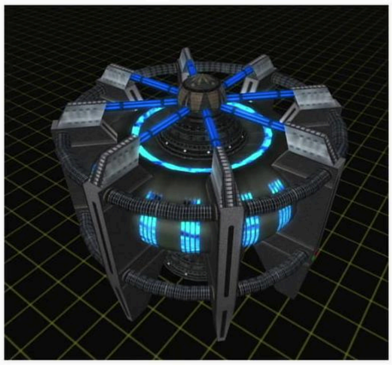
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

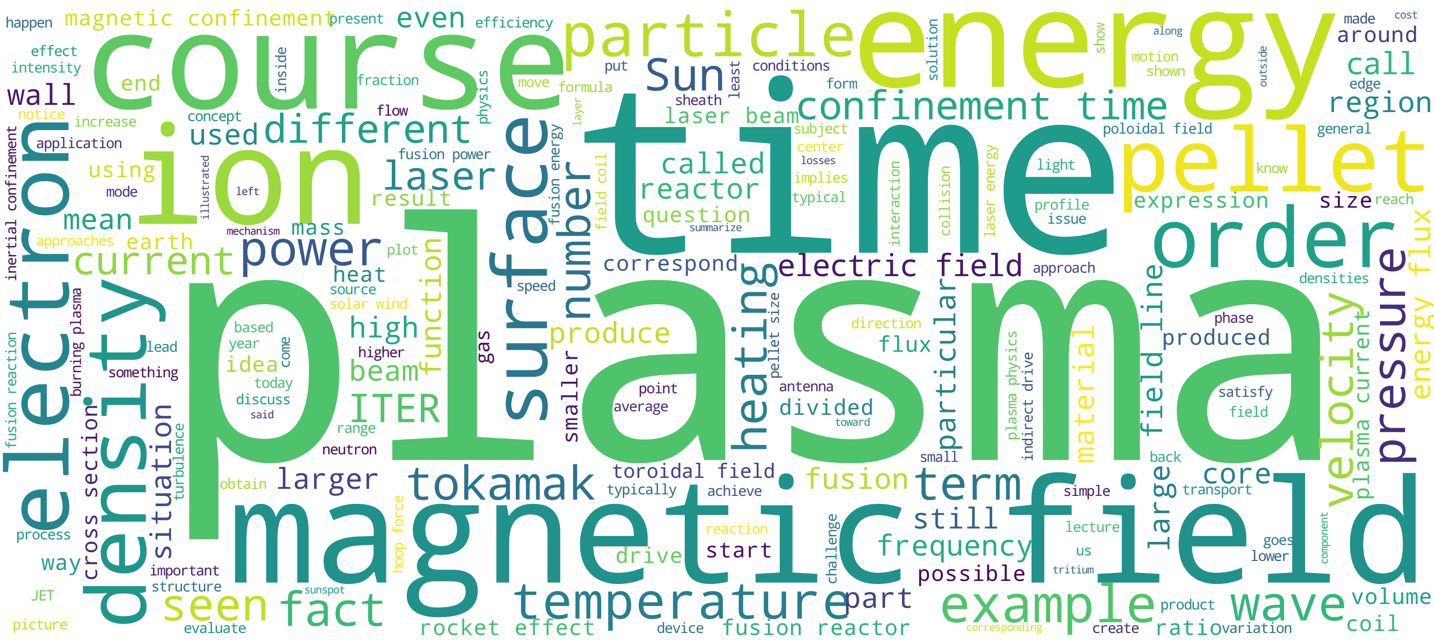


# Fusion: inertial and magnetic approaches

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

**Lecture 6c**

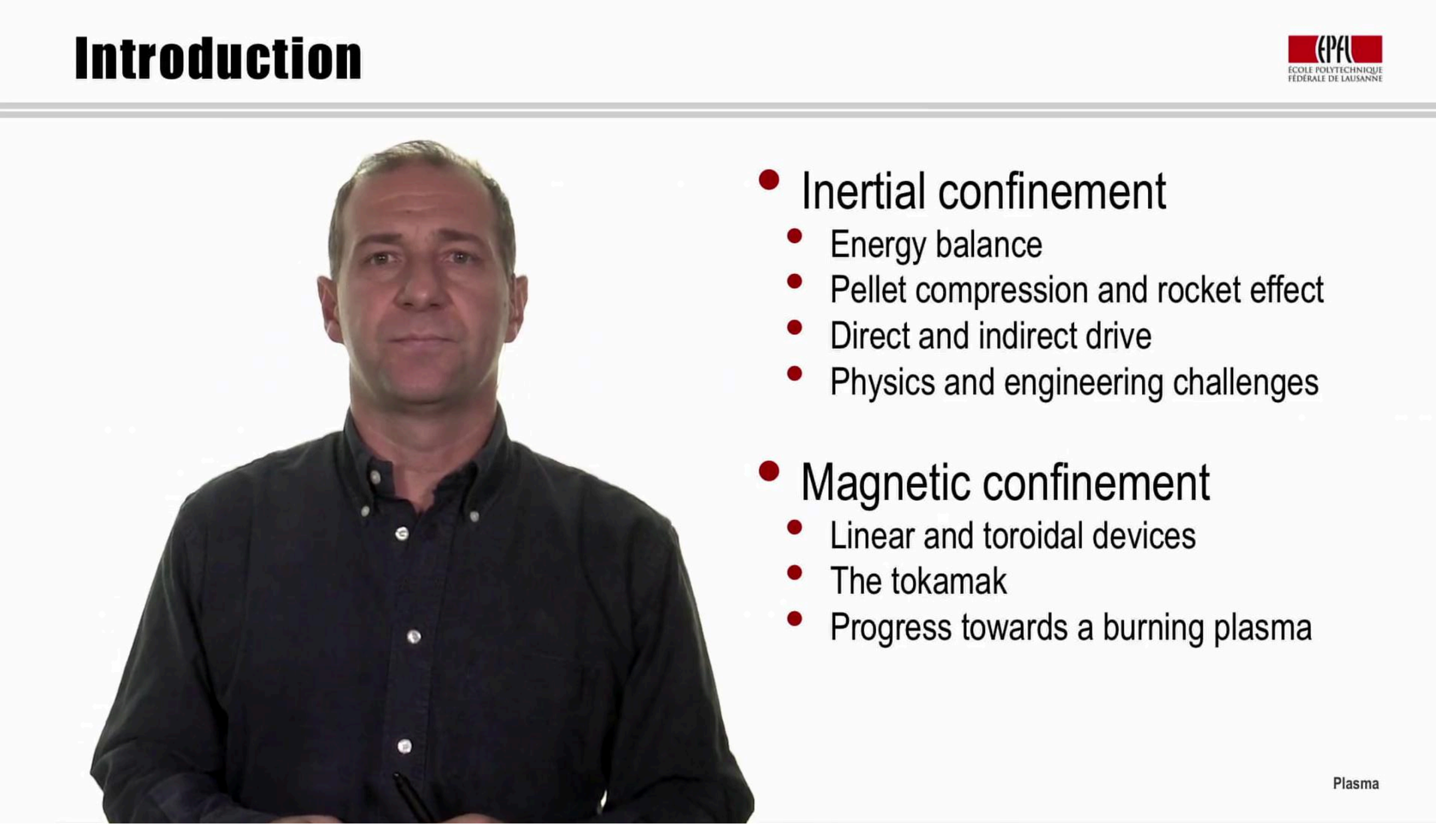
Ambrogio Fasoli



Search MOOC

Video

EPFL



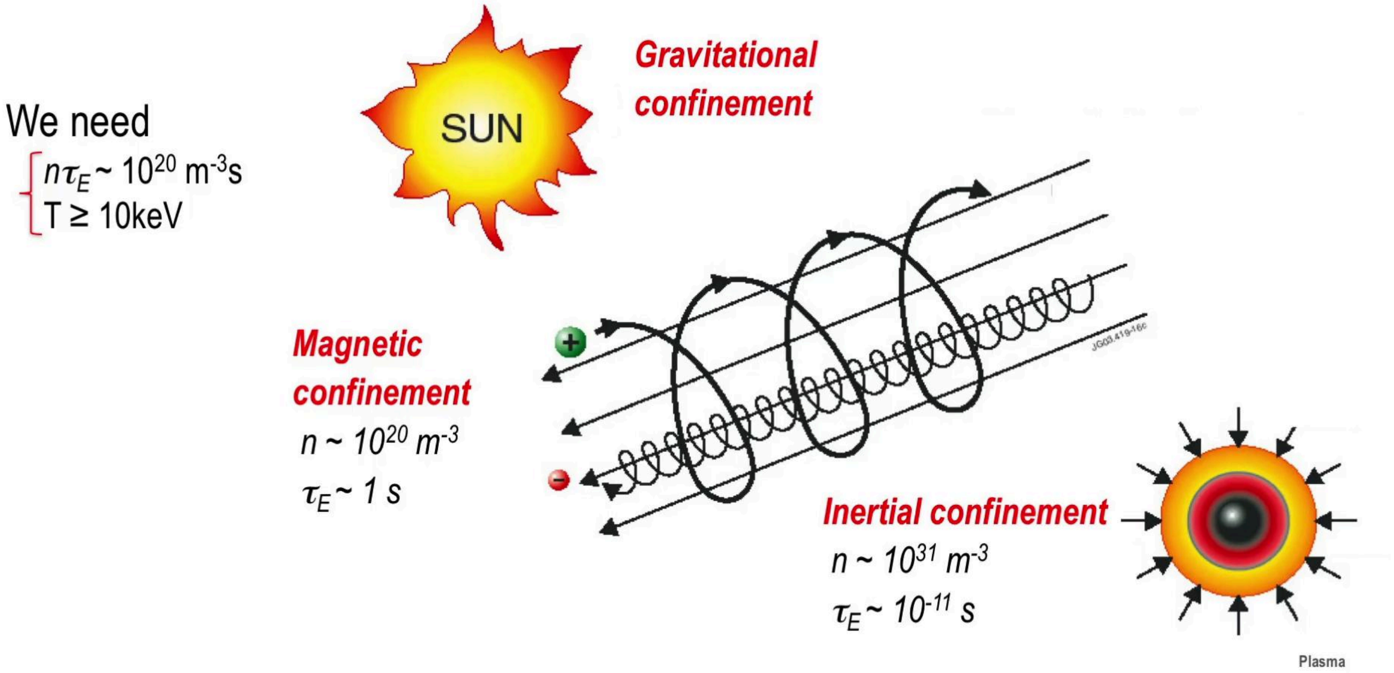

Welcome to the course on Plasma Physics and applications. Today, we will continue our discussion on thermonuclear fusion. We will study the two approaches that are possible on earth to confine a plasma and satisfy the conditions that are necessary to make a fusion reactor work. These two approaches are an inertial confinement and the a magnetic confinement. For inertial, we'll look at the energy balance, we'll look at the effect of the pellet compression and the rocket effect. We'll look at two possibilities of driving a pellet: direct and indirect drive. We'll also briefly investigate the challenges that physics and engineering impose to this approach. For magnetic confinement, we'll look at linear and toroidal devices, their difference and similarities. We'll look at the tokamak concept and we'll briefly illustrate the progress that we are achieving towards a burning plasma.

Notes

Summary

0m 05s

# Approaches to plasma confinement




We have calculated together that in order to achieve fusion in a reactor, we need to satisfy two conditions at the same time. We need to have a temperature that's about 10keV or higher, and we need to have a confinement quality, measured by the product of the density times the confinement time of the energy in our plasma that is at least of the order $10^{2\circ}$ per cubic meter ($m^{-3}$) times seconds (s). If we exclude the possibility of confining a plasma by gravitation, which is of course impractical on earth, we have two possibilities. We have the magnetic confinement, which will be based on the use of magnetic fields to trap the charged particles that form a plasma, or the inertial confinement which is based on the use of small pellets which we'll make implode by a large energy flux that will injected on their surfaces. For magnetic confinement, we can reach relatively large confinement times, of the order of a second, which implies that the densities that we'll need to satisfy the criterion for fusion will not be too large, in fact they will be much smaller than the density of the air that we breathe, for example.

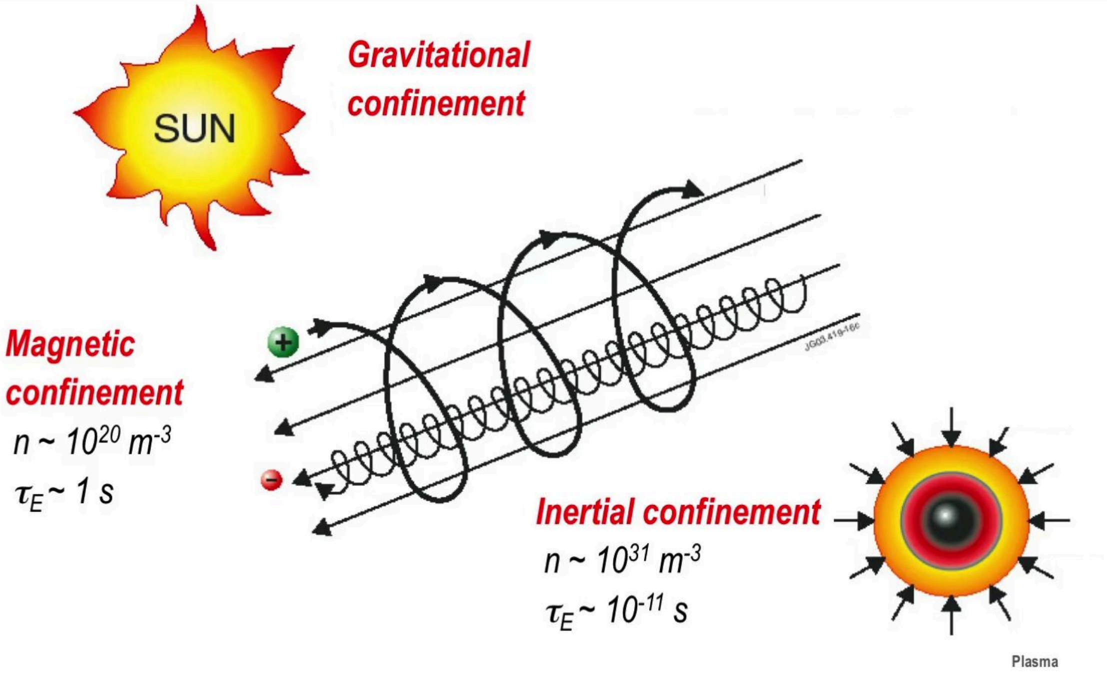
Notes

Summary

0m 57s

# Approaches to plasma confinement

We need
$\begin{cases} n\tau_E \sim 10^{20}\ \mathrm{m^{-3}s} \\ T \geq 10\mathrm{keV} \end{cases}$



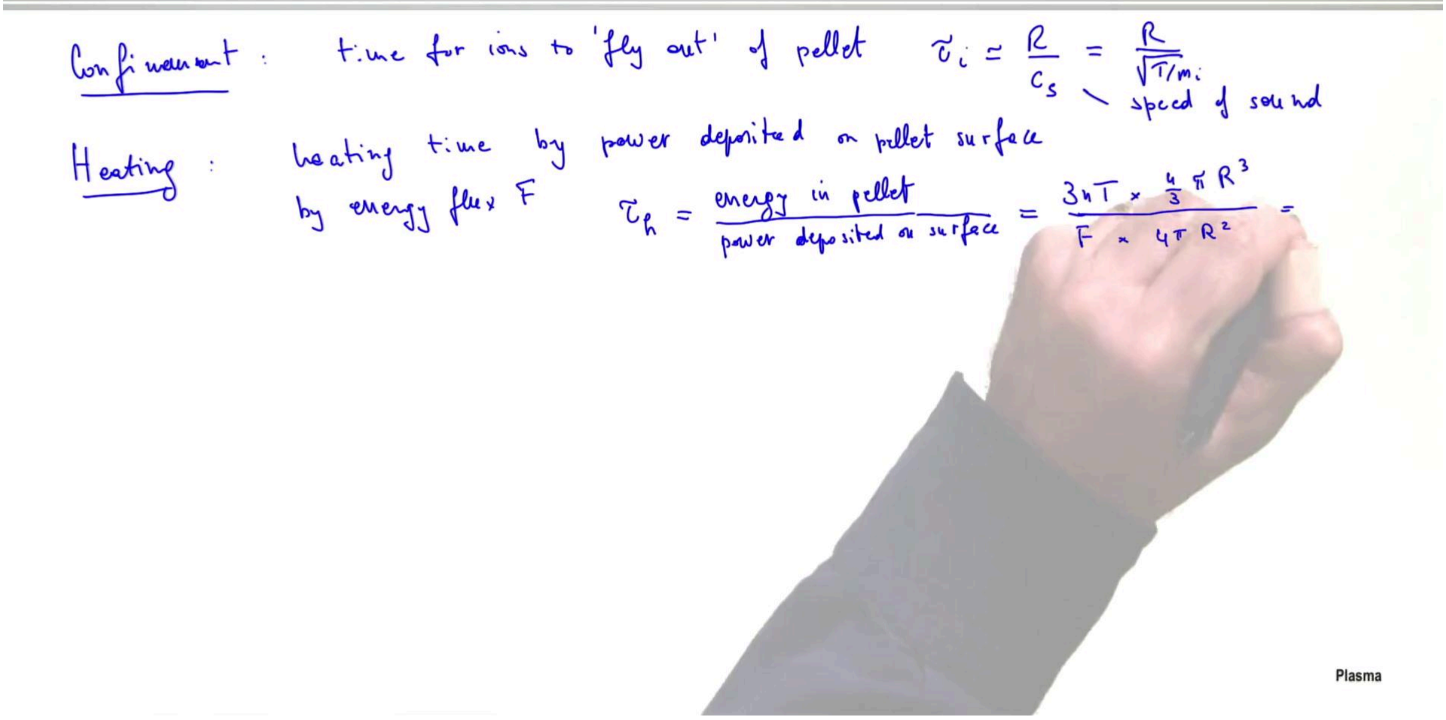

Typically in the order of $10^{2\circ}m^{-3}$ In the inertial confinement approach, which will be the one we discuss first today, we can only achieve very short confinement times for the energy, let's say, of the order of a nanosecond. That implies that we need to really reach extremely large densities of the order $10^{31}m^{-3}$. That is much higher than the density of solid material. Let's start our discussion with the basic principles of inertial confinement fusion (ICF).

Notes

Summary

2m 16s

# Inertial Confinement Fusion (ICF) – basic principles




Let's look at the confinement time first. For that, we can consider the time for the ions to fly out of the pellet. We can call that τi, and evaluate it as the size of the pellet, it's radius, divided by the typical speed which the ions will move inside the pellet. That is the speed of sound (cs). cs is evaluated by the square root of the temperature divided by the ion mass. This is the confinement time for particles. Now we have to compare that to the time that it takes for a certain energy flux to heat the pellet. To look at heating, in particular the heating time by power that's deposited on the pellet surface by an energy flux F. Let's call this time τh (for heating), and let's express it in a formula. The [heating] time is given by the energy in the pellet divided by the power deposited on the surface of the pellet. The energy in the pellet is the energy density of the plasma in the pellet, times its volume. So we have 3 n times the temperature, times the volume of the pellet which will assume to be a spherical shape, 4/3 π $R^3$. divided by the energy flux F, times the surface of the pellet which is $4\pi R^2$.

Notes

Summary

2m 46s

# Inertial Confinement Fusion (ICF) – basic principles

ECOLE POLYTECHNIQUE FEDERALE DE LAUSANNE

**Confinement**: time for ions to 'fly out' of pellet $\tau_i \simeq \frac{R}{c_s} = \frac{R}{\sqrt{T/m_i}}$ ($c_s$: speed of sound)

**Heating**: heating time by power deposited on pellet surface by energy flux F

$$\tau_h = \frac{\text{energy in pellet}}{\text{power deposited on surface}} = \frac{3nT \times \frac{4}{3}\pi R^3}{F \times 4\pi R^2} = \frac{nTR}{F}$$

$$\tau_h < \tau_i \Rightarrow \frac{nTR}{F} < \frac{R}{\sqrt{T/m_i}} \Rightarrow F > nT\sqrt{\frac{T}{m_i}}$$

**Ex.** $T = 10\,\text{keV}$ ; $n$ = density of solid D

$$\Rightarrow F > 5 \times 10^{19}\,\frac{W}{m^2}$$ huge!

→ lasers or heavy ion beams

Plasma

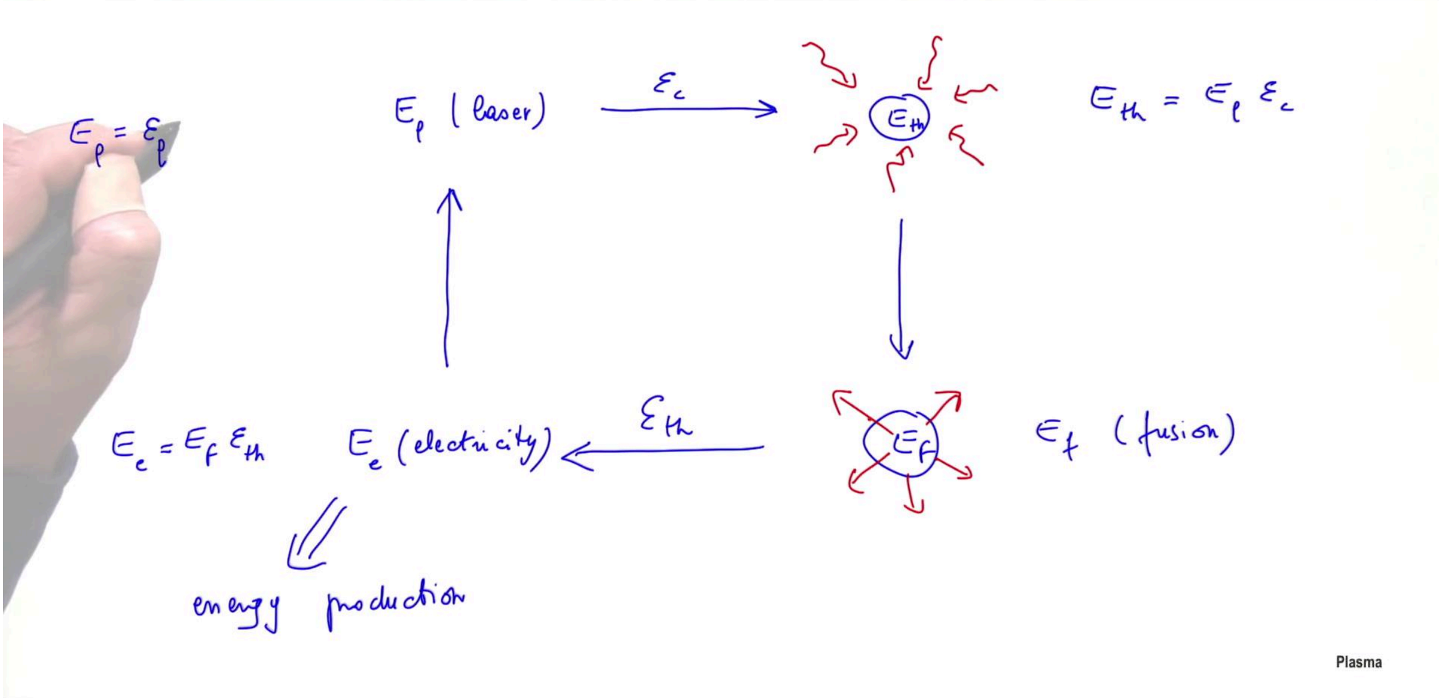
We can simplify the different terms and end up with a simple expression which n times T, times the size or the radius of the pellet (R), divided by the energy flux, F. Obviously, we need to have a heating time that's shorter than the confinement time. The condition is that τh is smaller that τi. Let's translate it into a formula for -- in particular into a condition -- for the energy flux, F. So let's write nT R/F smaller than the confinement time, R/ ( √T/ √mi) and express this in terms of F which therefore needs to be larger than n T times the square root of (T/mi). And we note that in this condition, the size of the pellet does not enter anymore. I remind you that here I have assumed no compression effects, just heating on the surface of the pellet by an energy flux *F*. Let's take a numerical example: typically we consider a temperature for fusion of about 10keV, let's take the density of solid deuterium for n; If put the numbers, this gives me a value of F that needs to be larger than about 5. $10^{19}$W/m² which is of course a very large value. The hope to achieve that is only perhaps via lasers or heavy ion beams.

Notes

Summary

4m 23s

# ICF – energy balance



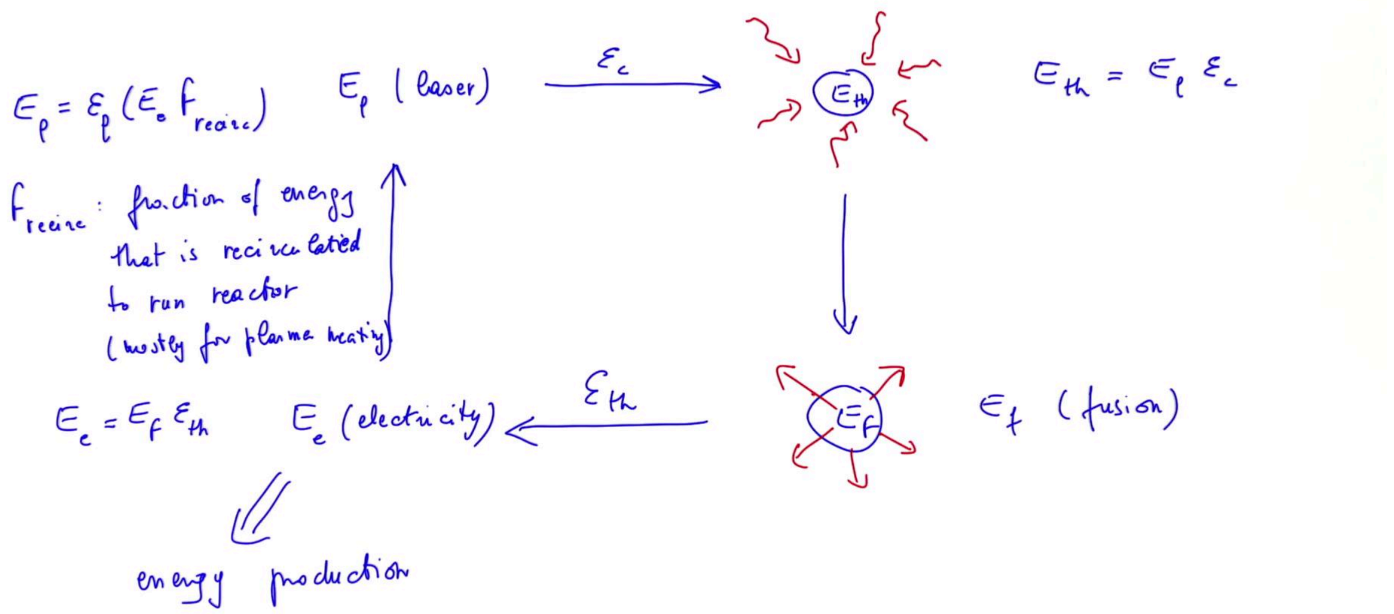

Having seen the basic principles for inertial confinement, we are now ready to evaluate the energy balance. We have a laser, chararacterized by your certain energy, El that is injected onto a pellet. There will be a certain efficiency with which laser energy will be transformed into the pellet thermal content. So the thermal energy in the pellet will be equal to the laser energy times this efficiency which we can call εc (epsilon c) This will lead to heating and hopefully fusion energy production. The pellet will therefore produce an energy Ef via diffusion reactions that will be happening in its core. This fusion energy Ef is used to create electricity for energy production. Let's call the energy for electricity Ee, and of course for this process there's a finite efficiency as well. Let's call that epsilon thermal εth Ee = Ef εth Of course this Ee will give energy production for the outside world if your like, but also part of it will be used to drive the laser. So the laser energy (El) will be equal to a certain conversion efficiency which we can call εl (epsilon-sub-l) times the electrical energy that would be used to drive it.

Notes

Summary

6m 14s

# ICF – energy balance




Plasma

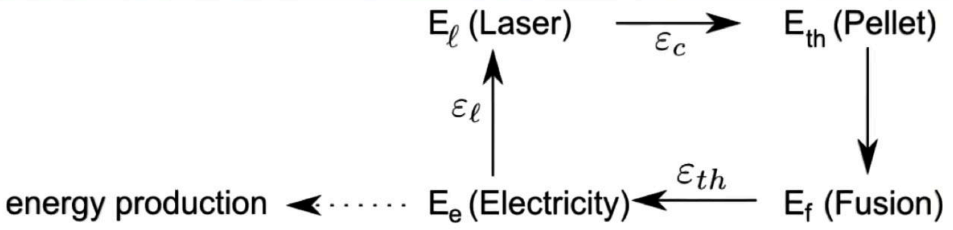
Now, of course not all fusion energy will be used to create electrical energy because of the final conversion efficiency and not all electrical energy would be used to drive the laser. We'd only have a fraction of it in principle, that would be Ee times a factor which we can call Frecirc which is the fraction of energy that is recirculated to run the reactor, mostly for plasma heating. So we now have the complete loop for our energy balance and we can evaluate what the different conditions are in the practical situations for a fusion reactor.

Notes

Summary

7m 53s

# ICF – energy balance




- By developing the relations between the different steps, considering the worst case scenario of 100% recirculating power, expressing the pellet size as function of $E_{th}$, hence of $E_\ell$, considering T=10keV and the relevant value of $<\sigma v>_{DT}$, using the reference value $n_0 = 4.5\times10^{28}\,m^{-3}$ (density of solid D), and the confinement time:

$$E_\ell \simeq \frac{1}{(\varepsilon_\ell \varepsilon_{th})^3 \varepsilon_c^4}\left(\frac{n_0}{n}\right)^2 \quad \text{in MJ}$$

Plasma

Here we see the same loop drawn in a more schematic way and what we do is that we develop the relations between the different steps. In this situation we consider the worst case scenario that is we recirculate 100% of the power or the energy. We need to express the pellet size as function Eth, therefore as a function of the laser energy (El), we consider our usual temperature for fusion of about 10keV, and the relevant value of diffusion cross section times velocity for the DT reaction. And if we introduce a reference value n0 for the density which is the density of solid deuterium and the confinement times for the ions that we have calculated before. We have a very compact expression that relates the densities of the pellet to the laser energy that is required to satisfy our criterion, and the efficiencies of the different steps that we have discussed. This expression is numerically correct if we consider the energy in megajoules.

Notes

Summary

8m 37s

# ICF – energy needed in driver

$$E_\ell \simeq \frac{1}{(\varepsilon_\ell \varepsilon_{th})^3 \varepsilon_c^4} \left(\frac{n_0}{n}\right)^2 \text{ in MJ}$$

- Driver energy needed for $n=n_0$ and $\varepsilon_c \sim 0.1$, $\varepsilon_\ell \sim 0.05$, $\varepsilon_{th} \sim 0.4$ → $E_\ell \sim 10^{15}$J

~50 × Hiroshima bomb! Orders of magnitudes more than achieved laser pulse energies (~2MJ)!

Plasma

Using this expression now, we can put some numbers. and evaluate a driver energy that's needed for a situation in which we consider the density n=n0, that is the density of solid deuterium. We consider the efficiency εc to be about 10%, efficience εl to be about 5%, that's the efficiency with which the electricity is translating into laser power, and the efficiency εth, which is the efficiency of the transformation of fusion power into electricity of about 40%. The number we reach for the laser, for the driver energy in general is very, very large, it's $10^{15}$J. That's about 50 times the Hiroshima bomb and if we consider the pellet size of the order, a few millimeters, that's really a very large number. And in fact this is orders of magnitude more than we can achieve in the laser pulses today which is about 2-3 megajoules.

Notes

Summary

9m 40s

# ICF – energy needed in driver

$$E_\ell \simeq \frac{1}{(\varepsilon_\ell \varepsilon_{th})^3 \varepsilon_c^4} \left(\frac{n_0}{n}\right)^2 \text{ in MJ}$$

- Driver energy needed for $n=n_0$ and $\varepsilon_c \sim 0.1$, $\varepsilon_\ell \sim 0.05$, $\varepsilon_{th} \sim 0.4$ → $E_\ell \sim 10^{15}$J

~50 × Hiroshima bomb! Orders of magnitudes more than achieved laser pulse energies (~2MJ)!

- To reduce $E_\ell$ we must increase efficiencies but also $n/n_0$
- For example if we take $\varepsilon_c$~0.2, $\varepsilon_\ell$~0.08, $\varepsilon_{th}$~0.4, for $E_\ell$ ~ 2MJ we need n~3000 $n_0$
- In this case we need to achieve pressure

$$p \sim 3000 n_0 T = 3000 \times 4.5 \times 10^{28} \text{m}^{-3} \times 10^4 \text{eV} \times 1.6 \times 10^{-19} \text{J/eV} \sim 2 \times 10^{17} \text{ N/m}^2$$

- Pressure from most powerful laser is far too small

$$p_{laser} = F / c \sim (3 \times 10^{20} \text{W/m}^2) / (3 \times 10^8 \text{m/s}) \sim 10^{12} \text{ N/m}^2$$

Plasma

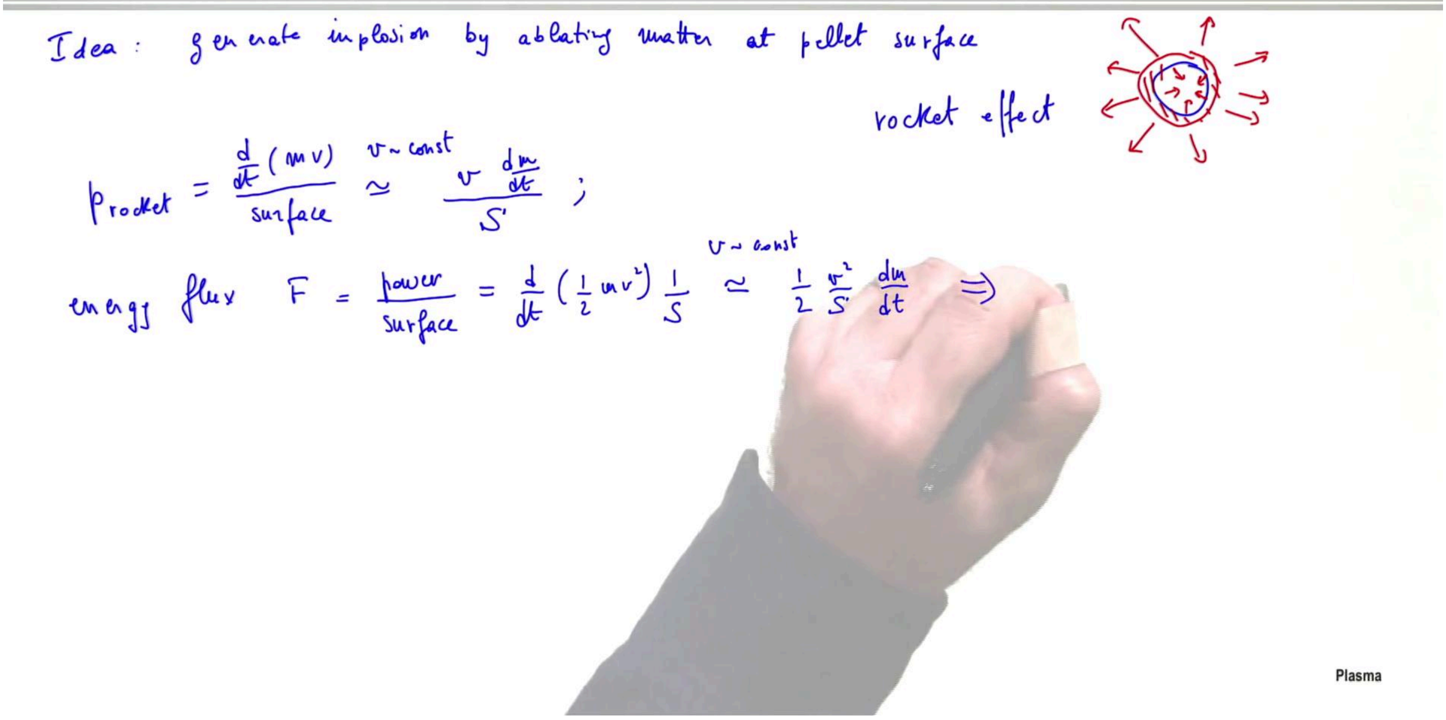
To reduce this value of the needed laser energy, we must increase the efficiencies. But we also must increase the ratio n/n0, that means we must compress the pellet. So let's take slightly more optimistic numbers: an efficiency εc of 20%, an efficiency εl of about 8%, we keep εth to about 40%, and then we do the exercise the other way around. So we impose that El be 2 megajoules which is what we can achieve today. What do we need for n? Well, we reach a value of n that must be about 3000 times n0. So the density must be 3000 times the density of solid deuterium. That means we have to achieve a pressure that is 3000 times n0 times the temperature and if we put the numbers, that corresponds to about $2 \times 10^{17}$ Newtons per square meter, which again is a gigantic pressure. If we consider the laser pressure, that is the pressure generated from the laser beam given a certain energy flux F for the most powerful laser beams we can create today, and that is calculated simply by dividing the energy flux F by the speed of light, that's about five orders of magnitude smaller. So we are really far away from what we need to achieve to satisfy the condition for the pellet to fuse.

Notes

Summary

10m 47s

# ICF – the rocket effect




The question is how to boost this pressure. Here's a simple idea. We can generate an implosion by ablating matter at the pellet surface. If we have our pellet, we have a layer, at the edge of it, which can be ablated for example, by launching onto it a very large amount of energy. By rocket effect, that is by conservation of momentum, there will be an inward motion of the first layers inside the ablated matter. This is the rocket effect. The pressure that results can be calculated with a very simple model. Let's call this Procket. The pressure is equal to the variation of the momentum (mv) with time, divided by the surface. We assume that v can be considered constant so the momentum varies because the mass varies not because the velocity varies, so that is equal to v dm/dt over the surface that we would call S. We will consider the energy flux F, that is the power divided by the surface and the power is the variation in time of the energy which is the kinetic energy of the matter in the pellet, divided by the surface *S*. Again, we consider that the velocity can be assumed to be roughly constant, so I take 1/2 $v^2$ out of the derivative and we have 1/2 $v^2$ over S times the variation of mass with time.

Notes

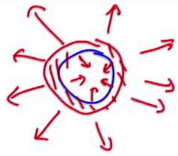
Summary

12m 28s

# ICF – the rocket effect

Idea: generate implosion by ablating matter at pellet surface

rocket effect



$$P_{rocket} = \frac{\frac{d}{dt}(mv)}{surface} \overset{v\sim const}{\simeq} \frac{v\,\frac{dm}{dt}}{S};$$

$$\text{energy flux } F = \frac{power}{surface} = \frac{d}{dt}\left(\frac{1}{2}mv^2\right)\frac{1}{S} \overset{v\sim const}{\simeq} \frac{1}{2}\frac{v^2}{S}\frac{dm}{dt} \Rightarrow \frac{dm}{dt} = \frac{2SF}{v^2}$$

$$P_{rocket} = \frac{v}{S}\frac{dm}{dt} = \frac{v}{S}\frac{2SF}{v^2} = \frac{2F}{v}; \qquad \frac{P_{rocket}}{P_{laser}} = \frac{2F}{v}\frac{c}{F} = 2\frac{c}{v} \gg 1 \text{ as } v \ll c$$

Plasma

That gives me a variation of mass with time dm/dt, that's equal to 2 S F / v². That I can use in the expression for the rocket effect pressure, or Procket which given by v/S dm/dt so that is v/S 2SF/v². The surface of the pellet cancels out and I'm left, simplifying also v² with v, I'm left with just 2F/v. So, we can now compare what we have achieved in terms of pressure by this rocket effect, and the pressure that comes simply from the light impinging on the surface, which we called Plaser before, let's take the ratio of the two and that is 2F/v c/F. So, for the same energy flux F, we a ratio that's two times the ratio of the speed of light, divided by the velocity of the motion of the particles at the pellet surface. So that is of course much, much bigger than 1 as the velocity is much smaller than c. So that's how we boost the pressure in the pellet by this rocket effect idea.

Notes

Summary

14m 02s

# ICF – additional effects

- Pressure from rocket effect is helped by inward propagation of the shock wave produced at the surface, if process is sufficiently symmetric
- As core is heated, fusion reactions and the resulting $\alpha$-heating help
  - For this to work, the pellet size must be larger than the $\alpha$ collisional mean free path (~1mm)
- Instabilities in the laser-plasma interactions impose a limit to laser intensity
- Density cannot be too high, otherwise the laser beam is reflected by cutoff ($\omega_p$)

Plasma

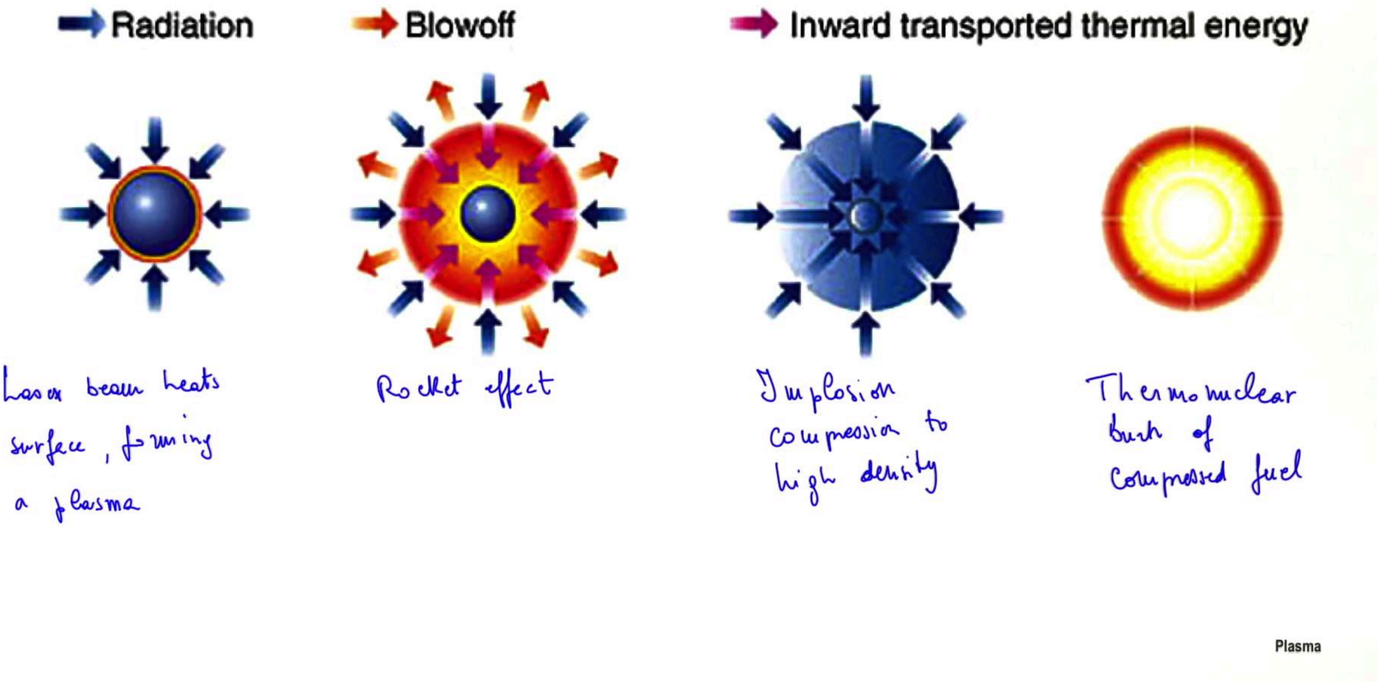
There are a few additional effects that we need consider: two that are positive that is they help us achieving higher pressure and higher temperature in the core, and two that are a little bit difficult to deal with. First of all, the pressure from the rocket effect is helped by the inward propagation of the shockwave and this is produced at the surface, assuming that this shock wave really goes to the center in a symmetric way. Second, as the core is heated, fusion reactions will start and the alpha (α) heating that is the consequence of the fusion reactions will start to help as well. However, for this to work, we need to make sure that the pellet size be larger than the collision mean free path for the alphas inside it. So we need a pellet size that's in the order of a few millimeters at least. The other two effects are a little bit more difficult to deal with and that they're not helping us. First, we have instabilities in the interaction between the laser and the plasma, and this imposes a limit to the laser intensity. Second, the density itself cannot be too high, otherwise the laser beam will be reflected by the plasma frequency cut-off that we have learned about in previous classes, ωp (omega p).

Notes

Summary

15m 18s

# ICF – summary of the sequence of events




We're ready now to summarize the sequence of events in inertial fusion. First of all, we have what we call the *radiation* phase. The laser beam heats the surface and forms a plasma. The second phase is the *blow-off* phase which is this rocket effect that we have discovered together. The surface material is blown off and by conservation momentum the rest is pushed over the center. The third phase is therefore the *implosion* phase. And with implosion comes the compression of the core to very high density. And the fourth phase, if everything works fine, is the *thermonuclear* burn of the compressed fuel.

Notes

Summary

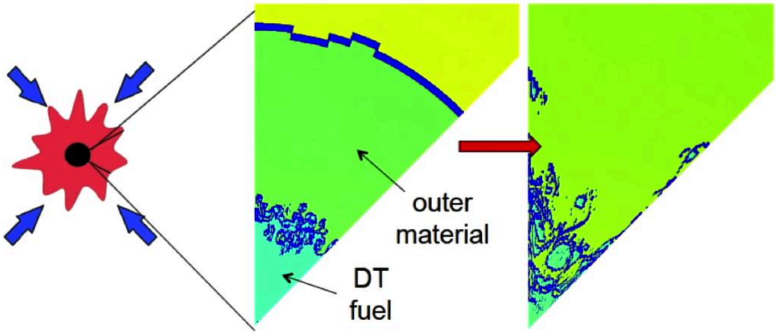
16m 36s

# ICF – physics challenges

- Core must not be heated before shock wave arrives and compresses it
  - Pellet design
  - Laser pulse timing
- Hydrodynamical stability
  - Pellet symmetry
  - Beam alignment, symmetry of drive

Simulated mixing due to Rayleigh-Taylor instability

*Courtesy of Mathias Groth, Aalto Univ.*




Plasma

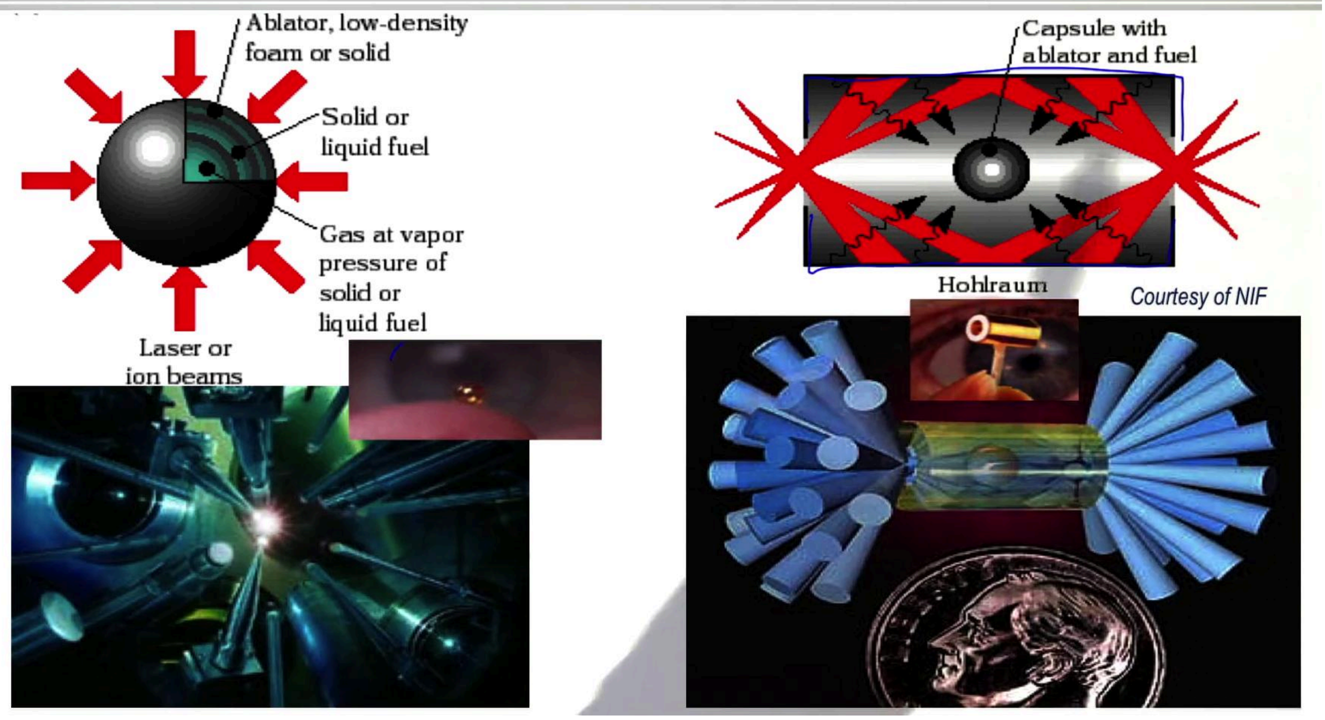
Let us now briefly discuss the challenges, that physics poses to this approach. First of all the core must not be heated before the shock wave arrives and compresses it. That implies that the design of the pellet needs to be really carefully done. It also implies that the timing of the laser pulse is very delicate. Second, there is the question of the hydrodynamical stability of the pellet itself. That imposes a very high degree of symmetry in the pellet as well as in the drive, therefore in practice a very, very delicate question of aligning the beams onto the pellet. The simulation shown here indicates a mixing from the core material that is formed by the DT fuel and the outer material due to a so-called Rayleigh-Taylor instability.

Notes

Summary

17m 24s

# ICF – direct and indirect drive



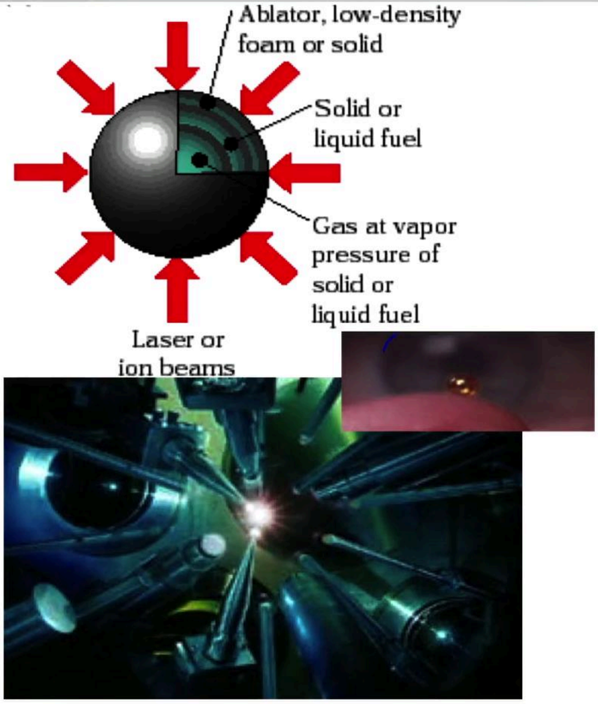

Two approaches are taken to drive the pellet: direct and indirect drive. The direct drive is shown here on the left. This is the simpler of the two, conceptually. We really have just the pellet on which we inject in an as symmetric fashion as possible all the laser beams. The pellet construction is relatively complicated. there is an ablator, low-density around, there's a solid or liquid fuel, and there's a gas at the vapor pressure of the solid or the liquid fuel. The pellet size, here shown compared to a human eye, is in the order of a millimeter. This is the direct drive. The second option is a clever idea that came about to actually lower the requirements on the symmetry of the laser injections onto the pellet. And that's the so called indirect drive. The idea is the following: instead of just having the laser beams impinging on the pellet itself, we have a very small, little chamber around it, called a hohlraum, bigger than the pellet itself of course, but still a relatively small size of a centimeter or so. This is the image of one version again compared to a human eye. What does this holhraum do? Well, it receives the laser beams through two holes.

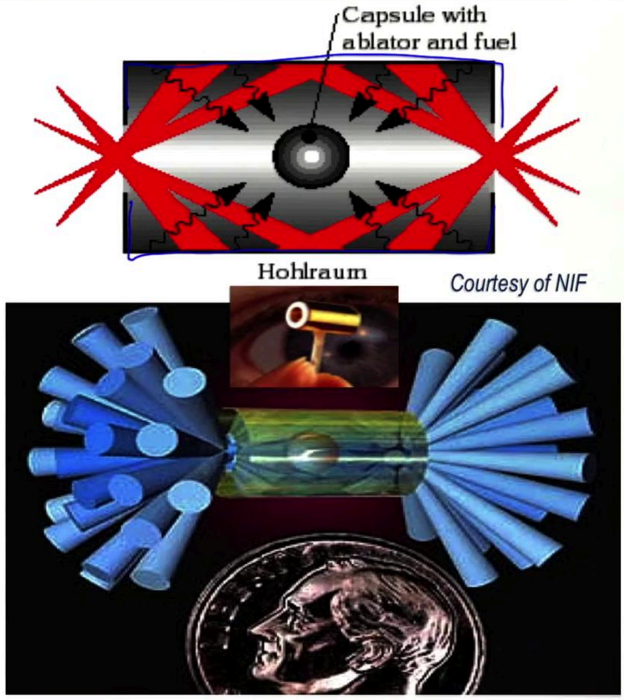
Notes

Summary

18m 16s

# ICF – direct and indirect drive



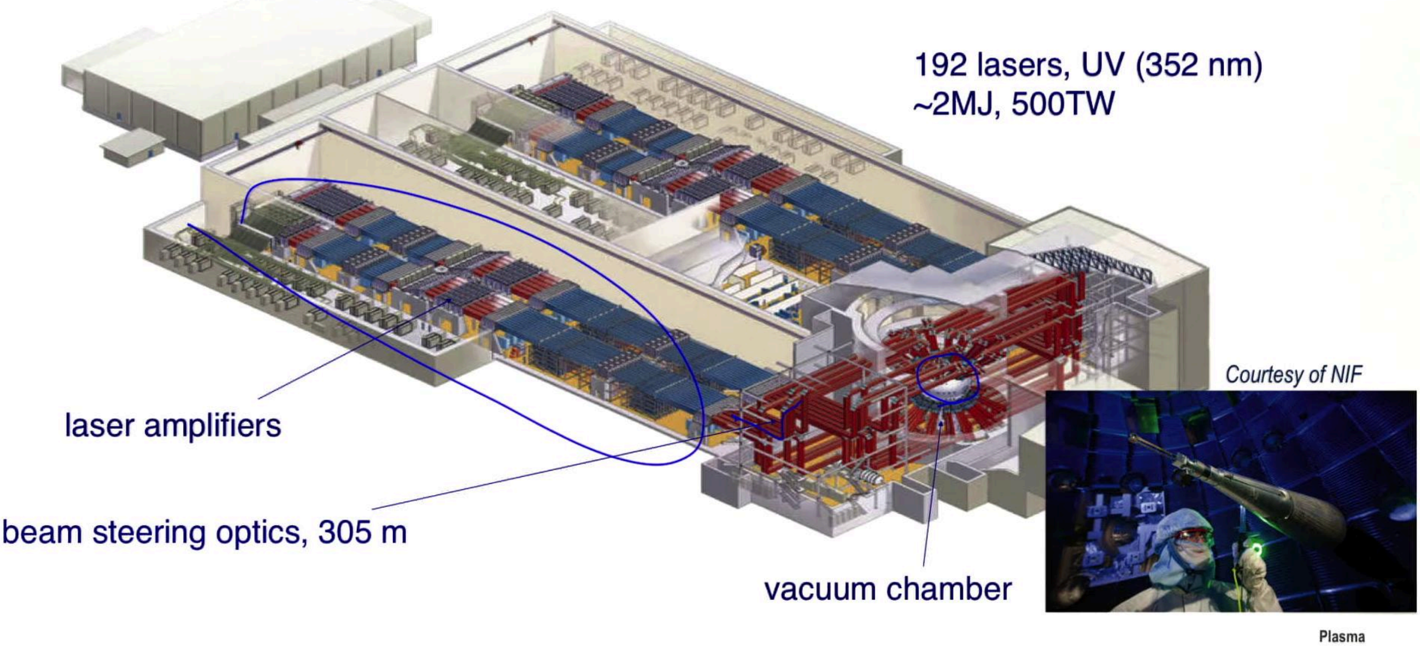

It acts like a black body radiator of x-rays because the laser beams are so powerful that by heating the surfaces of these holhraum inside, which are made typically of a high Z material like gold, this surfaces emit x-rays. An advantage is that this x-ray bath in which the pellet is embedded is more symmetric than the injection of the lasers themselves. It reduces the conditions on the symmetry for the beams.

Notes

Summary

19m 44s

# The NIF facility at Lawrence Livermore Lab (US)




The image shown on this slide is that of the National Ignition Facility which is the largest operating experiment on inertial fusion, and that's located at the Lawrence Livermore Laboratoty in California, US. It shows you how big the facility of this kind is. This system has 192 lasers for a record energy in a pulse of about 2 megajoules, and a power of about 500 terawatts. These are lasers in the UV regime at 352 nano meters of wavelength. You see in this picture all the amplifiers for the lasers. You see the beam steering optics here, which is of the order of 300 meter length, and at the end you see the vacuum chamber which contains the pellet, which is kept in place by a special positioning sytem and of course occupies a very small volume of the vacuum chamber at the end.

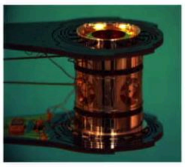
Notes

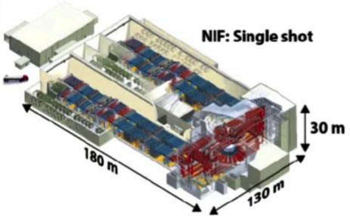
Summary

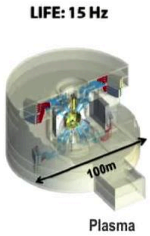
20m 18s

# ICF – engineering challenges

- Efficiency, cost and reliability of high energy driver
- Materials for first wall of vacuum chamber
- Complexity and cost of capsule
- From single to repetitive pulses (3-10Hz)





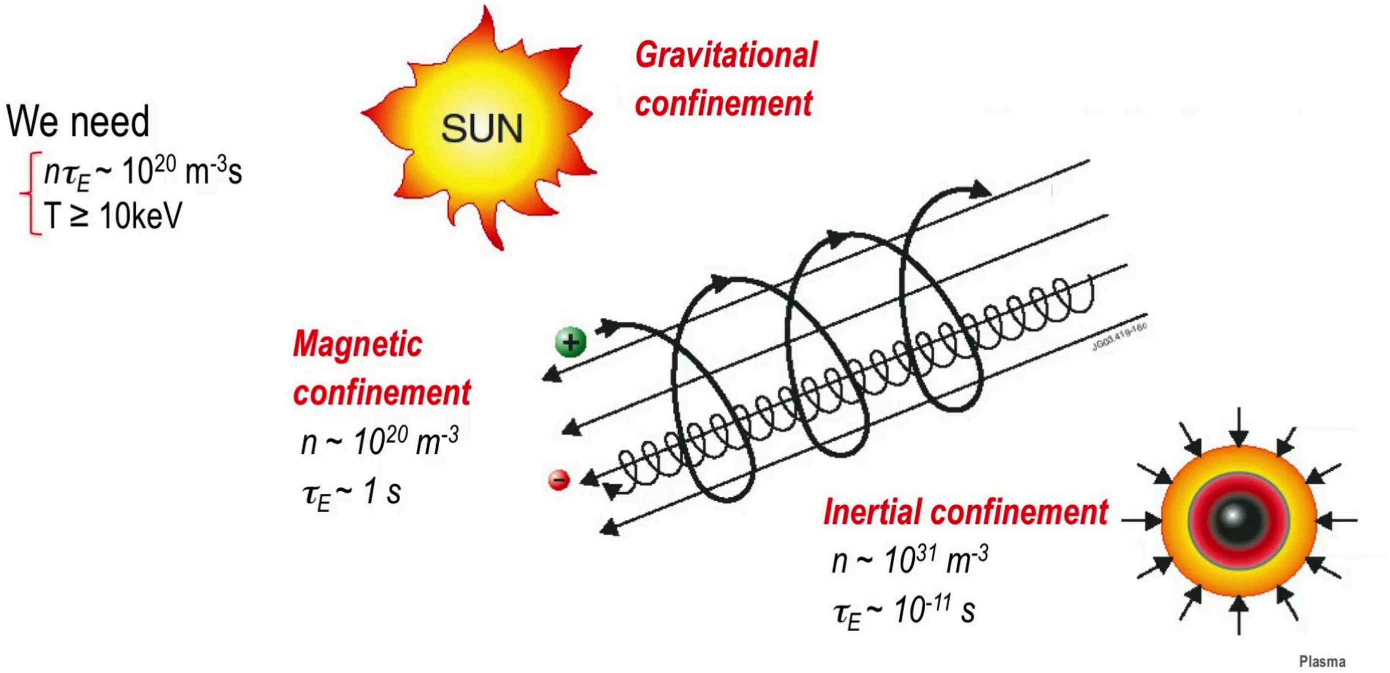

Let us now discuss a few of the engineering challenges that this approach entails. First of all, we need to address the question of the efficiency cost and reliability of the high energy driver, for example, the lasers. Second, we need to solve the question of the materials for the first wall of vacuum chamber. Third, and this is perhaps the most difficult ones, we need to address the issue of complexity and therefore cost of the capsule, the pellet itself and the hohlraum in the case of the indirect drive. At present these elements cost orders of magnitude more than that they need to cost if we want the reactor to be economical. And last but not the least is the issue of going from a single to repetitive pulses. A reactor will need to operate with a few hertz of a pulsed rate in order to be economical and produce power.

Notes

Summary

21m 22s

# Approaches to plasma confinement



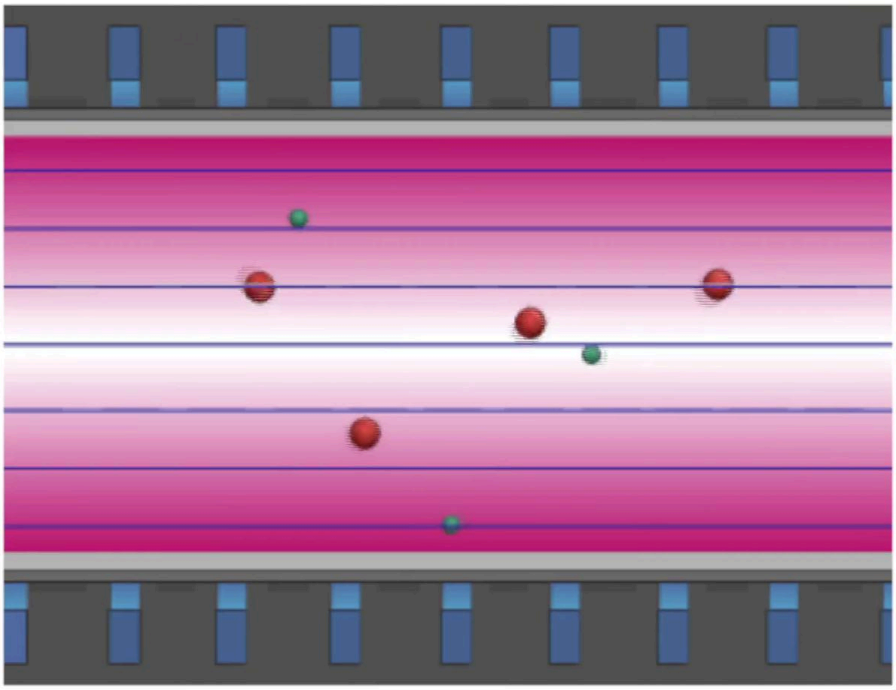

Having seen some of the problems of inertial confinement and some of the elements of its basic principles, we're now ready to move to the second approach that we can have on earth to get a plasma confined in the given region and therefore produce a fusion reactor. That is the approach of magnetic confinement based on the fact that the plasma is made by charged particles, ions and electrons, then they are subject to electromagnetic force, and particular, they tend to rotate and gyrate around magnetic field lines. This approach allows us to have confinement times that are macroscopic of the order of seconds which means we can afford densities that are relatively low, the order 10²° per cubic meters, much lower than the densities of the air that we breathe.

Notes

Summary

22m 16s

# Magnetic confinement – basic principle



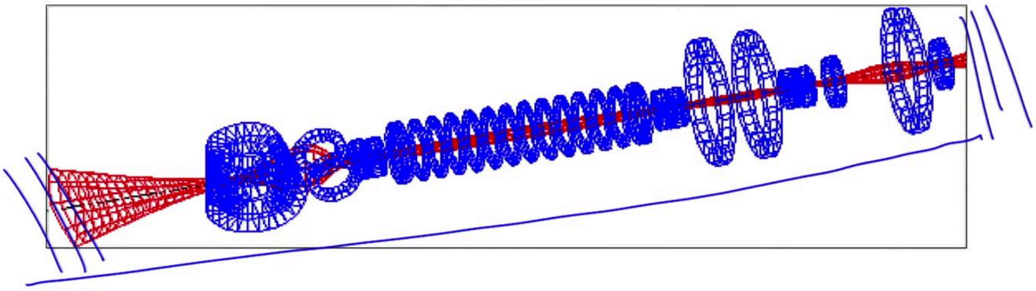

As illustrated in this little movie, this approach is based on a very simple principle that is, the charged particles that make up the plasma are subject to the electromagnetic forces in particular to the magnetic force that holds them to the magnetic field lines in their gyromotion around them. Without field of course, the particles will hit the wall of our reactor immediately and get lost, and the plasma will disappear. With the field, they will be contained in the volume for enough time.

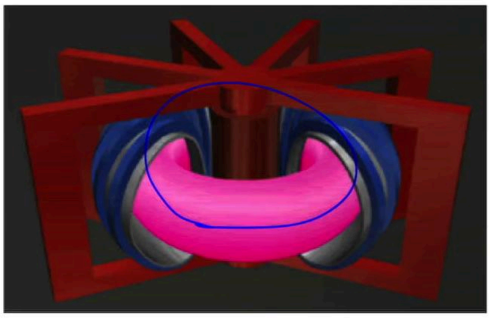
Notes

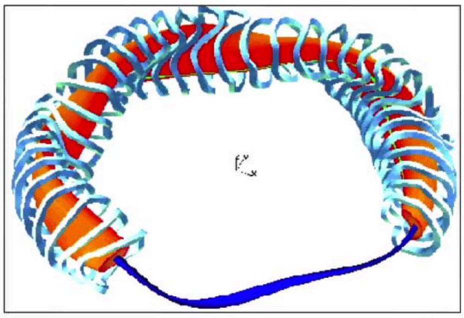
Summary

23m 05s

# Magnetic confinement – linear and toroidal devices







Plasma

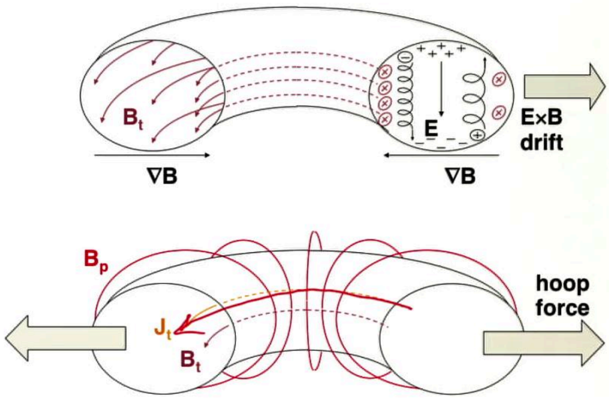
The idea of magnetic confinement was declined since the early times into different kinds of schemes. First of all, came the linear devices, in which the plasma was confined around magnetic fields lines producing linear configurations, but of course, in this situation, you would have a problem with the two ends of the device itself. So, early enough of course came also the idea of having a plasma made into a toroidal configuration. This toroidal configuration can take different forms and different details in its concept. We'll look at a very simple approach next.

Notes

Summary

23m 38s

# Magnetic confinement – concept of toroidal devices




Idea: avoid charge separation by imposing poloidal field, so that particles sample regions with opposite drifts

- Tokamak: poloidal field is produced by plasma current →hoop force

Plasma

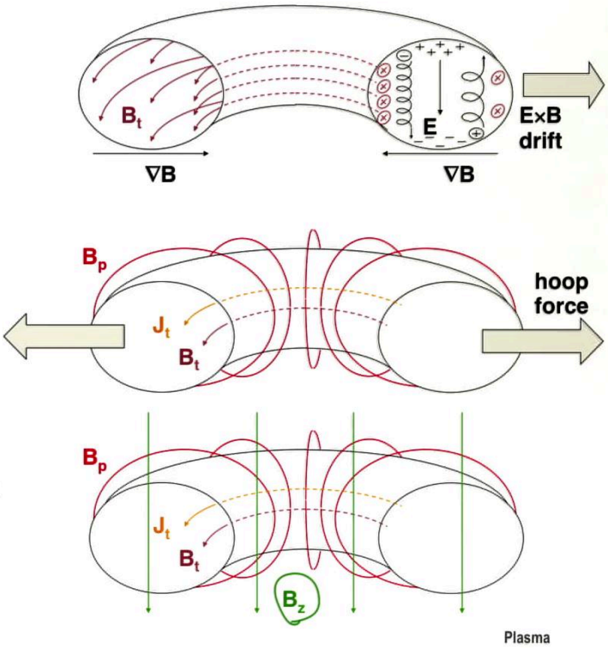
So let's take a simple toroidal field. SImple toroidal field implies, if we close a toroidal machine, implies that there is a certain curvature of the field lines and there is also a certain gradient of the intensity of the field. These two things lead to drifts as you have learned in the first part of the course, that separate positive and negative charges. In this example, we have the positive charges on the top, and the negative charges at the bottom. When you separate charges, you create an electric field, *E*, and that will act, together with the ambient magnetic field which is toroidal in this case. It (E) will combine with that (B) to create an (E x B) drift that will take all the plasma out irrespective of the charges of the particles that compose it. So, very, very soon, we will lose the plasma to the outside in a purely toroidal device. (i.e. in a device with a purely toroidal B) The idea therefore is to avoid charge separation by imposing a poloidal field, so that the particles can sample in their motion regions with opposite drifts and on average have no net drift. In the case of a tokamak configuration, the poloidal field is produced by a plasma current, which is this, Jt.

Notes

Summary

24m 25s

# Magnetic confinement – concept of toroidal devices




Avoid hoop force by adding a vertical magnetic field

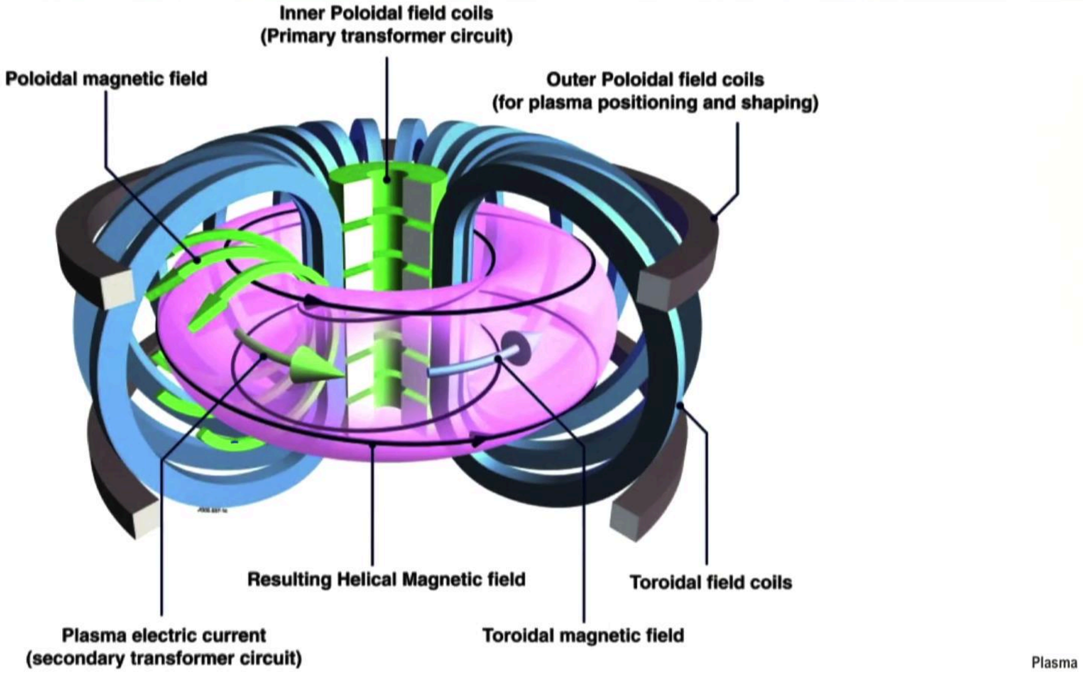
However, another relatively minor problem arises this plasma current going around toroidally, is subject to the so-called hoop force which tends to move the current filaments that is the plasma itself all the way outside on both sides, and all the sides in fact. How to avoid the hoop force? To avoid the hood force or to counter balance it, we add a vertical field, indicated here as Bz in green, and with the presence of Bz, this hoop force can be actually counterbalanced completely.

Notes

Summary

25m 45s

# Magnetic confinement – the tokamak



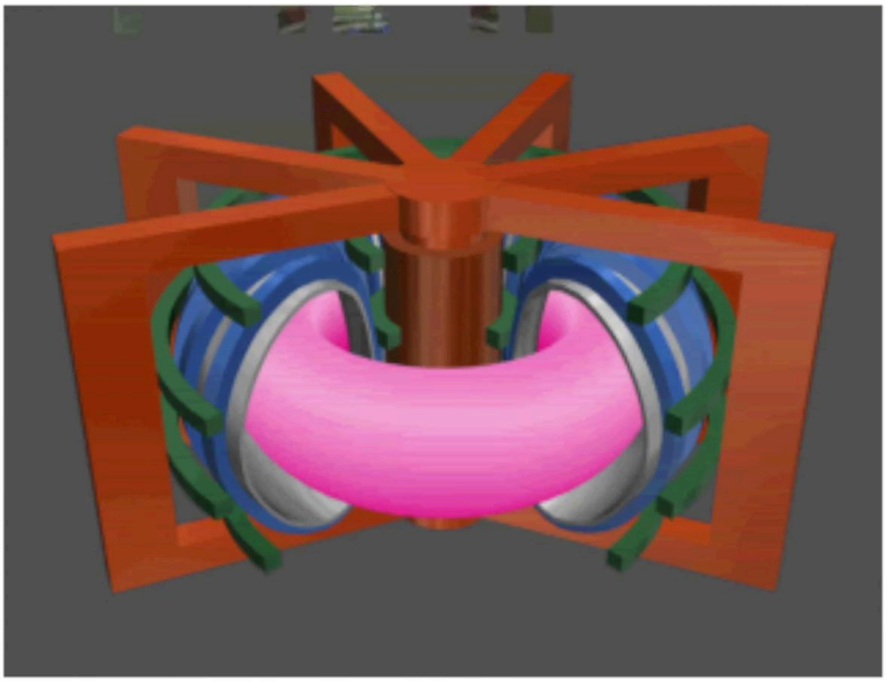

Here we summarize the different elements of this tokomak concept. We have the toroidal field coils in blue. They generate a toroidal magnetic field, we have a plasma current here in green, which generates a poloidal magnetic field. Therefore the sum of the two will give a helical magnetic field around, so that particles will experience inward and outward drifts, and on average experience in fact no net drift and be confined. And in addition we have so-called outer poloidal field coils that produce the vertical field to counteract the hoop force and also can produce field for plasma positioning and shaping. The one thing we still need to clarify is how to drive the current in the plasma. Well, that's the idea of the tokamak, -- one of the ideas of the tokamak-- that is to use a transformer in which the plasma acts as a secondary circuit, the primary circuit being a coil that's inside the core of the tokamak. If we swing the flux in this coil by changing the current in the coils, we can induce by Faraday's Law, a current in the plasma which again in turn will produce the poloidal field that we need.

Notes

Summary

26m 19s

# Magnetic confinement – particle orbits in tokamak



Plasma

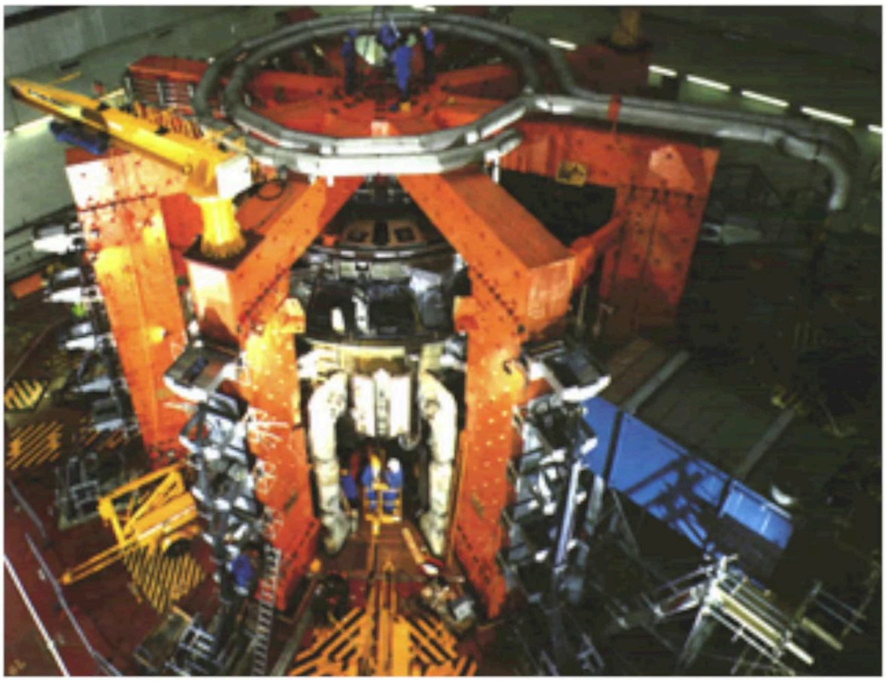
And this little movie summarizes what we have just said. Here are the set of toroidal field coils producing a toroidal field. [The] poloidal field is produced by the plasma current, created by transformer action, and the helical field then traps particles as illustrated by having them go around the torus in-out, in-out. An additional set of coils will produce the vertical field to counteract the hoop force and to shape the plasma.

Notes

Summary

27m 46s

# Magnetic confinement – particle orbits in tokamak



Plasma

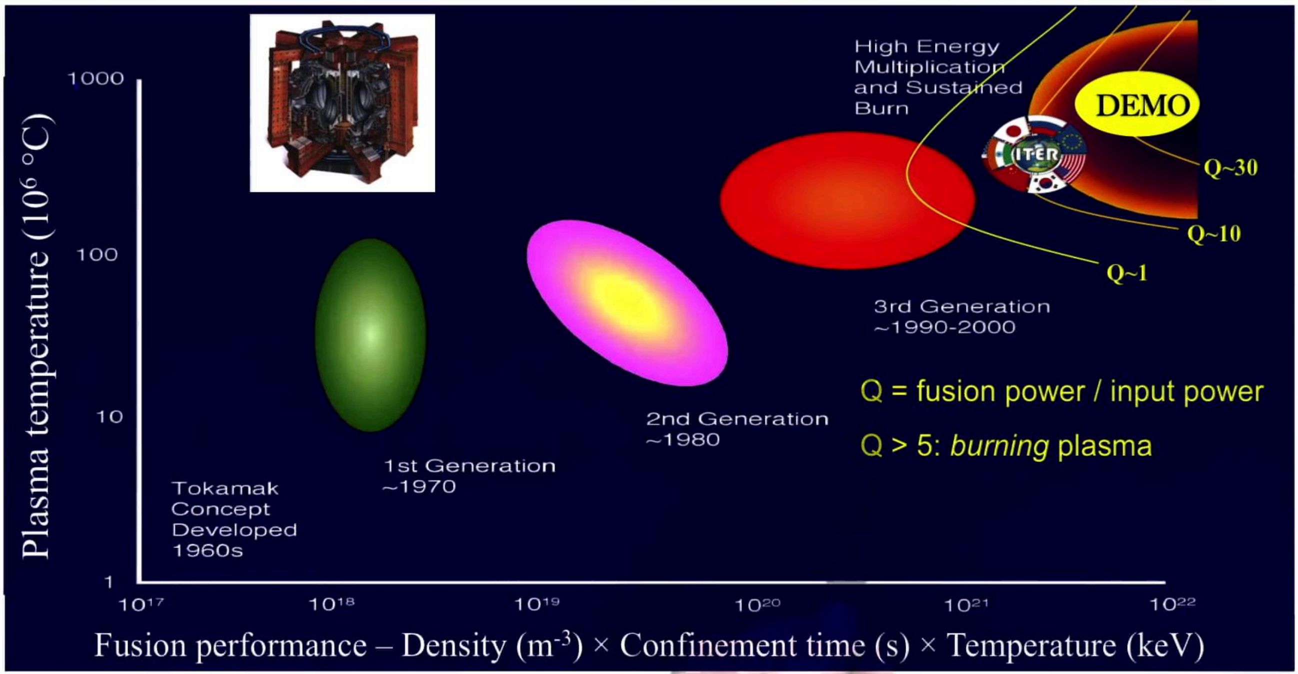
The picture which we end this movie is that of the largest tokamak existing so far, that is the JET Tokamak in Europe, in England, close to Oxford.

Notes

Summary

28m 18s

# Progress in magnetic confinement fusion




Plasma

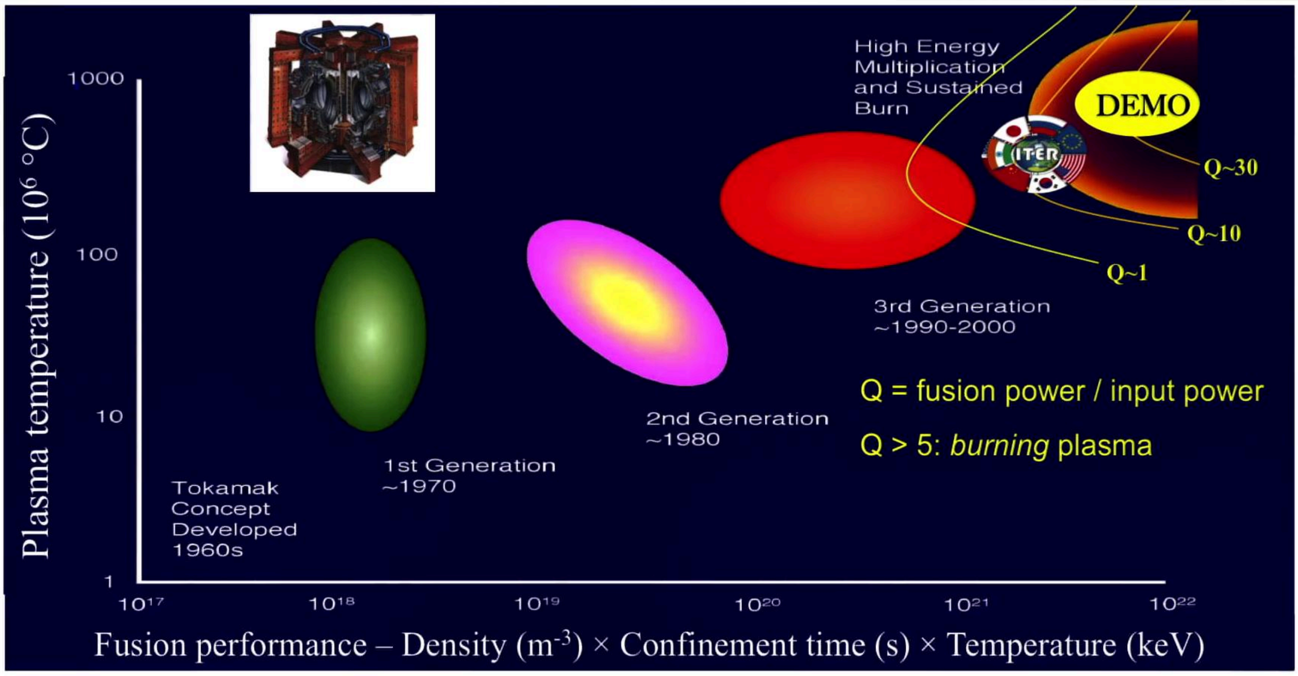
The progress in magnetic confinement fusion using the tokamak concept primarily has been fantastic. If you look at this progress in terms of the temperature achieved for the plasma, here illustrated on the vertical axis, as a function of what I call here the *Fusion Performance* which is the product of the density times confinement time our famous n τe, times the temperature, we see that the different generations have really made significant jumps into this graph. The tokamak concept was developed in the 60s, very soon in the 70s, we reached temperatures of the order of 50 or even 100 millions of degrees, so temperatures that were already taking us in the fusion conditions for that part. What was still to be done, - and somewhat is still to be done-, is to obtain those temperatures at very large values of confinement times and densities. The second generation in the 80s made a significant jump, not so much in temperatures, but again in intensity and confinement time. And the third generation, which we achieved almost breakeven, typically in two machines: an American machine, TFTR, and in the European machines JET which we have just seen, and a richer picture is actually reproduced on this graph.

Notes

Summary

28m 28s

# Progress in magnetic confinement fusion




Plasma

This breakeven conditions were approached by having very significant increase in confinement time. What we still need to do is to make the jump from Q slightly lower than 1, where Q is the fusion gain, again fusion power divided by input power, into the regime of a burning plasma with Q larger than 5. And that's what we intend to do with the ITER project which aims at obtaining about 10 for Q and of course for the reactor values of capital Q that are in a range of 30 to 40.

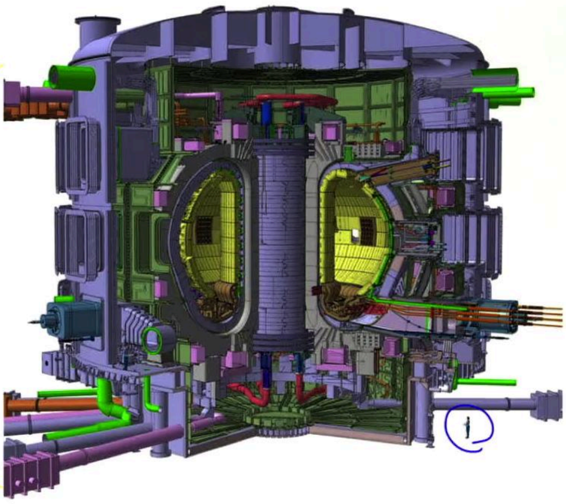
Notes

Summary

29m 57s

# ITER – the first burning plasma

- Demonstration of scientific / technological feasibility, and safety of fusion energy
- Q ≥10; Fusion power ≥ 500MW; ~500s

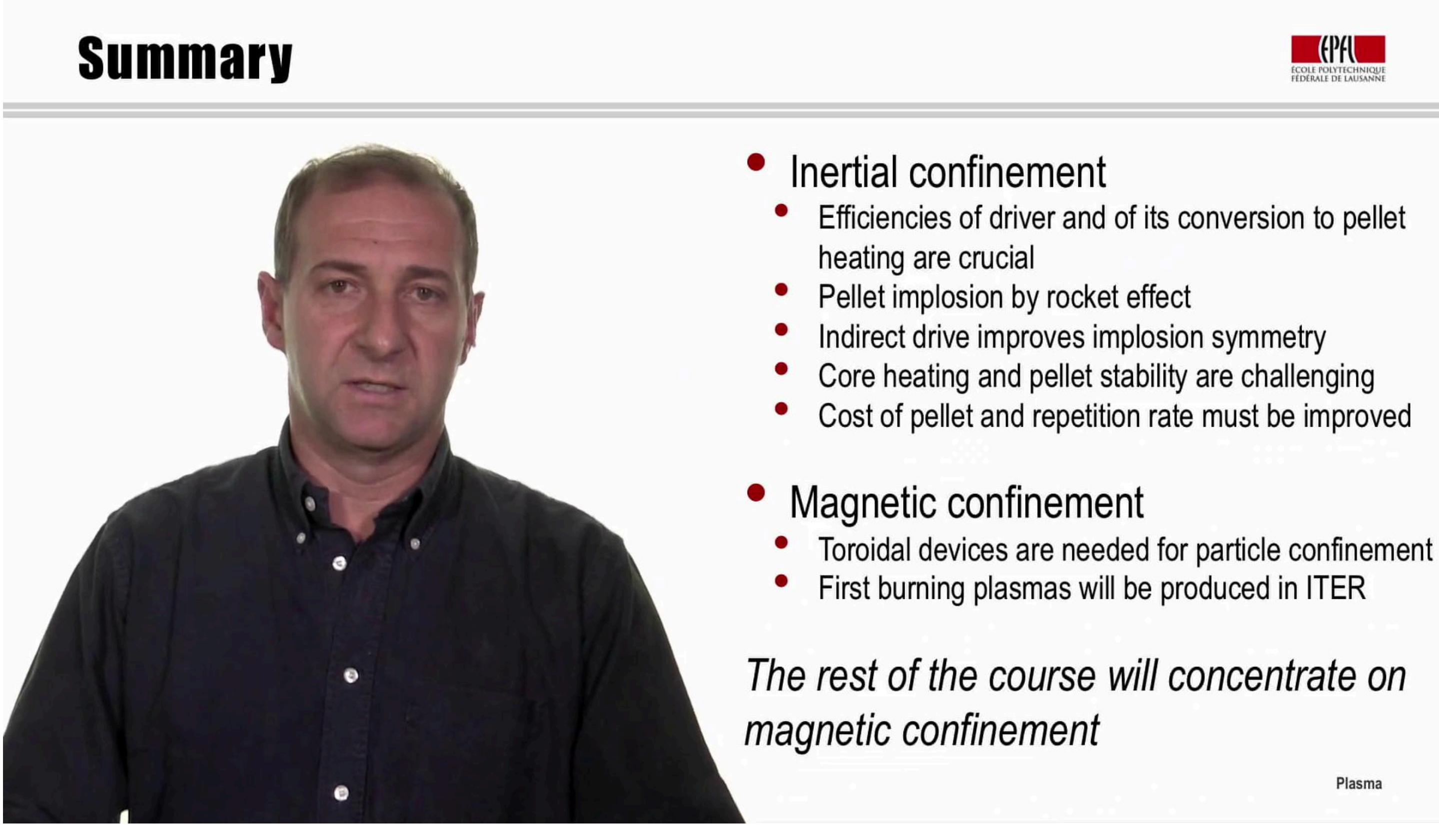



Let's say a few words about ITER which will be the first burning plasma. You see here the construction site for ITER, which is located in the south of France, Cadarache. ITER is the result of a very large international collaboration involving several partners representing about 80% of the world population. You see here the pit in which the tokamak will be constructed and you see on the right the layout of the tokamak itself, with all the systems we have discussed today and of course much more ancillaries to make the system work overall. You'll also notice the size of the plant as compared to the typical size of a human person here. ITER will be aiming at providing a fusion gain, capital Q of 10 or more, a fusion power of about half a gigawatt for a duration of several hundreds of seconds. It will therefore be the first demonstration of the scientific and technological feasibility of fusion and of its safety.

Notes

Summary

30m 32s

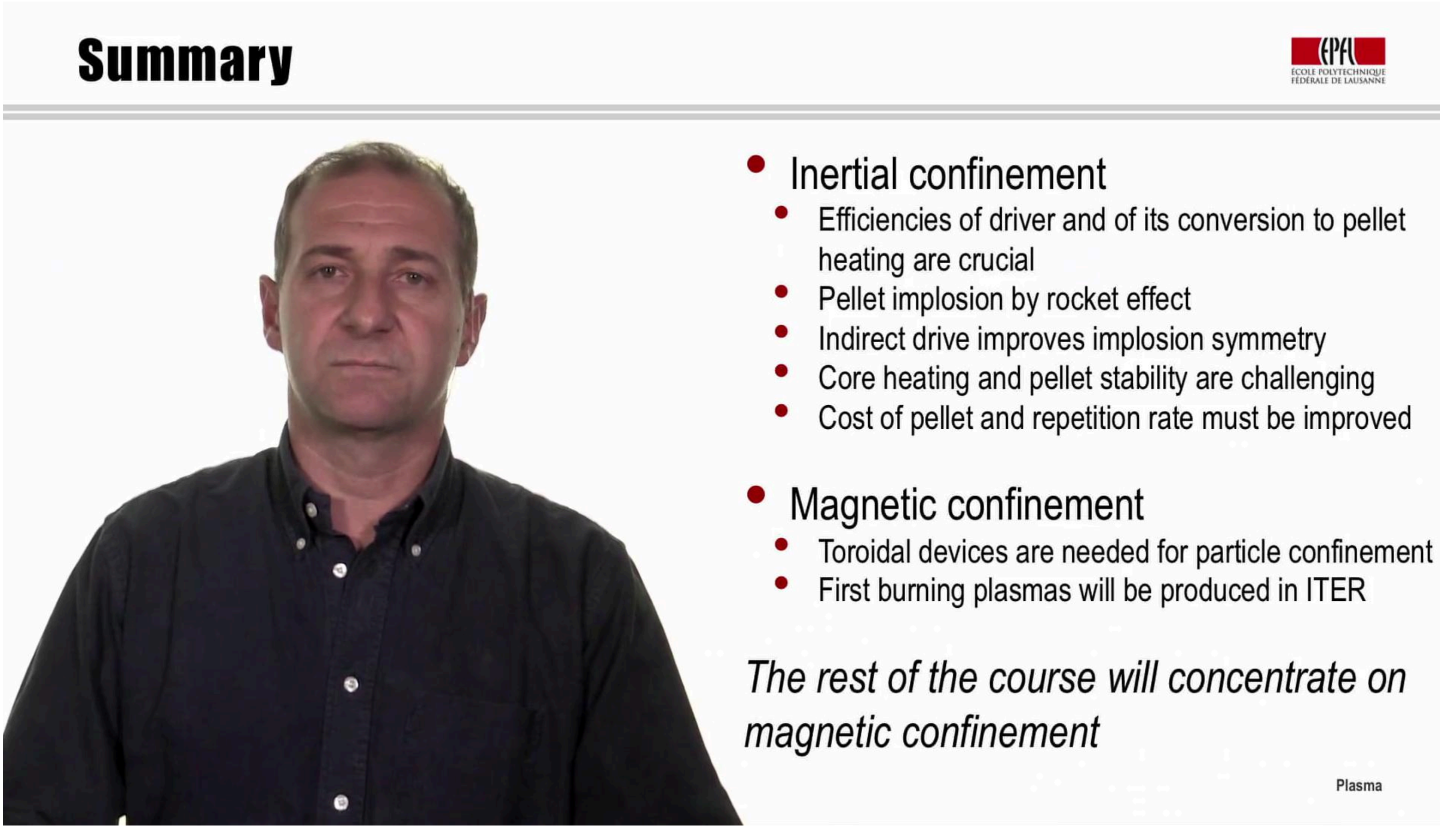



We can now summarize the lecture. We have seen today that we have two approaches on earth to reach the conditions that are necessary for a fusion reactor to work: inertial and magnetic. For inertial confinement, we have seen that the efficiency of the driver and of its conversion to pellet energy, and heating are crucial. The implosion of the pellet can be helped by the rocket effect. We have seen that the indirect drive can help, improving the symmetry of the implosion. We have also noticed that there are challenges on the physics side and on the engineering side. On the physics side, the heating of the core and the stability of the pellet are the most important ones. On the engineering side, we need to really address the issue of the cost of the pellet and of the repetition rate of the pulses. We have introduced the concept of magnetic confinement based on magnetic fields to hold the plasma together in a cleverly designed cage. We have seen that toroidal devices are needed for this cage to be efficient, and we have mentioned and briefly introduced the ITER project which will be the one to provide us with burning plasmas, and therefore the one that will demonstrate that fusion is feasible both scientifically and technologically, and that it is safe.

Notes

Summary

31m 42s




In terms of magnetic confinement, we did not go into much depth because we will concentrate on it in several lectures in the rest of this course.

Notes

Summary

33m 01s