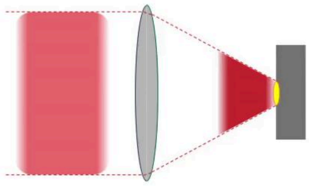
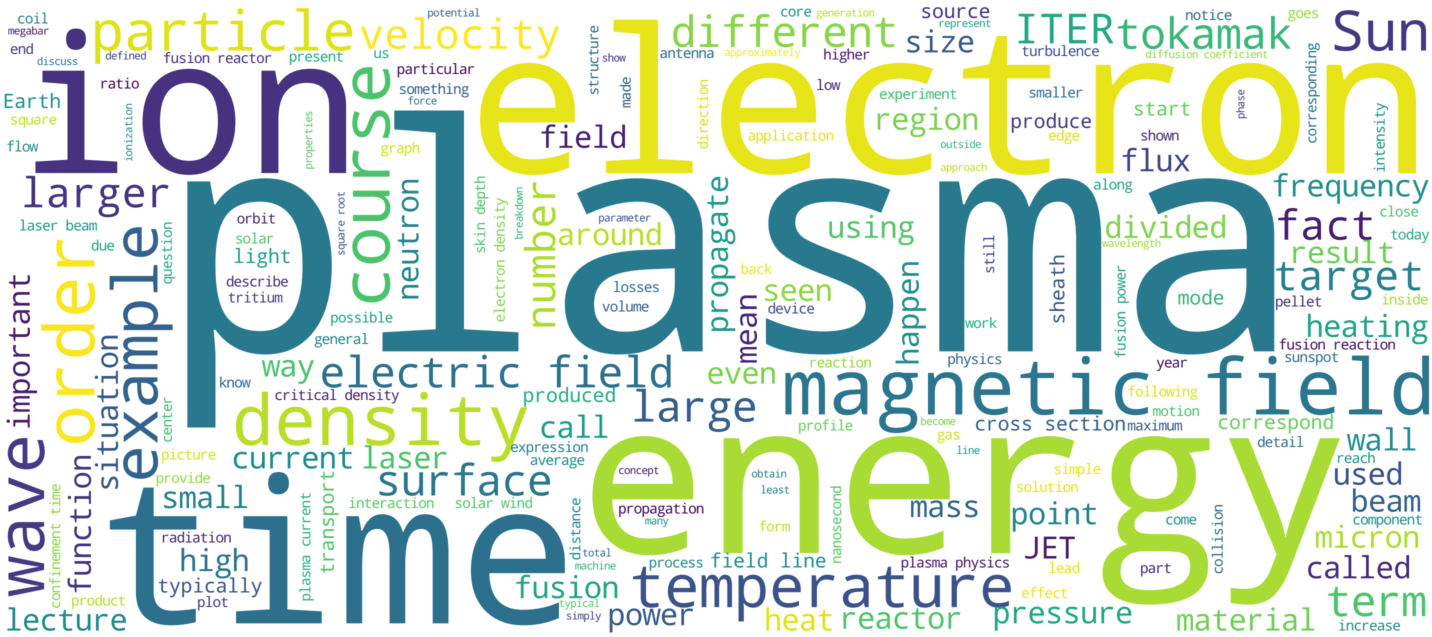


A general picture of laser-target interaction

Plasma Physics and Application to Fusion Energy, Astrophysics and Industry

Lecture

François Amiranoff



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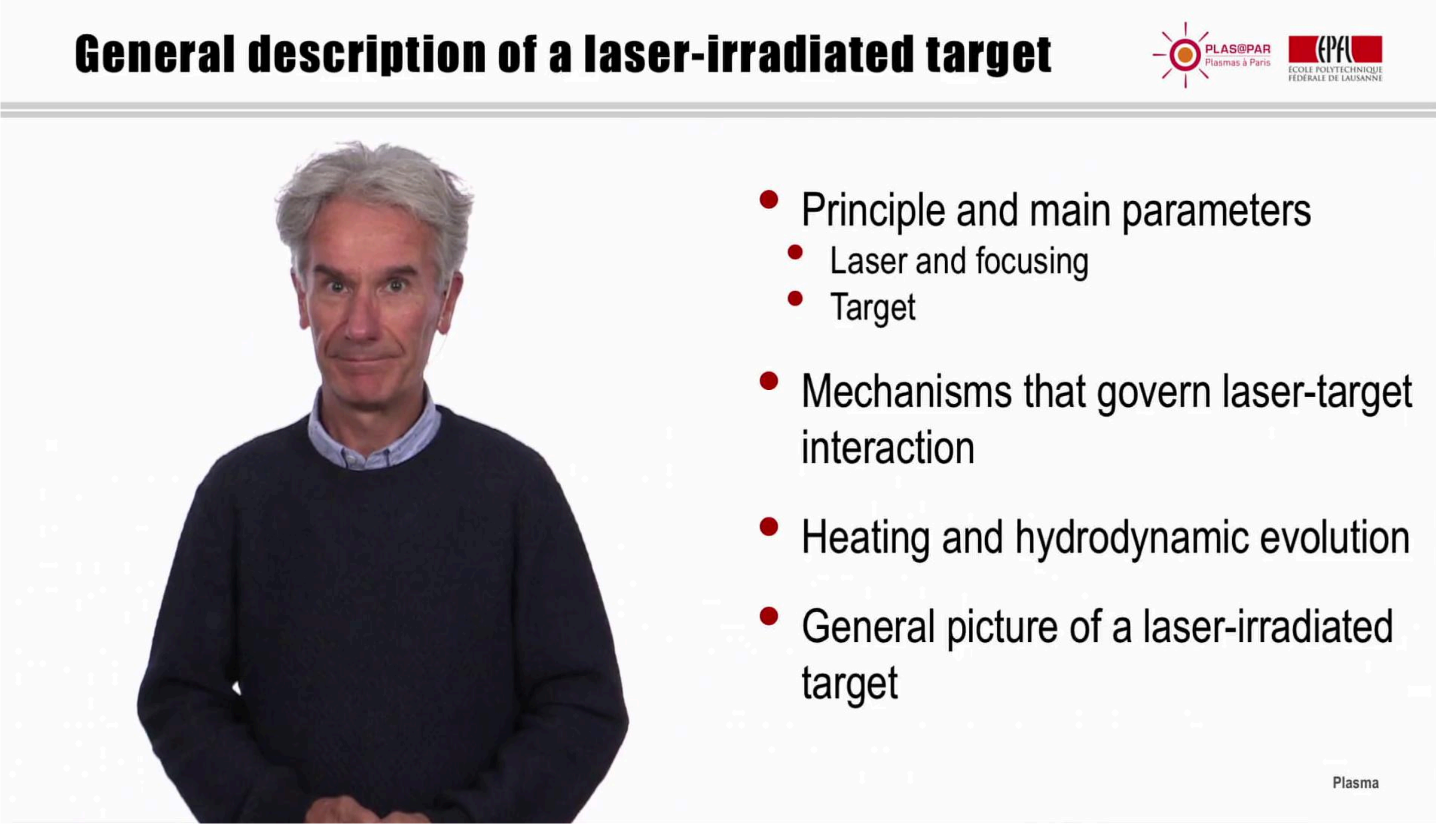
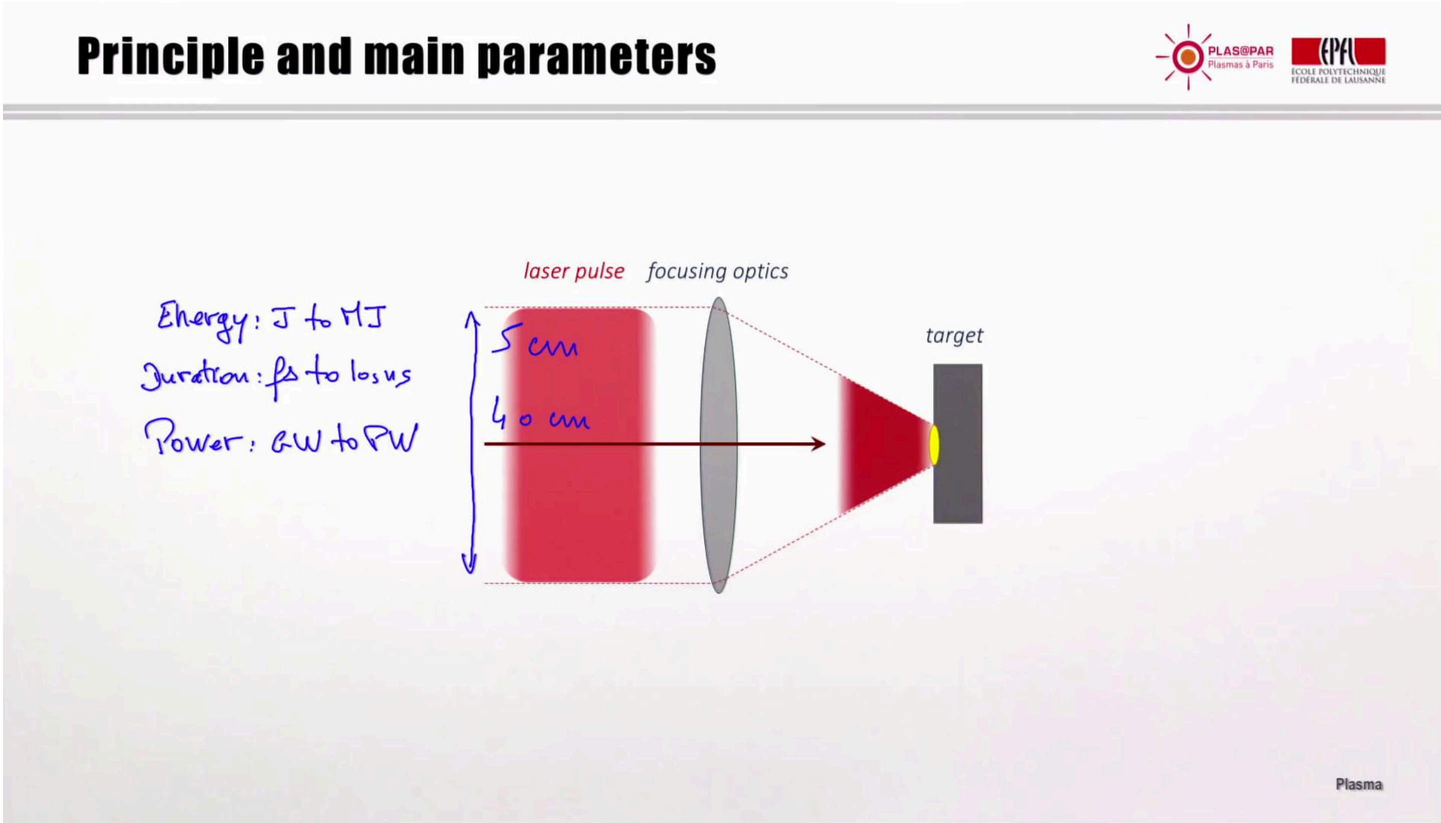


Welcome. In this first lecture, I'm going to give you a general picture of laser-target interaction, and I will describe the evolution of a laser-irradiated solid target. After showing the general scheme and the relevant parameters, I will progressively describe the main mechanisms that govern the heating and the hydrodynamic evolution of the plasma. I will then end that with a general picture of a laser-irradiated target.

Notes

Summary

0m 05s

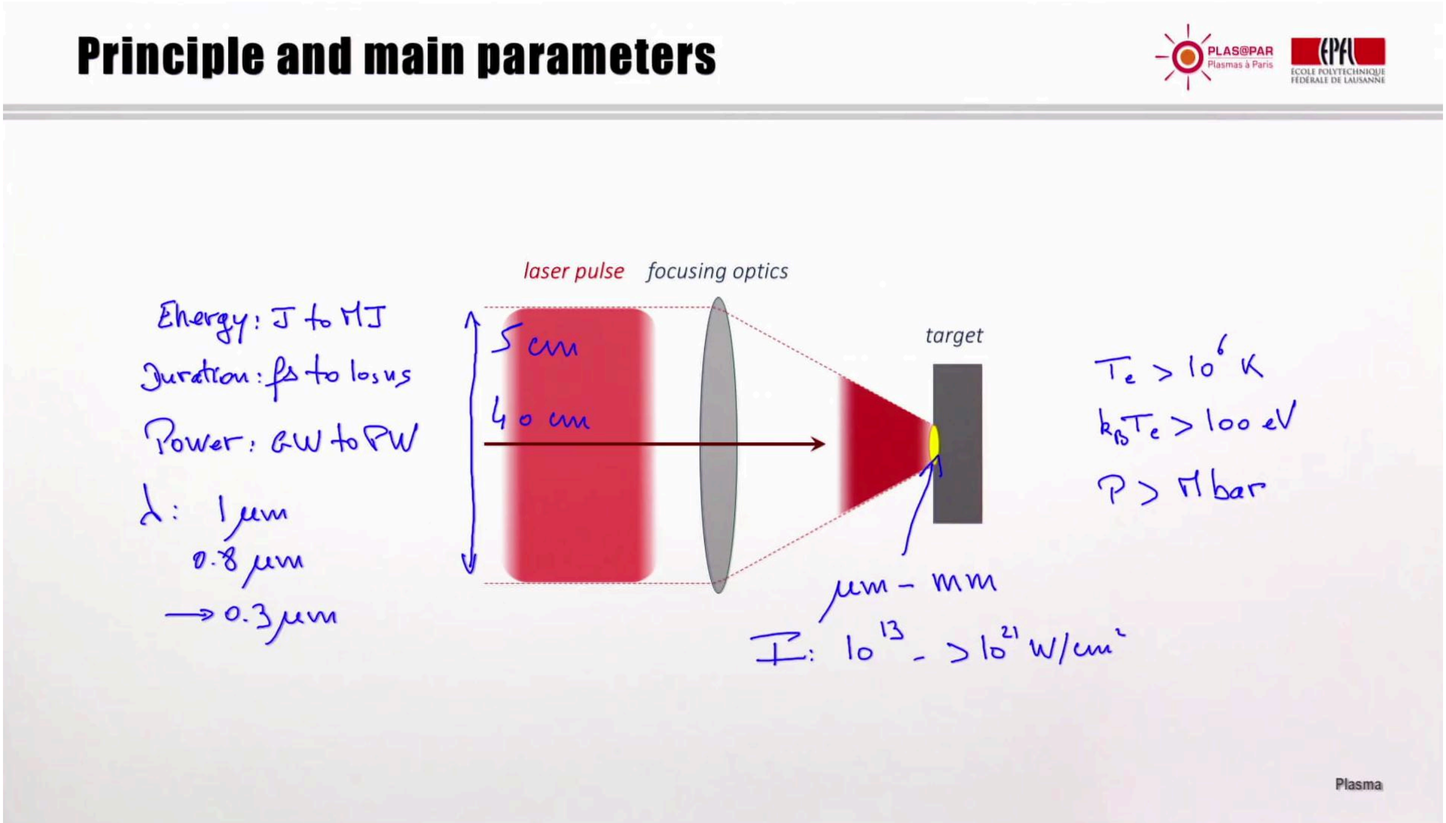


The principle of an experiment is shown on this graph. A laser pulse is focused onto a target where it produces and heats the plasma. For the high-power laser pulses, we are going to concentrate on, the main parameters are the energy per pulse and the pulse duration from which we get the laser power and the laser wavelength. The energy per pulse ranges from typically joules, to a maximum of a little bit more than one megajoule. Pulse durations go from femtoseconds to a few tenths of nanoseconds If the energy per pulse is not so large in itself because it's only of the order of what you need to prepare coffee or an Italian pasta. The power of this beam is really gigantic. It starts at gigawatt level and reaches a few petawatts. And petawatts are really a huge power. Its order of magnitude is larger than the total electrical power produced on Earth, which is only a few terawatts. The size of an individual beam ranges from a few centimeters to 40 centimeters. Some of these lasers fit onto a single table, while megajoule lasers consisting in more than 100 beams 40 centimeters inside are as large as the Eiffel Tower.

Notes

Summary

0m 34s

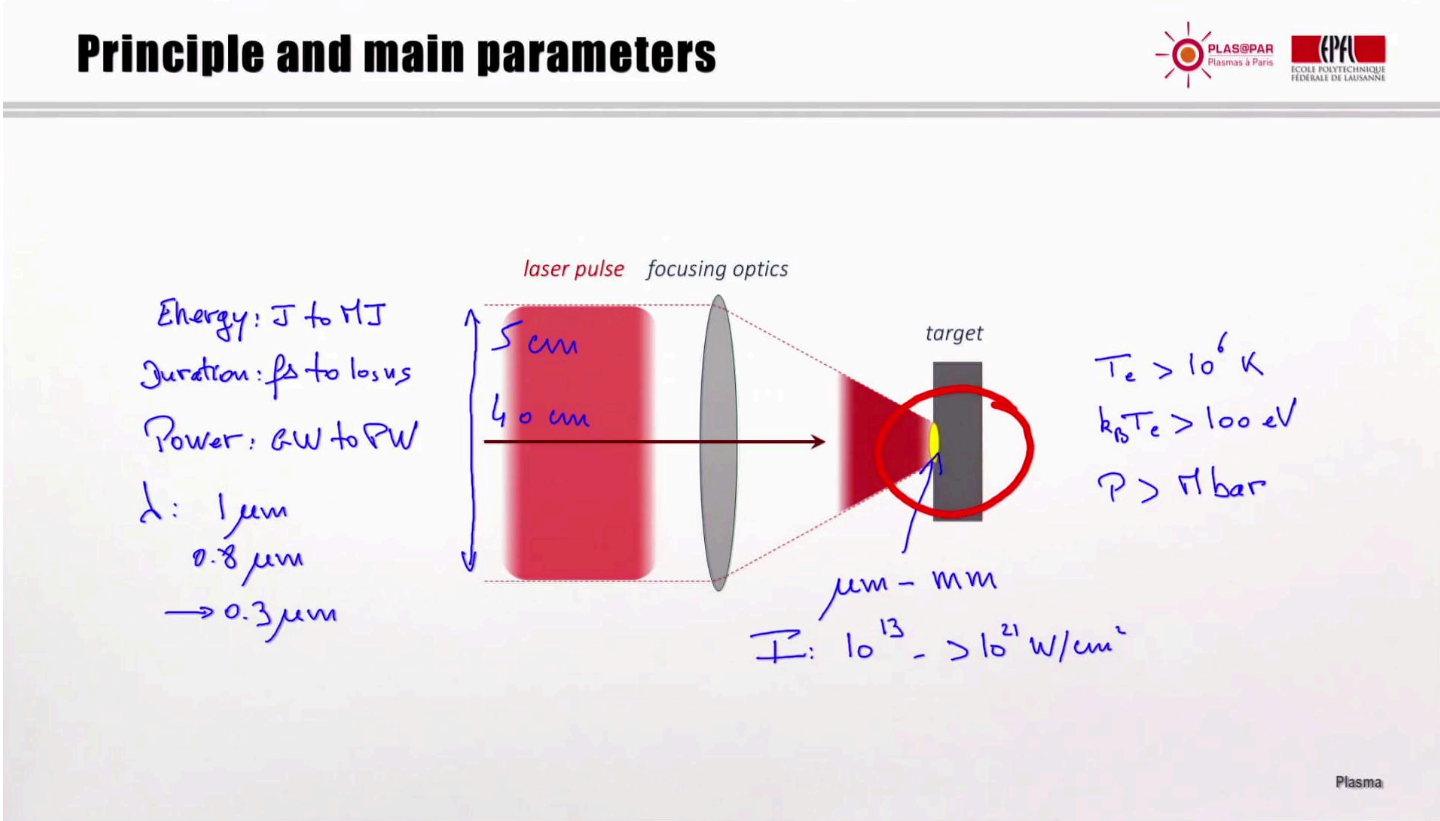


For these high-energy beams, the initial wavelength is close to one micron for neodymium glass lasers, or 0.8 microns for titanium-sapphire lasers. Neodymium glass lasers are most often frequency-doubled or frequency-tripled, leading to wavelengths down to 0.3 microns. If most of the beams can be focused by transmission optics, like on this graph, the most powerful ones have to be focused by mirrors instead. The quality of the beams and of the optics is such that the size of the focal spot can be as small as a few microns. Whereas some applications require millimeter-sized focal spots. The energy flux on target most generally called intensity is today in the range of 10 to 13, to more than 10 to 21 watts per square centimeter. Its intensities are so high that the produced plasma heat reaches temperatures as large as millions of kelvin, corresponding to an energy larger than 100 electronvolts, while the pressure itself reaches values larger than 1 million times the atmospheric pressure that is one megabar. These parameters show that with high-power lasers, one can reproduce conditions that exist in the interior of planets or in stars.

Notes

Summary

2m 26s

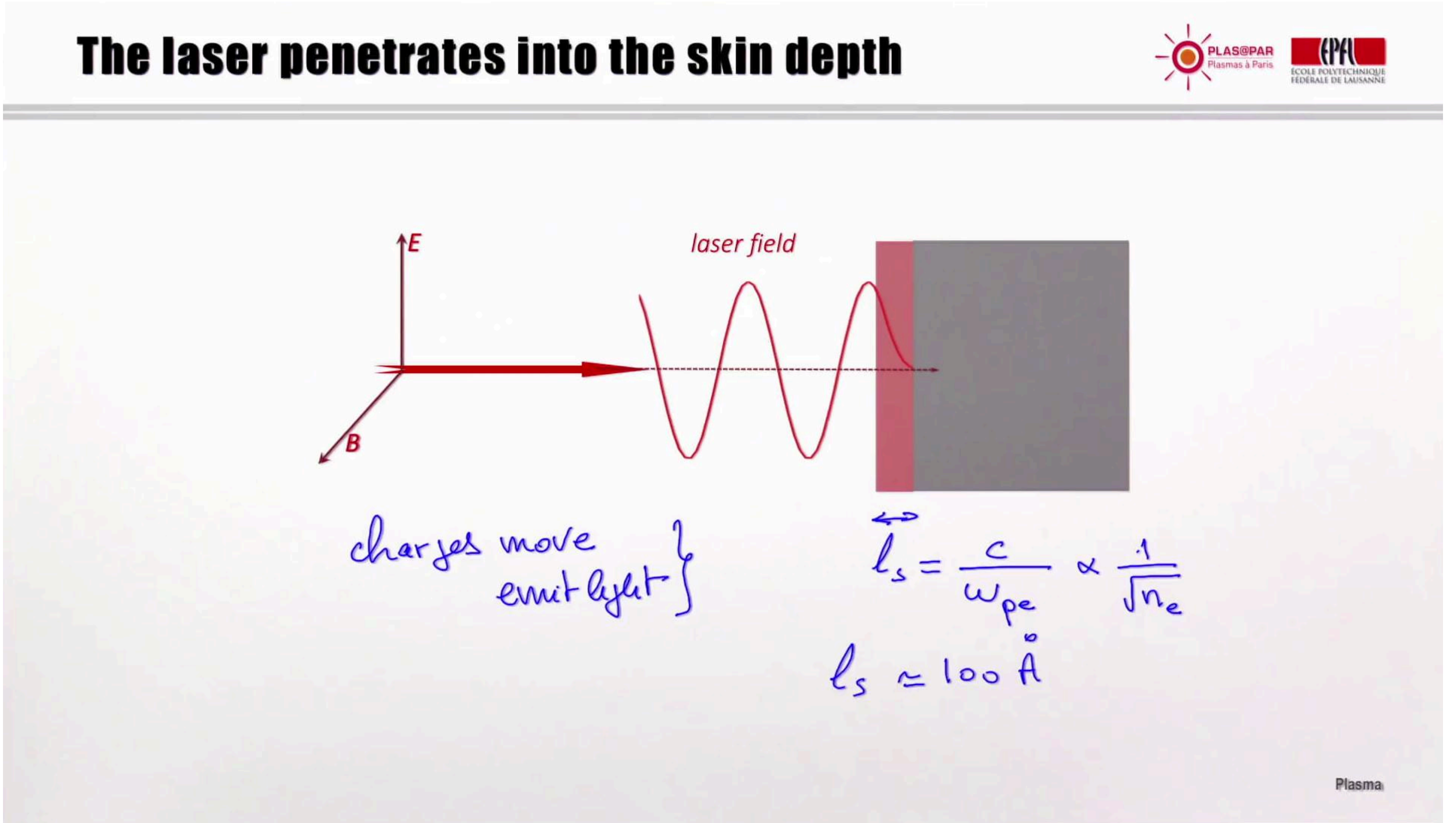


In the following, we will restrict the intensities of about 10 to 13 to 10 to 16 watts per square centimeter that are used, for instance, for initial confinement fusion experiments. We will now describe in more detail the region of interaction between the laser pulse and the target.

Notes

Summary

4m 35s



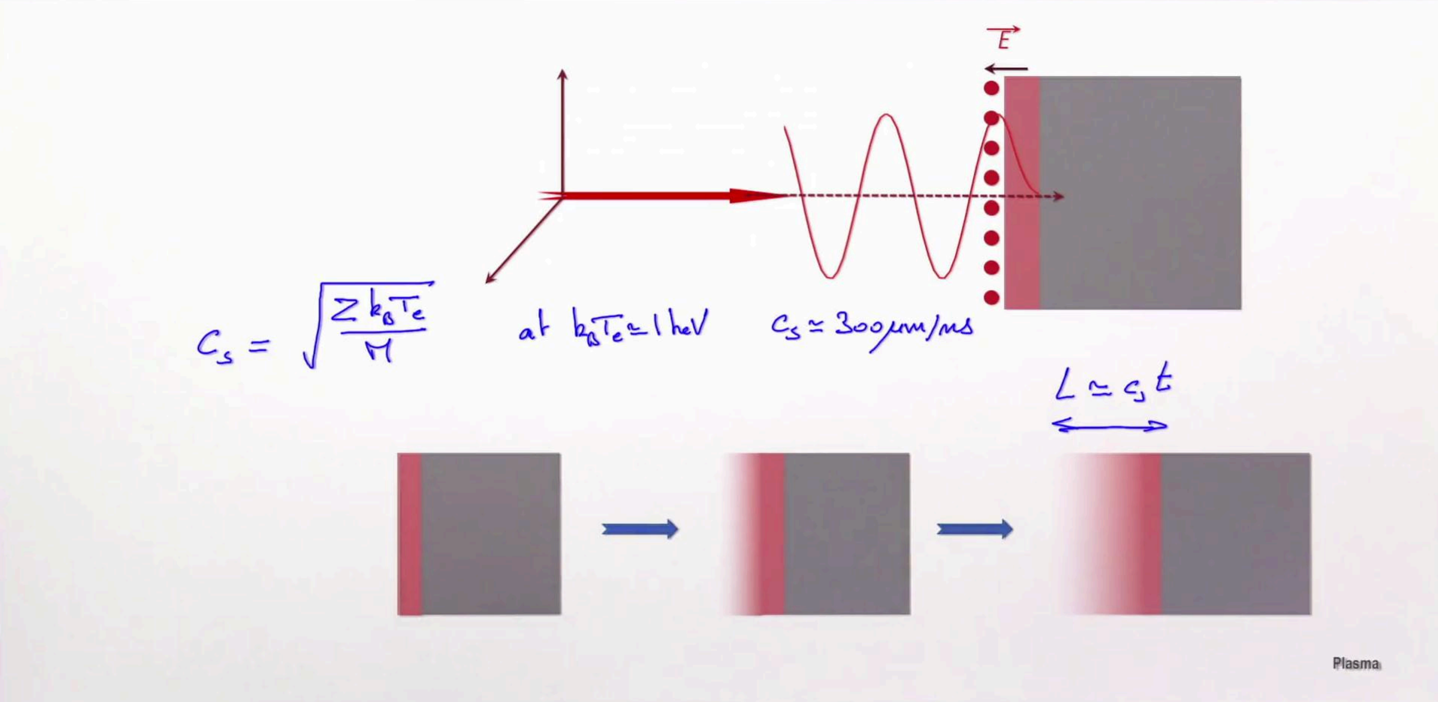
When the laser beam reaches the surface, its electric field induces motion of electrical charges inside the target. As these charges move, they emit light that adds to the incoming light. This then determines what happens to the laser beam itself. For low densities of available moving charges, a light can go through the target that is then transparent. For high enough densities, such as in metals, light is reflected and the laser film can only penetrate into the skin depth. The size of the skin depths here is given by the speed of light divided by the electron plus mass frequency, which is itself proportional to the square root of the electron density. In metals or hot and dense plasmas, the skin depth is of the order of 100 angstroms. At low intensities, nothing more happens and the target is not significantly modified. At larger intensities, however, the penetrating part of the laser electric field and the associated charge motion induce an important heating in this region and additional ionization of the plasma. You have to know that the laser mainly heats the electrons while the ions remain initially cold.

Notes

Summary

5m 00s

Ionized and heated matter expands into vacuum



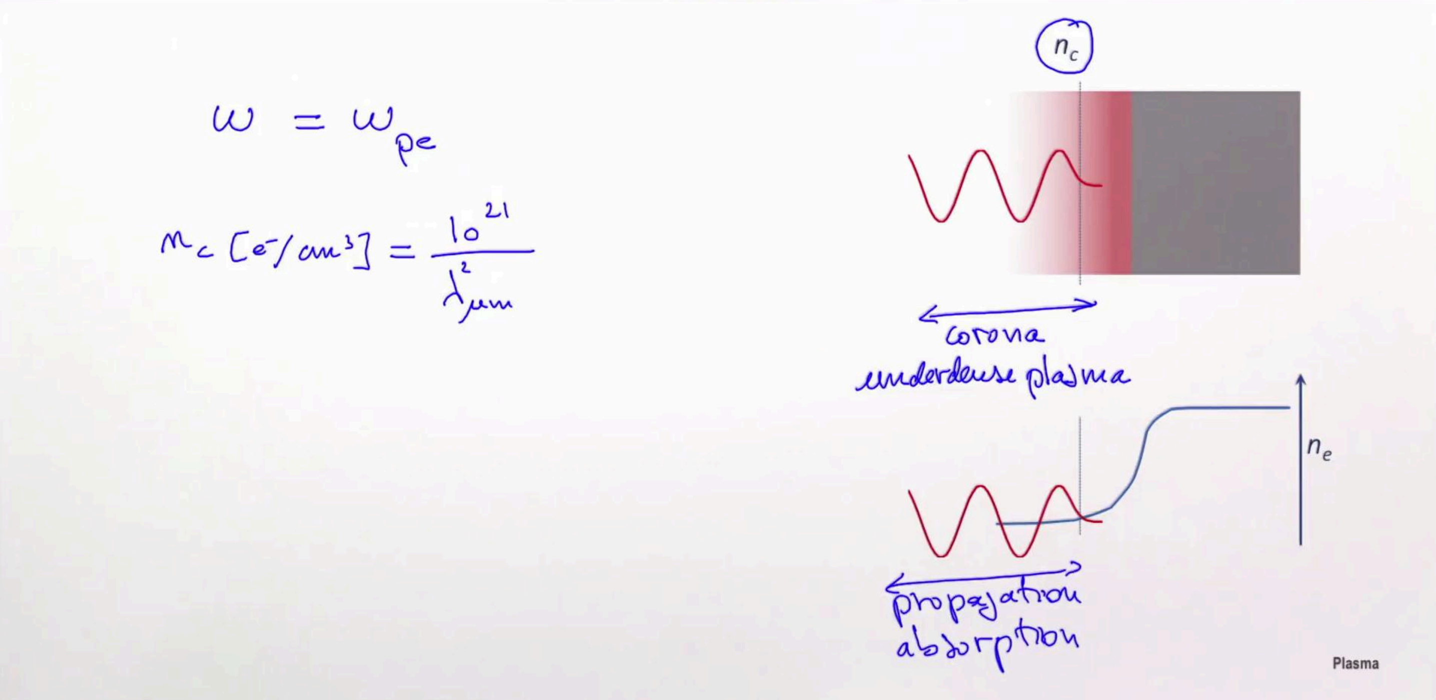
Due to the thermal motion, the electrons close to the surface try to escape from the target here. But by doing so, they produce an important charge separation between electrons and ions, and a large associated electric field. This field both stops the electrons here and drags the ions outwards. The front of the target that expands at a velocity close to the ion-acoustic velocity. This velocity is given by Cs equals the square root of Z, times the thermal energy of the electrons, divided by the mass of the ions. At the temperature of the order of one kiloelectronvolt, this velocity is close to 300 microns per nanosecond. The laser beam now propagates in a density profile going from zero to the solid density.

Notes

Summary

6m 50s

The laser beam propagates up to critical density

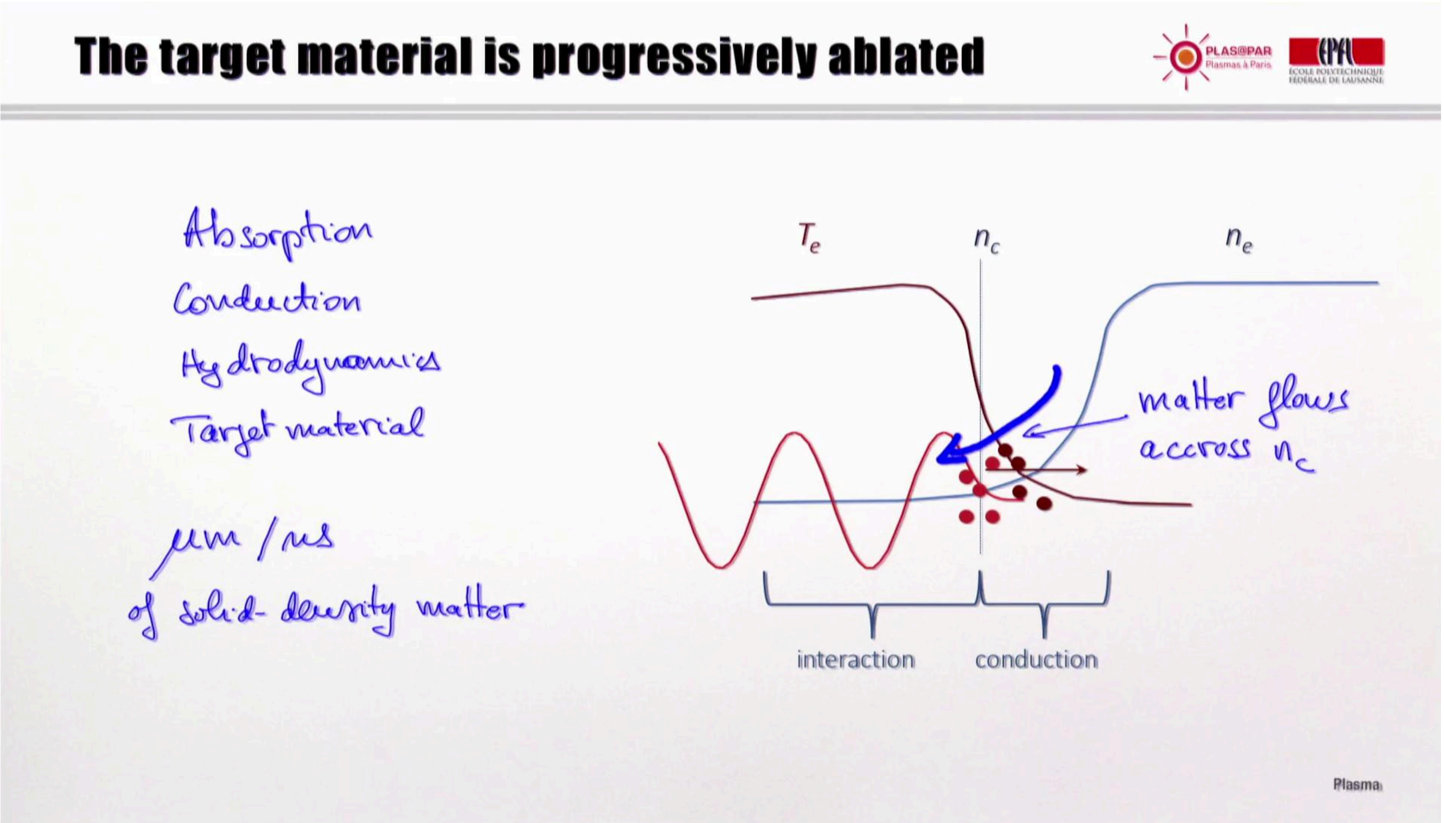


You have seen already, and we will see in the next lecture that an electromagnetic wave cannot propagate in plasmas where the electron density is larger than the so-called critical density, which is defined as the density for which the laser position is equal to the local electron plus mass frequency. In practical units, this critical density is given by critical density in electrons per cubic centimeters equal to 10 to 21, divided by the square of the wavelengths in microns. So for visible and infrared light, this density is much smaller than the electron density in the solid, which is typically of the order of 10 to 23 electrons per cubic centimeter. The interaction between the laser beam and the plasma, including the absorption of the laser energy by the plasma, takes place in the corona that you can see here on this graph or on this picture where I have drawn the density as a function of space. This corona is also-called the underdense plasma. So all interaction mechanisms between the laser and the plasma itself will take place in this region where you will have propagation and absorption.

Notes

Summary

8m 12s

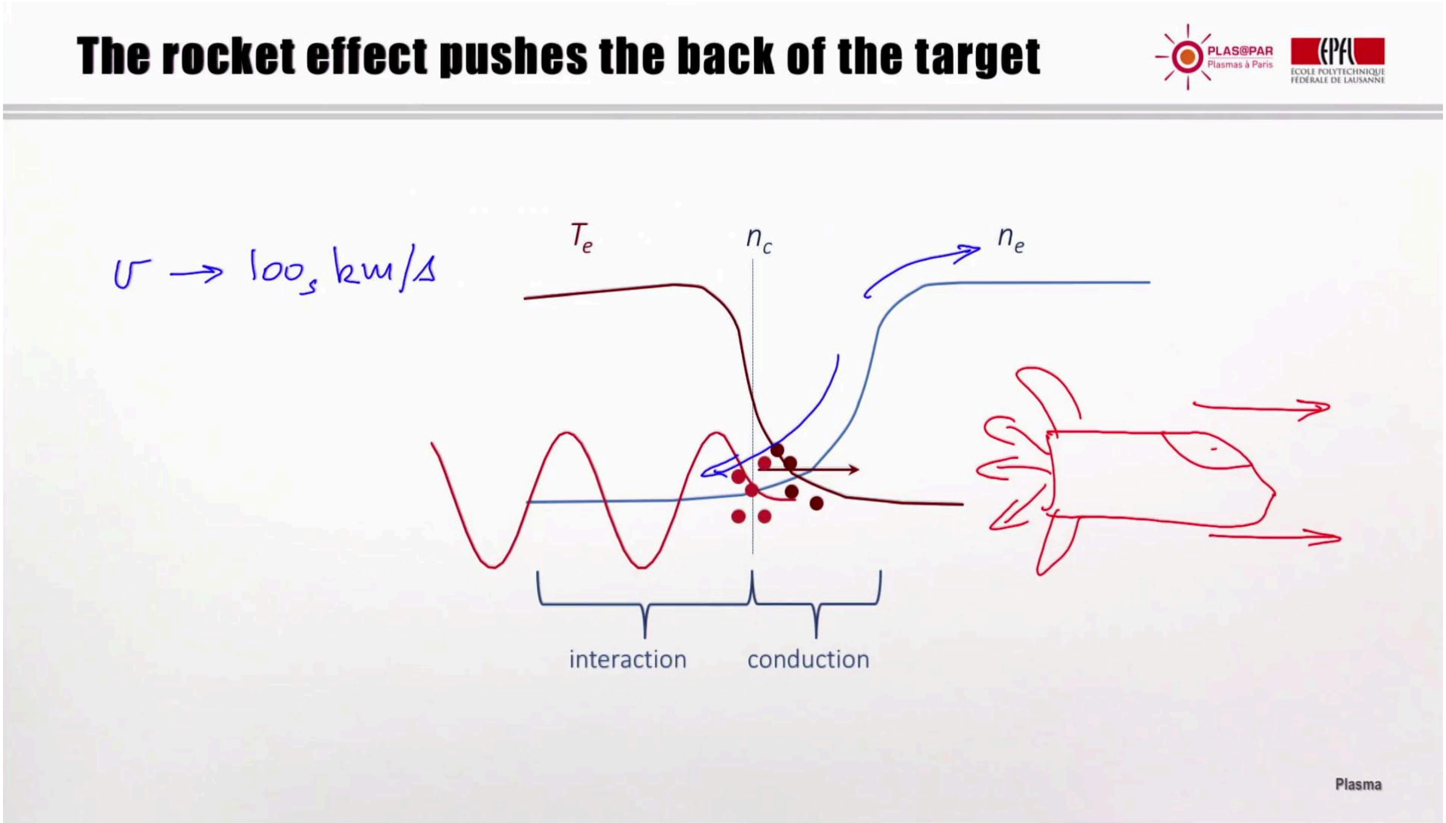


As we have seen, the absorption of the laser energy takes place far from the solid itself in the underdense corona up to the critical density. The over critical region is heated not directly by the laser beam but by conduction. This conduction is mainly due to thermal electrons but can also be influenced by so-called suprathermal electrons that have larger energy and are produced by specific absorption mechanisms. Conduction is also due to radiation of the hot plasma in the UV and x-ray range. Due to heating, the plasma expands toward vacuum and matter crosses the critical density. The target is then progressively ablated. Taking into account absorption, conduction of heat between the corona and the overdense region, hydrodynamics, and the properties of the target material, such as its density, the flow of ablated material is of the order of microns per nanosecond of solid density matter.

Notes

Summary

9m 53s

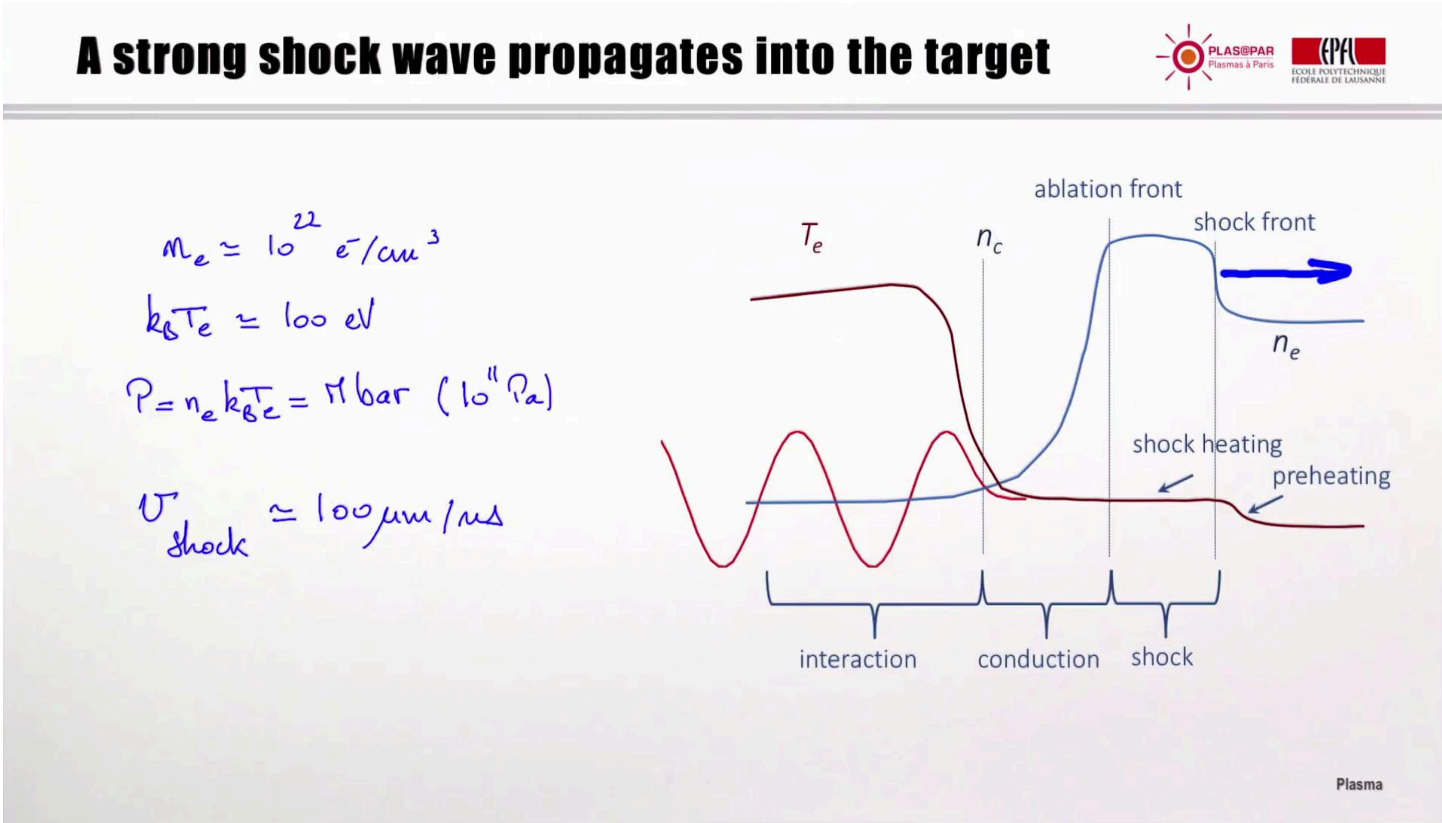


Due to plasma expansion and exactly in the same way as a rocket is accelerated by throwing matter behind the motors, the back of the target is accelerated forward. It might be accelerated to very, very high velocities, up to a few hundreds of kilometers per second. This is exactly the principle that is used to compress a D-T fuel to produce fusion reactions using high-power lasers as has been explained in a preceding lecture.

Notes

Summary

11m 33s

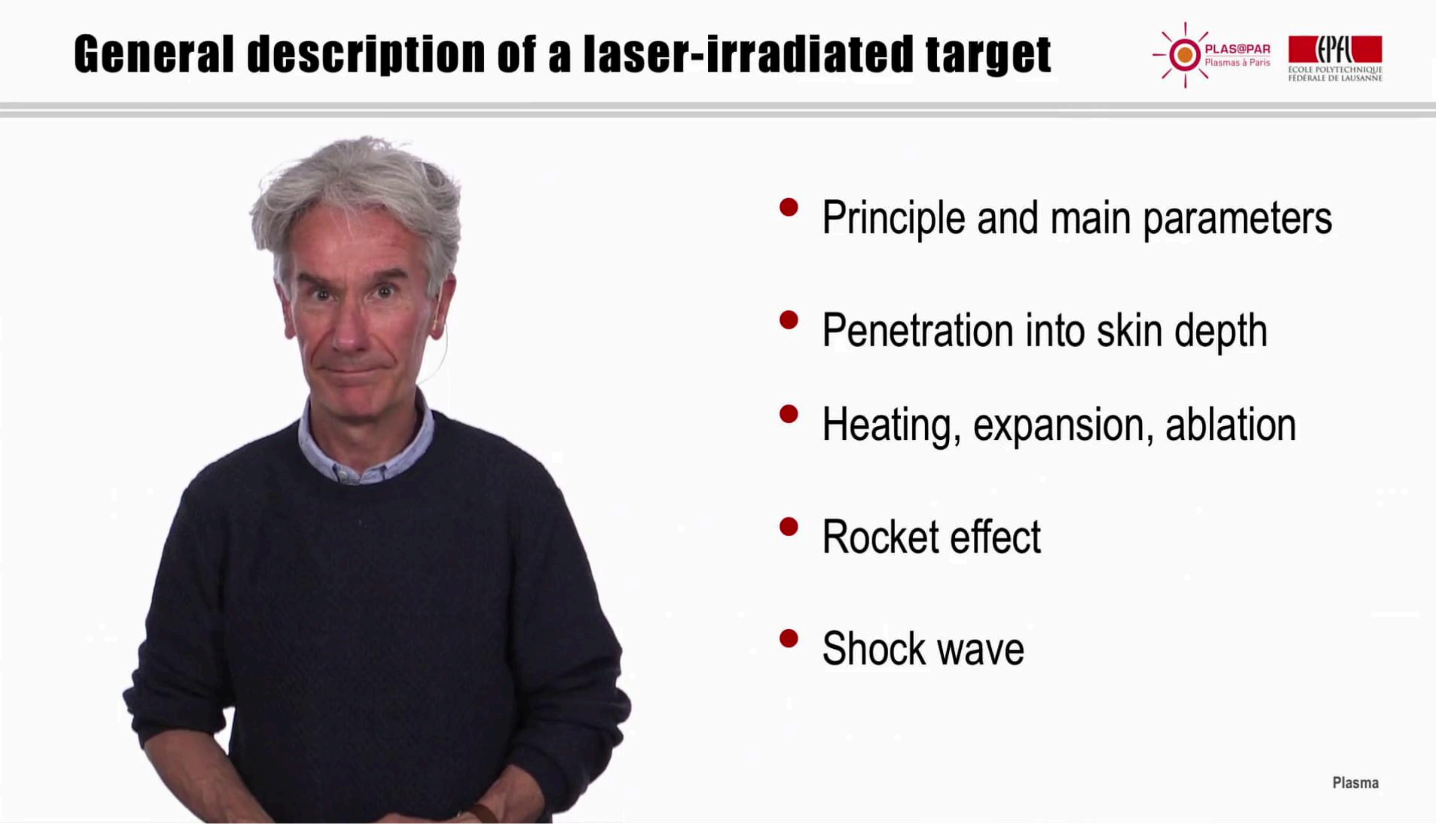


If we now look at pressures inside the plasma, we see that it is very large and can lead to the generation of shockwaves. Taking typical parameters in this region, for instance, with density of the order of 10 to 22 electrons per cubic centimeters, the temperature of the order of 100 electronvolts, we end up with a pressure which is a product of the density by the thermal energy of the order of one megabar that is about 10 to 11 pascals. This can be compared with the pressure in the center of the Earth, which is 3.5 megabar. And still, much higher pressures can be reached with lasers up to hundreds of megabars to gigabar. If maintained long enough, these high pressures generate a shock wave that propagates in the target material at velocities of the order of V shock, about 100 microns per nanosecond. In the shock region here, the compression factor in density may reach a factor four and the shock also heats the material up to few electron volts here in this region. That is a few times 10,000 degrees. It may be preceded by a preheated region, mainly by radiation, and this preheating can modify the target properties before the arrival of the shock.

Notes

Summary

12m 11s



In this lecture, we have described the different steps that occur during laser irradiation of solid targets. First, penetration into the skin depth, possibly preceded by ionization, then heating expansion of the plasma leading to ablation of the target. We have then presented the acceleration of matter by the rocket effect and the generation of strong shocks that propagate in the material. I hope that this lecture has shown you both the complexity of this field as well as its interest in terms of physics and applications.

Notes

Summary

14m 13s