evaluate this condition for the value of Q to be larger or equal to one. As the sum of the input power from outside the reactor and the alpha particle power has to be equal to the losses. I can replace *Pin* by the difference between the losses and the alpha particle power. Here I have a specifically indicated the two kinds of losses. The direct losses: convection and conduction. And the bremsstrahlung losses. Now we can replace the expressions that we have derived before in this ratio. Notice that in the expression for total fusion power, the energy gained per reaction is the total ΔEF while in the expression for the alpha particle power all the other terms are the same but the energy gain per reaction is of course only the power carried by the α, ΔEα.

Notes

Summary

10m 33s

Power balance in a fusion reactor - calculation

Define physics fusion gain $Q = \frac{\text{Fusion power}}{\text{Input power}} = \frac{P_f}{P_{in}}$ Reactor : $Q > 1$

$Q = 1$ break even : $P_f = P_{in}$

$$Q = \frac{P_f}{P_{in}} = \left(\text{as } P_{in} + P_\alpha = P_{losses}\right) = \frac{P_f}{P_{de} + P_b - P_\alpha} = \frac{\frac{1}{4} n^{\cancel{2}} \langle \sigma v \rangle_{DT} \Delta E_f}{\frac{3\cancel{n}T}{\tau_E} + A n^{\cancel{2}} Z_{eff} T^{1/2} - \frac{1}{4} n^{\cancel{2}} \langle \sigma v \rangle_{DT} \Delta E_\alpha} \geq 1$$

$$n \tau_E \left\{ \langle \sigma v \rangle_{DT} \left(\underbrace{\Delta E_f + \Delta E_\alpha}_{\Delta E_f \left(1 + \frac{1}{5}\right) = \frac{6}{5} \Delta E_f} \right) - 4 A Z_{eff} T^{1/2} \right\} \geq 12 T$$

$$\Rightarrow \boxed{n \tau_E \geq \frac{12 T}{\frac{6}{5} \langle \sigma v \rangle_{DT} \Delta E_f - 4 A Z_{eff} T^{1/2}}}$$

Plasma

Let's simplify this expression a little bit. And write n τE in front of all the other terms. I notice that the sum of the total energy output of a single reaction and the alpha particle output of a single reaction appears here but we know that the total energy output of a single reaction is about five times the energy carried by the alpha. So I can write this as ΔEF times 1 + ⅕ which of course is 6/5 ΔEF. I can therefore write n τE in a more compact way and impose that it be equal or bigger than 12 times the temperature divided by 6/5 times the reaction rate times the energy produced in a single reaction minus the bremsstrahlung term. This is the first expression that tells us how good the quality of the confinement needs to be at least in a situation in which we start gaining energy from a fusion reactor.

Notes

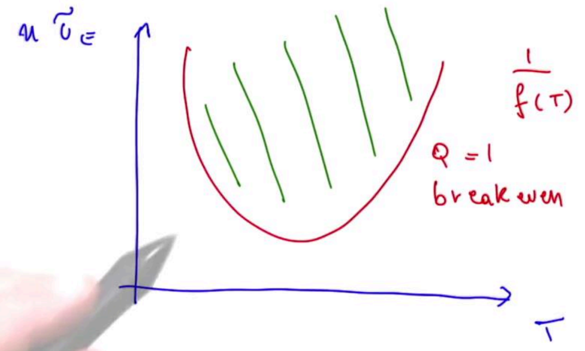
Summary

12m 23s

Power balance – breakeven

For $T >> 1\,\mathrm{keV}$ $\quad 4 A Z_{eff} T^{1/2} << \frac{6}{5}\langle\sigma v\rangle_{DT}\,\Delta E_F$

$$n\tau_E \ge \frac{12\,T}{\frac{6}{5}\langle\sigma v\rangle_{DT}\,\Delta E_F} = \frac{10\,T}{\langle\sigma v\rangle_{DT}\,\Delta E_F} = \frac{1}{f(T)}\ ; \quad f(T) = \frac{\langle\sigma v\rangle_{DT}\,\Delta E_F}{10\,T}$$



Plasma

That expression is a little bit complicated still, so let's simplify it by observing the following. At temperatures that are significantly larger than 1keV, that is temperatures that are of interest for our thermonuclear burn, the bremsstrahlung term becomes very small compared to the other term. So that we can neglect it all together and write n τE equal or larger than 12T divided by the usual fusion power production term. We can simplify this expression and come up with a very simple expression that is 10 times the temperature, divided by <σv> times the energy of a single reaction. We can call this 1/f(T). Having defined the function of temperature, and I'd like to underline the fact that it is depending on temperature, which is <σv>, which itself is a function of temperature, times the energy of a reaction, divided by 10 T. We can represent this condition graphically. Plotting n τE on the vertical axis and the temperature on the horizontal axis. The function 1/ f(T) is represented by this red curve. That corresponds to the Q = 1 situation or breakeven situation. So reactors can have a hope to work in a region in green here at both that line.

Notes

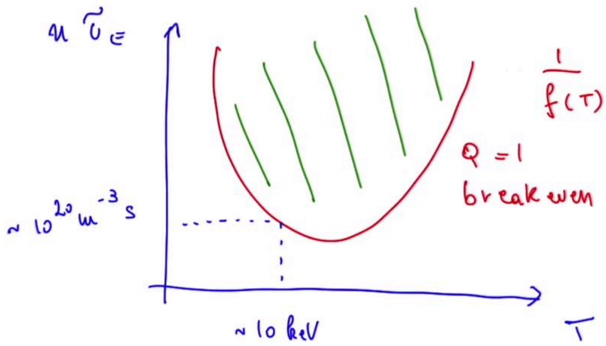
Summary

13m 54s

Power balance – breakeven

For $T \gg 1\,\text{keV}$ $\qquad 4 A Z_{eff} T^{1/2} \ll \frac{6}{5} \langle \sigma v \rangle_{DT} \Delta E_F$

$$n\tau_E \geq \frac{2\,\cancel{12}\,T}{\frac{\cancel{6}}{5}\langle \sigma v \rangle_{DT} \Delta E_F} = \frac{10\,T}{\langle \sigma v \rangle_{DT} \Delta E_F} = \frac{1}{f(T)} \quad ; \quad f(T) = \frac{\langle \sigma v \rangle_{DT} \Delta E_F}{10\,T}$$



Plasma

If we take a typical value on this curve, we have about 10^{20} per cubic meter times second in terms of n τE and about 10keV of temperature. So we have to do better than the combination of these two values in order to be in a region where the reactor can work.

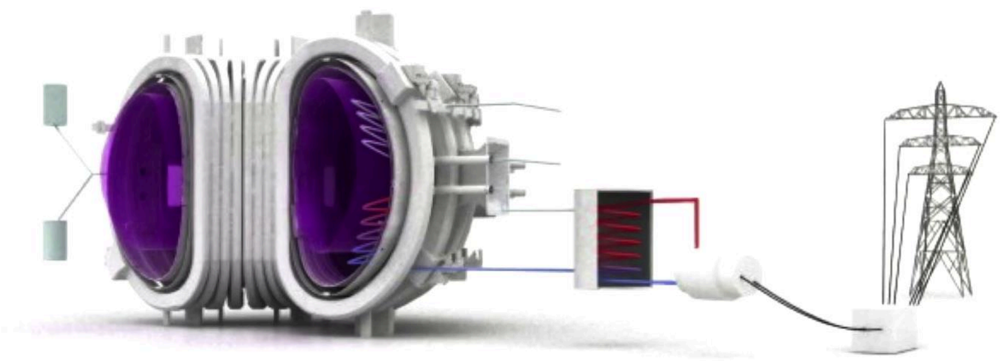
Notes

Summary

15m 28s

Power balance – beyond breakeven

- In actual reactors breakeven must be exceeded, as the efficiency of conversion of fusion power to electricity and of electricity to plasma heating is less than 100%



Plasma

In actual reactors, of course breakeven must be exceeded because the efficiency conversions of fusion power into electricity and the efficiency of conversion of electricity into plasma heating they're both less than 100 percent.

Notes

Summary

15m 53s

Power balance – ignition

The limit at which all the plasma heating is provided by the fusion α's and no external power is needed to sustain fusion reactions is referred to as *ignition*

$$Q = P_f / P_{in} \rightarrow \infty \text{ as } P_{in} \rightarrow 0$$

$P_{in} = 0 \qquad P_\alpha \geq P_{losses} \simeq P_{dl}$

$$\frac{1}{4} n^2 \langle \sigma v \rangle_{DT} \Delta E_\alpha \geq \frac{3nT}{\tau_E}$$

$$n\tau_E \Big|_{ignition} \geq \frac{12\,T}{\langle \sigma v \rangle_{DT} \Delta E_\alpha} = \frac{6}{f(T)} = 6 \times n\tau_E \Big|_{breakeven}$$

Plasma

Let's look at the ultimate limit, which we refer to as *ignition*. That's the limit at which all the plasma heating is provided by the fusion alphas and no external power is needed to sustain the reactions. In a quantitative manner we can define that as Q which is the ratio of fusion power to input power as going to infinity or as the input power goes to zero. Let's translate this into an expression for n τE. So we have Pin equals zero, that means that Pα must be larger than the losses which we have said can be represented only by the direct loss term as we can neglect bremsstrahlung. So we can write the expression for Pα and impose that it be larger than the losses by direct losses, which are given by 3nT divided by the confinement time. So that means I can write n τE at ignition and impose that it be larger than 12 times the temperature divided by <σv> times the energy that the alpha particles carry after a fusion reaction. We notice that that is 6/f(T) where f(T) was the function that described breakeven introduced before, which we can write six times the condition from breakeven in terms of n τE.

Notes

Summary

16m 09s

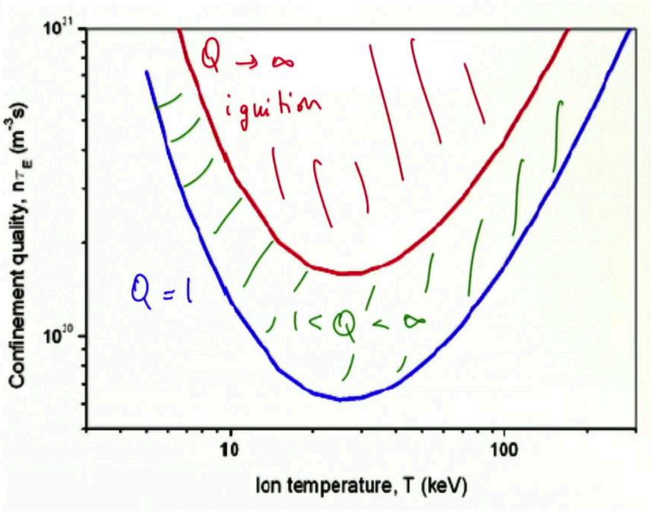
Power balance - between breakeven and ignition

- A reactor can work between break-even and ignition: 1 < Q < ∞
- Fraction of α-particle heating

$$f_\alpha = \frac{P_\alpha}{P_{\text{heating}}} = \frac{P_\alpha}{P_\alpha + P_{\text{in}}} \approx \frac{Q}{Q+5}$$

- Burning plasma regime is achieved for

$f_\alpha > 50\%$ ⟷ $Q \geq 5$



Plasma

In practice a reactor can and will work between breakeven and ignition. That is between one and infinity for the value of the fusion gain Q. So if we look at the graph here, we have two curves. The red curve corresponds to ignition. The blue curve corresponds to breakeven. And the reactor will operate in between, in this green region. If we define the fraction of alpha particle heating, that is the fraction between the heating from the alphas to the total heating of the plasma that corresponds to about Q over Q + 5, this expression. So if you want the alpha particle heating to dominate over the total heating and that is what we originally refer to as the *burning plasma*, that is achieved for Q larger than five.

Notes

Summary

17m 51s

Engineering fusion gain

- To account for finite conversion efficiency, define $Q_E = \frac{\text{net electric power out}}{\text{net electric power in}} = \frac{P_{\text{out}}^{(E)} - P_{\text{in}}^{(E)}}{P_{\text{in}}^{(E)}}$
  - $P_{\text{in}}^{(E)} = \frac{P_{\text{in}}}{\eta_e}$, η_e: efficiency of the conversion of electrical power into plasma heating
  - Fusion (thermal) power is converted intro electricity with efficiency η_t $\Rightarrow P_{\text{out}}^{(E)} = \eta_t[P_f + P_{\text{in}}]$

$$Q_E = \frac{\eta_t(P_f + P_{in}) - P_{in}/\eta_e}{P_{in}/\eta_e} = \frac{\eta_e\eta_t(P_f + P_{in}) - P_{in}}{P}$$

Plasma

Finally we need to look at the reality of a reactor. We have finite conversion efficiencies and to account for those we actually define a value of gain, which is referred to as the *engineering gain*, Q sub E and we define it as the ratio between the net electric power out to the net electric power in. Or Pout(E) (in engineering terms) minus Pin(E) (in engineering terms) divided by Pin(E) (in engineering terms). Now the Pin(E) corresponds to the power that goes in the plasma divided by the efficiency, which we call ηe of the conversion of the electrical power into the plasma heating. We also have to consider that the conversion of fusion power to electricity is not 100 percent efficient, therefore we evaluate that as follows: Pout will be a finite efficiency term, ηt, times the input power plus the fusion power. So let's elaborate on this engineering QE. QE is equal to ηt (Pf + Pin) - Pin/ηe. These two terms are respectively the output power in engineering terms (Pout(E)) and the input power in engineering terms (Pin(E)) divided by the input power engineering terms (Pin(E)). That is equal to the product of the two efficiencies, times the total power, minus input power, divided by the input power.

Notes

Summary

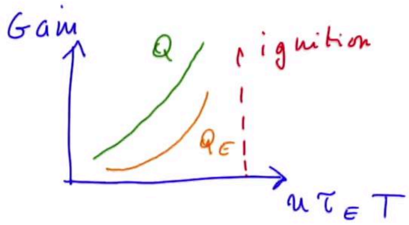
18m 46s

Engineering fusion gain

- To account for finite conversion efficiency, define $Q_E = \frac{\text{net electric power out}}{\text{net electric power in}} = \frac{P_{\rm out}^{(E)} - P_{\rm in}^{(E)}}{P_{\rm in}^{(E)}}$
  - $P_{\rm in}^{(E)} = \frac{P_{\rm in}}{\eta_e}$, η_e: efficiency of the conversion of electrical power into plasma heating
  - Fusion (thermal) power is converted intro electricity with efficiency η_t $\Rightarrow P_{\rm out}^{(E)} = \eta_t[P_f + P_{\rm in}]$

$$Q_E = \frac{\eta_t(P_f + P_{in}) - P_{in}/\eta_e}{P_{in}/\eta_e} = \frac{\overbrace{\eta_e\eta_t}^{\eta}(P_f + P_{in}) - P_{in}}{P_{in}}$$

$$Q_E = \frac{\eta(P_f + P_{in}) - P_{in}}{P_{in}} = \eta Q - (1 - \eta)$$



Ex. $\eta_e \simeq 70\%$; $\eta_t \simeq 40\%$ $\Rightarrow$ $\eta = 28\%$

$$Q_E = 0.28\,Q - 0.72$$

$$\begin{cases} Q_E \sim 10 \iff Q \cong 40 \\ Q_E \sim 2 \iff Q = 10 \end{cases}$$

Plasma

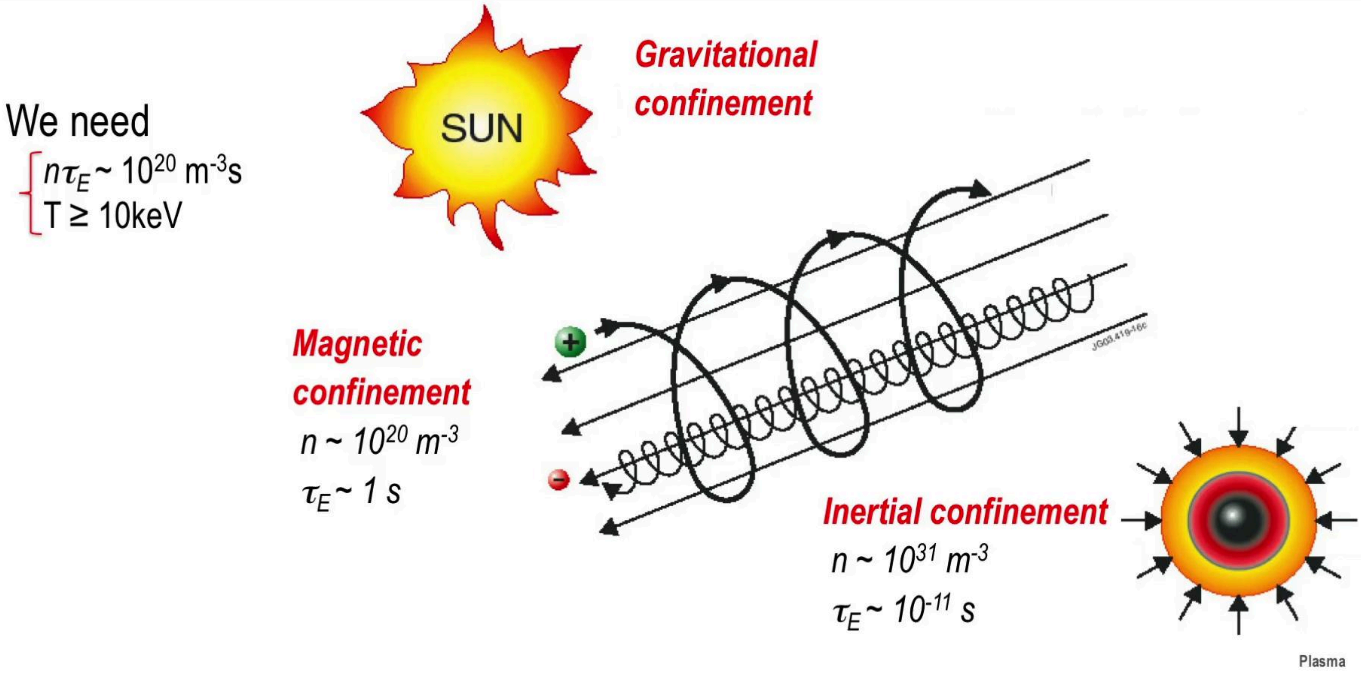
We define an overall efficiency η as the product of the two efficiencies. So that we can simplify the expression and use the definition of the fusion capital Q, the fusion gain, to get a final expression that relates the engineering gain to the fusion gain via, of course, the overall efficiencies of the two processes combined into a single parameter η. We can represent this relationship in a graphic term. And plot the gain as a function of what we refer to as the *triple product*, the product of n times the confinement times times the temperature. (n τE T) There is a value at which this gain will go to infinity that corresponds to ignition and we can compare the two curves in a qualitative fashion. The physics fusion gain and the engineering fusion gain, which would be significantly lower. Let's conclude with a numeric example. I take a reasonably optimistic set of values, I take 70% for the conversion efficiency of electrical power into plasma heating and 40% for the conversion efficiency of fusion power into electricity. That means the product of the two is 28% and QE corresponds to.28 times the physics gain Q minus.72 For example, if I have an engineering Q of about 10 that corresponds to or in fact needs a physics gain of about 40. Vice versa, if I have a value of the physics gain that is Q = 10, that corresponds to an engineering gain of about 2.

Notes

Summary

20m 31s

Approaches to plasma confinement



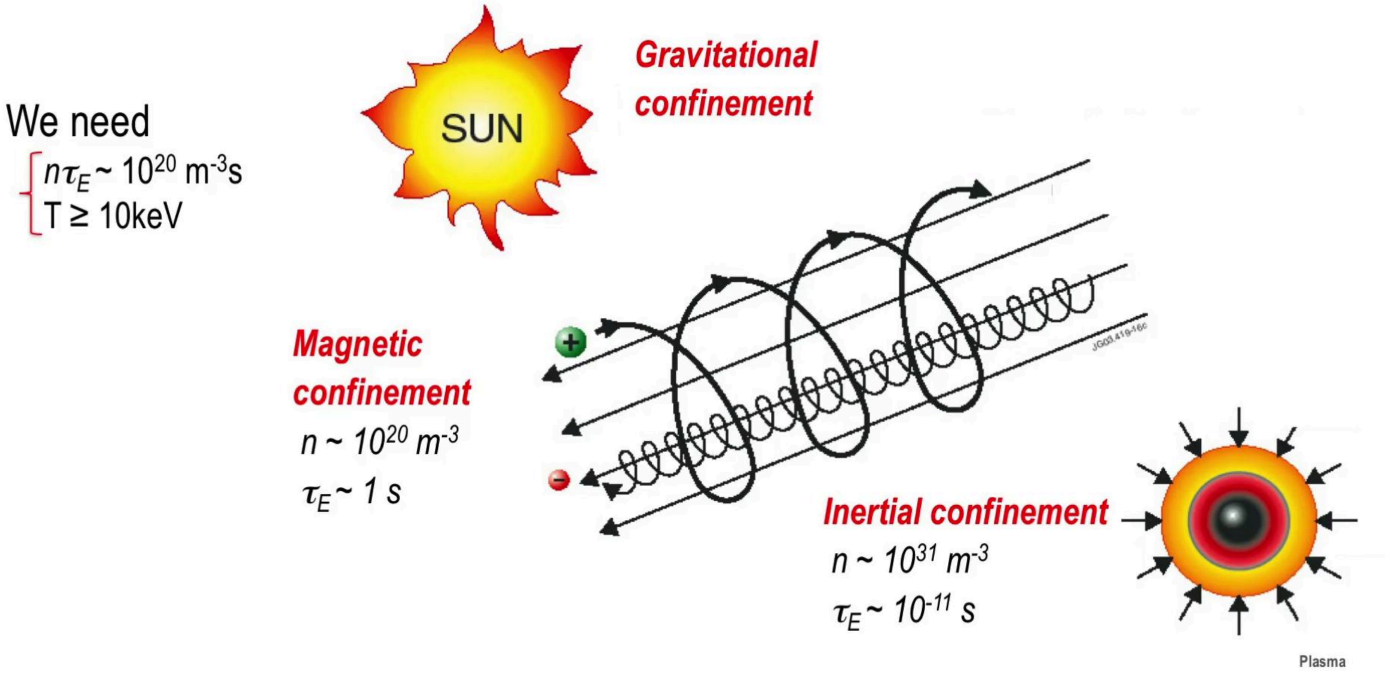
So we have seen that we need for a reactor to work two conditions to be satisfied at the same time: the product n τE, where τE is a confinement time and n is the density, must be of the order of 10^{20} per cubic meter second, --at least of that order-- and the temperature has to be at least of about 10keV. We have three ways to achieve these conditions or three possible ways to achieve these conditions. First of all, we have the gravitational confinement. That's the way the stars work, like the sun. They hold the plasma together by gravitational forces. That's very impractical on earth, of course. And we have two possibilities for a reactor. We have the possibility of magnetic confinement which corresponds to a density of about 10^{20} per cubic meter, very small amount of particles in fact in space there but because their product has to be about 10^{20} per cubic meter times second, that means having a confinement time for the energy of about one second and this confinement scheme which we'll discuss in the next lecture, of course is based on the usage of magnetic fields to trap the particles of the plasma in a given volume.

Notes

Summary

22m 42s

Approaches to plasma confinement



The sort of opposite approach is that of a inertial confinement where the density would be pushed to very very large values, typically 10^{30}, 10^{31} per cubic meter which means that the confinement time can be very small like 10^{-9} seconds (1 nanosecond) yet to have a product that would make it work. This inertia confinement, again, will be discussed in the next lecture and it's based on very small pellets that are made to implode via a very large deposition of power on their surface.

Notes

Summary

24m 04s

Summary

- Fusion power density is calculated from plasma temperature and density, from the values of fusion reaction rate $<\sigma v>_{DT}$
- Power losses in a fusion reactor are dominated by convection and conduction, quantified by energy confinement time τ_E
- Net power production requires a physics fusion gain Q>20, between breakeven (Q=1) and ignition (Q=∞)

Plasma

In summary, we have seen that we can evaluate the fusion power density on the basis of plasma density and temperature using the fusion reaction rate <σv>. We can evaluate the power losses, which are dominated by direct losses. That is conductive and convective. And they're quantified by a single parameter called the confinement time τE. We also demonstrated that the net power production, that's all we want from fusion reactor, requires a physics fusion gain larger than 20 and that is between the breakeven condition where Q = 1 and the ignition condition where Q equals infinity.

Notes

Summary

24m 39s