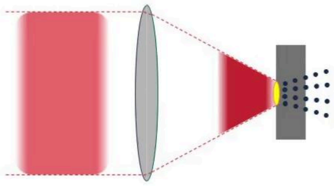
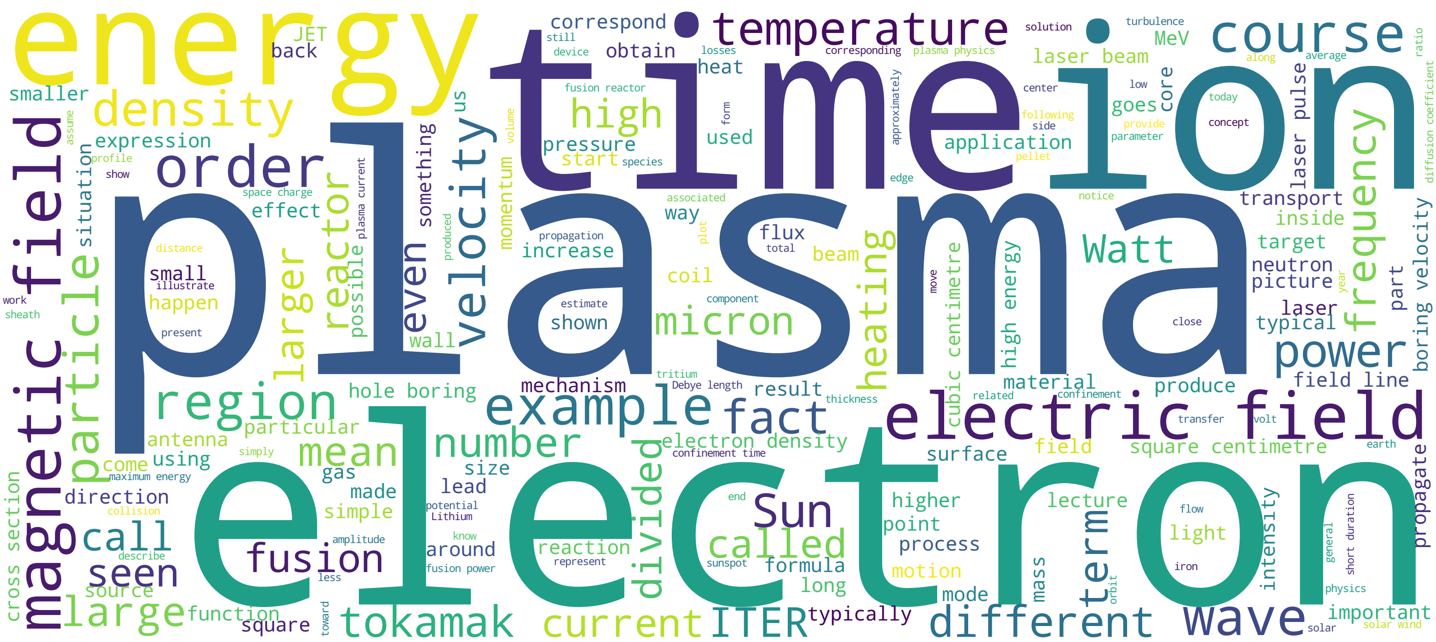


Ion acceleration with lasers and plasmas

Plasma Physics and Application to Fusion Energy, Astrophysics and Industry

Lecture

François Amiranoff



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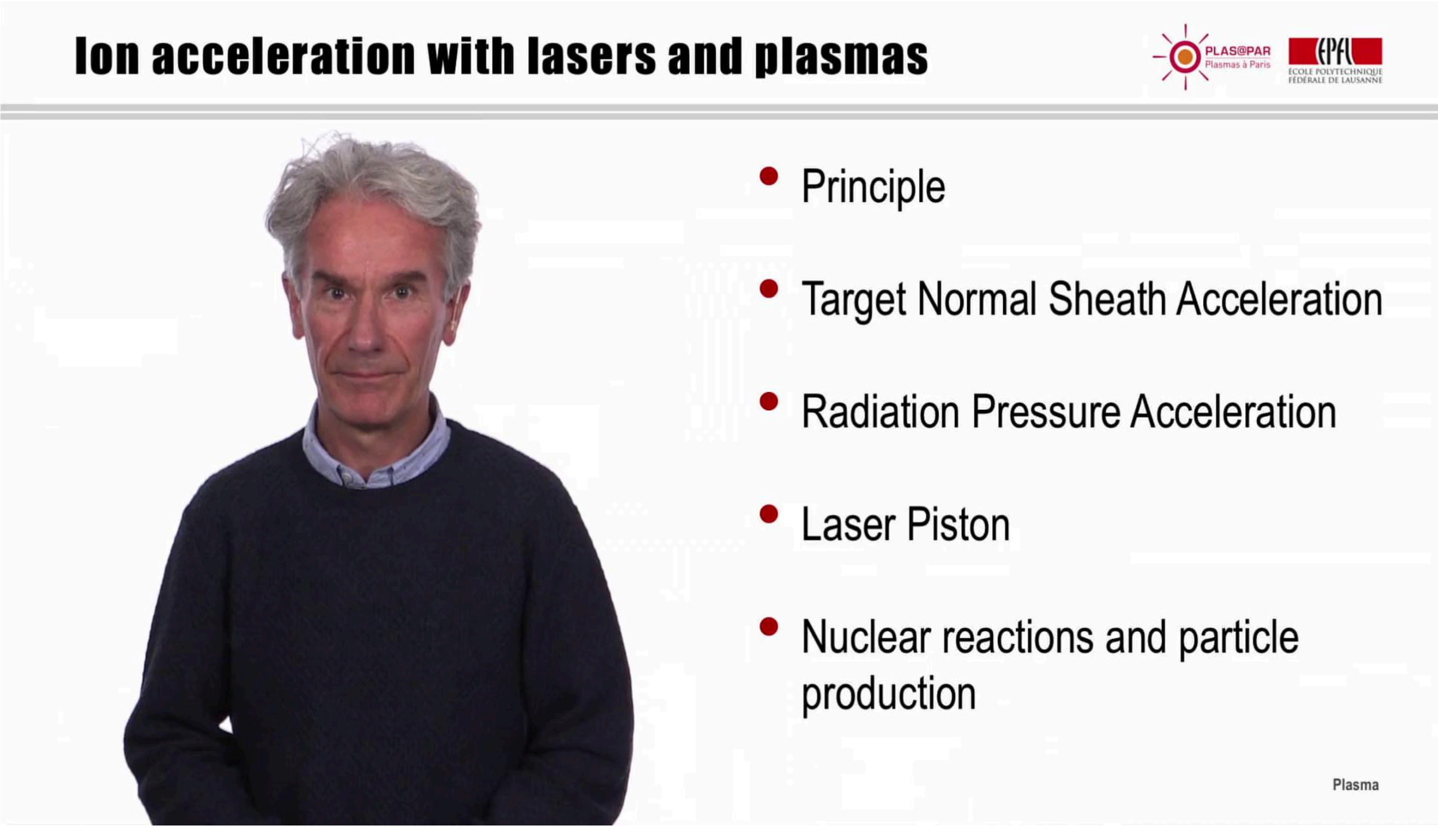
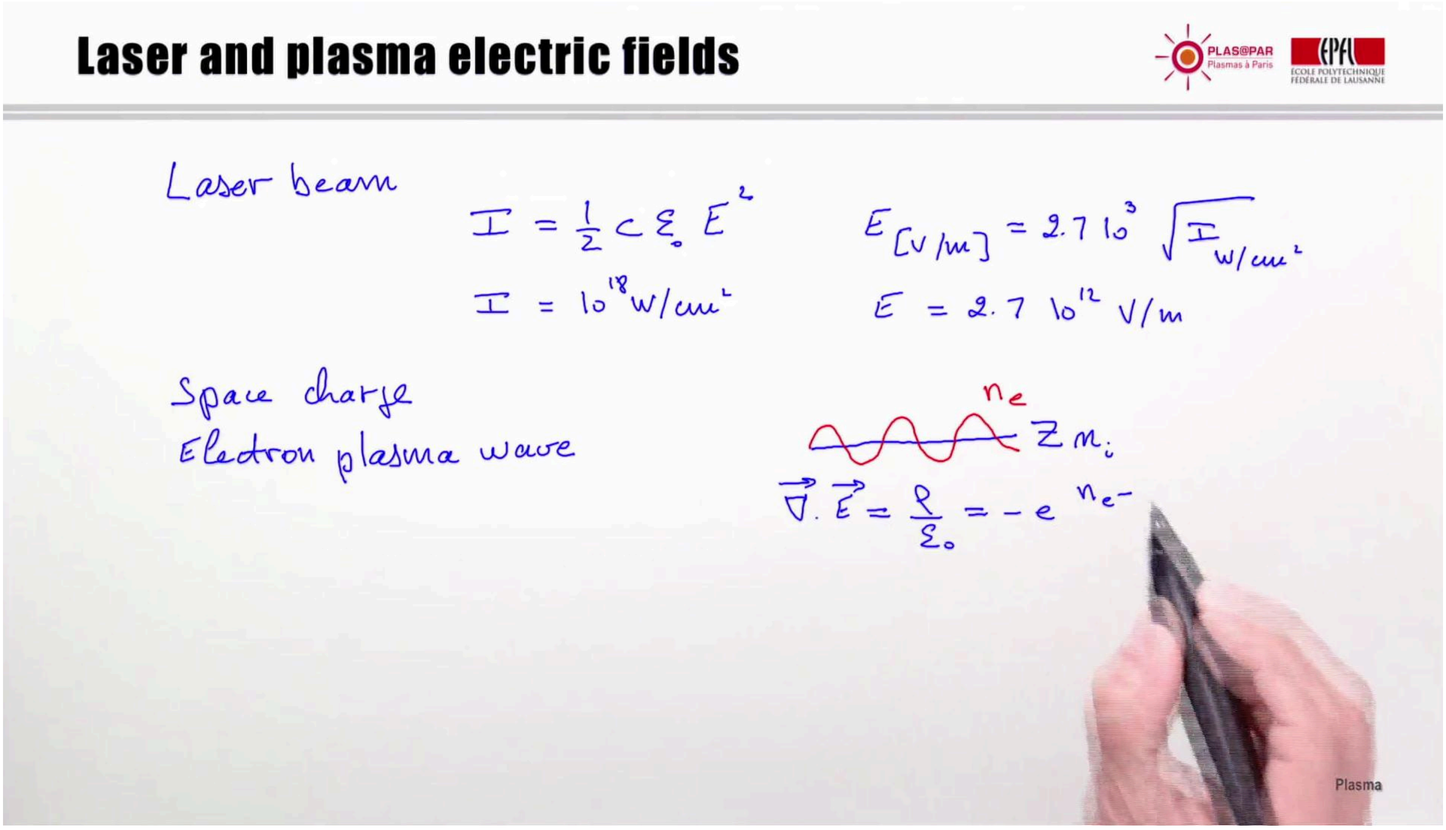


Welcome. In this lecture, I will show that the generation of plasmas by laser irradiation of matter at high intensities is associated with extreme electric fields, not only the transverse field on the laser beam itself, but also space charge fields in the plasma. These electric fields orders of magnitude larger than the fields produced by conventional techniques can accelerate particles of the plasma, electrons, or ions to very large energies over very short distances. As an example, I will describe three mechanisms of iron acceleration in a laser generated plasma, target normal sheath acceleration, radiation pressure acceleration, and acceleration by laser piston. I will then give an example of application of these iron beams to the production of secondary particle beams through nuclear reactions.

Notes

Summary

0m 05s

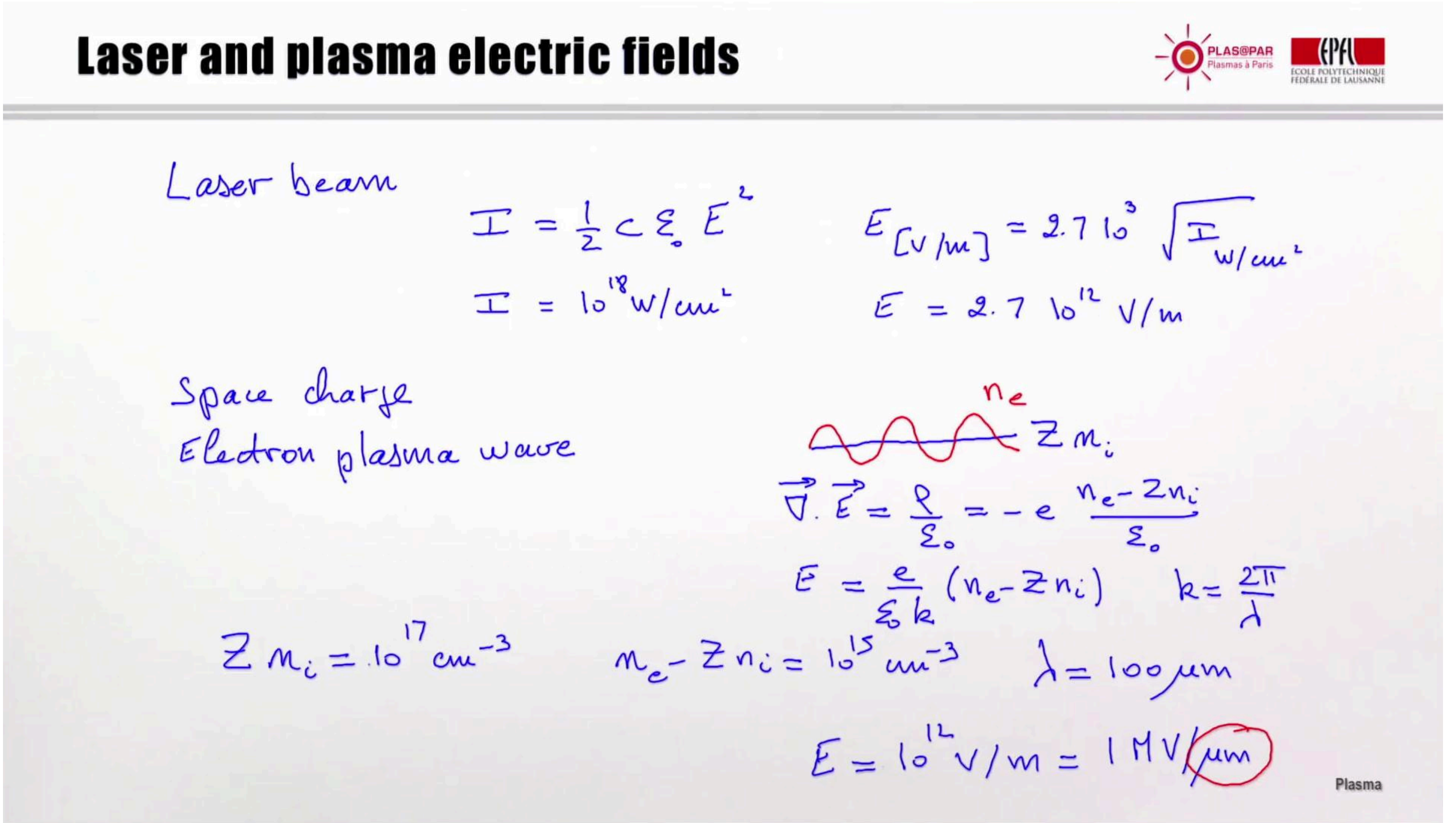


If we first consider the transverse electric field of a laser beam, its amplitude is related to the intensity by the pointing vector, so that for a laser beam intensity is equal to one-half C is velocity of light Epsilon 0 relativity of vacuum times E squared, where E is the maximum of the electric field. In practical units, it reads E in volts per metre is 2.7 10 to 3 square root of the laser intensity in Watts per square centimetres. At an intensity equal to 10 to 18 Watts per square centimetres, which is very easily reached with today's short burst lasers. The electric field is 2.7 10 to 12 volts per metre. If we now consider the space chart field, for instance, related to an electron plasma wave, we can estimate this field from the density of the ions and the electrons. So in an electron plasma wave, the ion density is constant because the heavy ions don't move, and I multiply by Z, in this case. The electron density oscillates around this equilibrium density, so you have some space charge non-neutrality in this region. So the electric field, in this case, is easily obtained from [inaudible 00:03:11] equation.

Notes

Summary

1m 05s

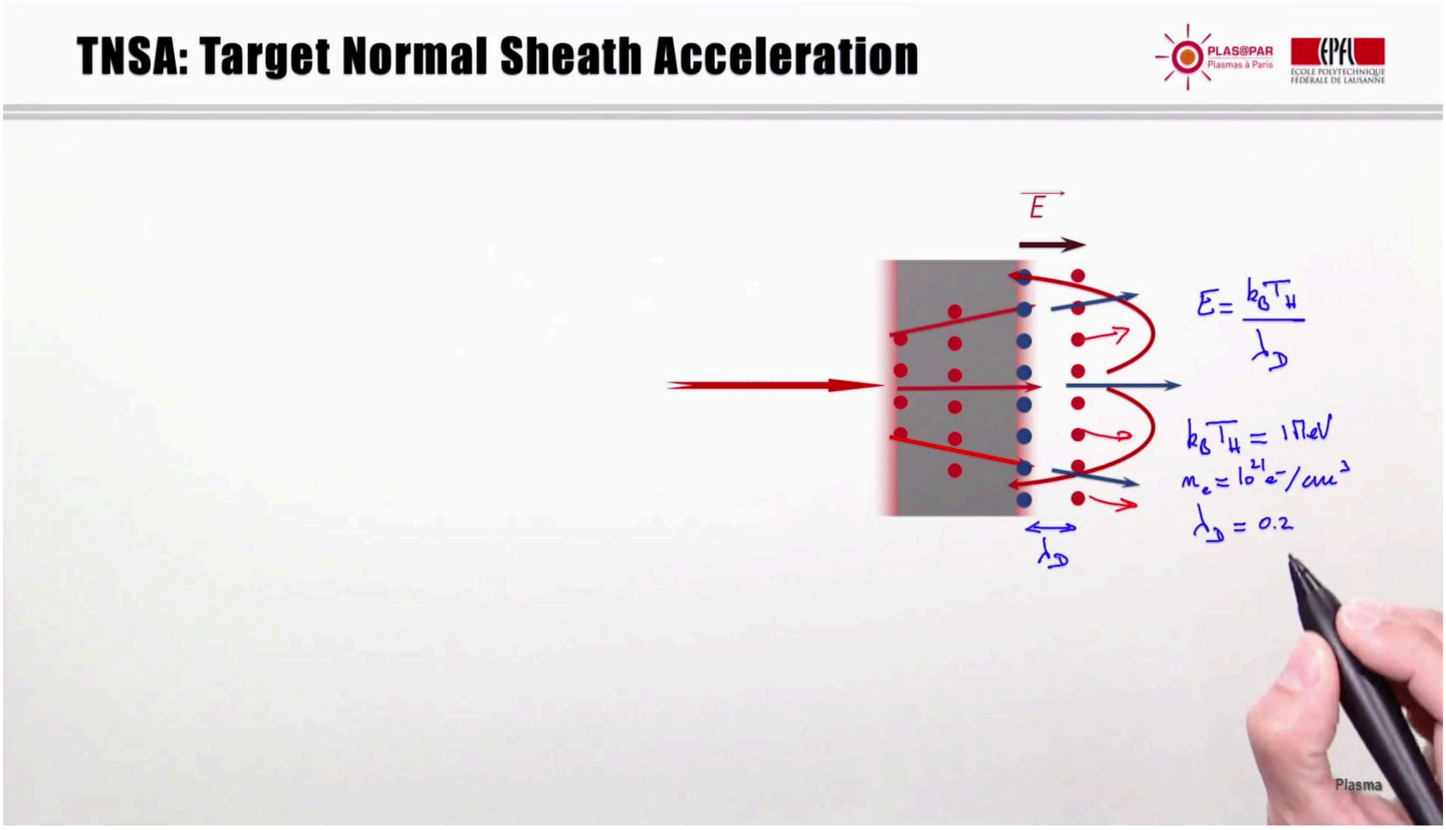


And for a given wave vector k associated with wavelengths Lambda, the amplitude of the field is given by this formula now, where k is simply 2 Pi over Lambda. So if I take typical numbers for the densities and the plasma wavelengths, such as Z ni equal 10 to 17 per cubic centimetre, if I assume a density perturbation of only one percent of this value, meaning ne minus Z ni equal 10 to 15 per cubic centimetre and a wavelength of the plasma wave of the order of 100 microns, I end up with an electric field which is equal to 10 to 12 volts per metre. And you can see that this value is much comparable to the value of the electric field of a laser beam at 10 to 18 Watts per square centimetre. We can also note that this field can be written as one megavolt per micron. And this means that in plasmas, one should be able to accelerate particles to high energies over very short distances. The three following examples will illustrate the interest of lasers and plasmas to accelerate iron beams.

Notes

Summary

3m 13s

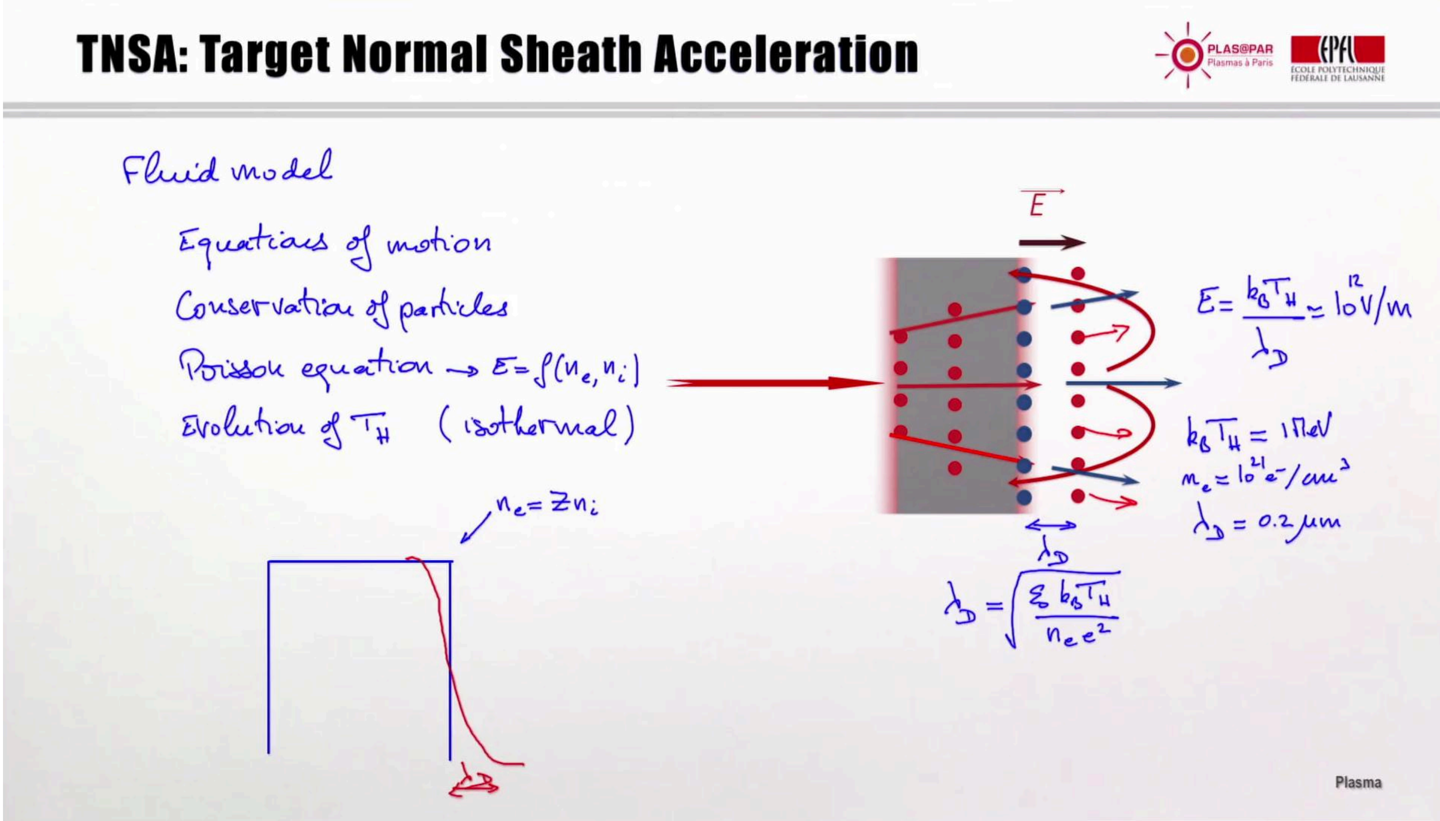


The first mechanism is called target normal sheath acceleration. The principle of target normal sheath acceleration is the following: a laser beam, a high intensity laser beam typically at intensities of the order or larger than 10 to 18 Watts per square centimetre, and a very short duration mainly from centiseconds to a few picoseconds irradiates a solid target. We have seen already in the preceding lectures that laser plasma interaction leads to the acceleration of some plasma electrons to very large energies in this region here. An important fraction of these electrons, are emitted in the forward direction. And if the target is not too thick, such as a few micron thick foil, they can propagate through the target and leave the back surface. Rapidly, the space charge field due to the separation between electrons and ions in this region here, both stops the electrons and accelerates the ions that are close to the back surface here, most generally, protons. The electric field is of the order of the electron energy divided by the Debye length taking values for the temperature of kBT equal 1 MeV. An electron density equal to the critical density for one micron laser beam, we obtain a Debye length equal to 0.2 microns.

Notes

Summary

5m 07s

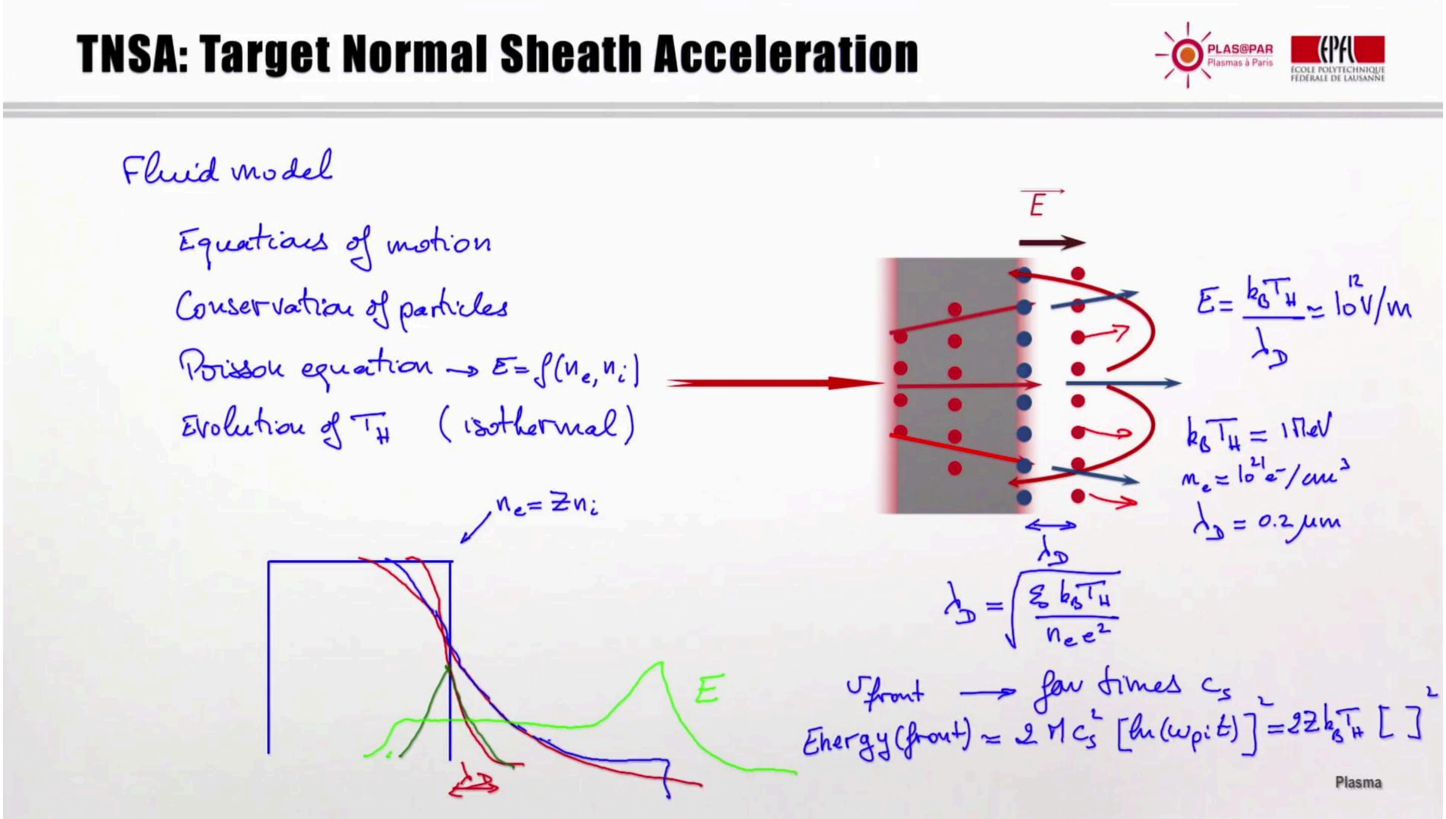


I remind you that the Debye length is given by this expression, where you have the energy of the electrons and the density of the electrons. So if you take now 1 MeV and 0.2 microns, you get something of the order of, once again, 10 to 12 volts per metre. So more generally, how can you solve this problem and predict the evolution of the electron and the iron density in this region here? So you can use a fluid model, where you have to take into account the equations of motion, the conservation of particles, the personal equation, which relates the electric field, and the electron and iron densities. And you have to assume how the temperature of the electrons will evolve in time. The simplest assumption is of a constant temperature TH, which can be reasonable if you assume that electrons are replaced by new electrons as long as the laser pulse is still irradiating the target. So I will now draw the evolution of the electron and iron densities. Before the irradiation of the laser pulse, the electron and iron densities are equal. As soon as the laser accelerates some electrons and as soon as these electrons have crossed the target, you get a new electron profile which looks like this, whereas this is typically the Debye length and the ions have not moved yet.

Notes

Summary

7m 07s

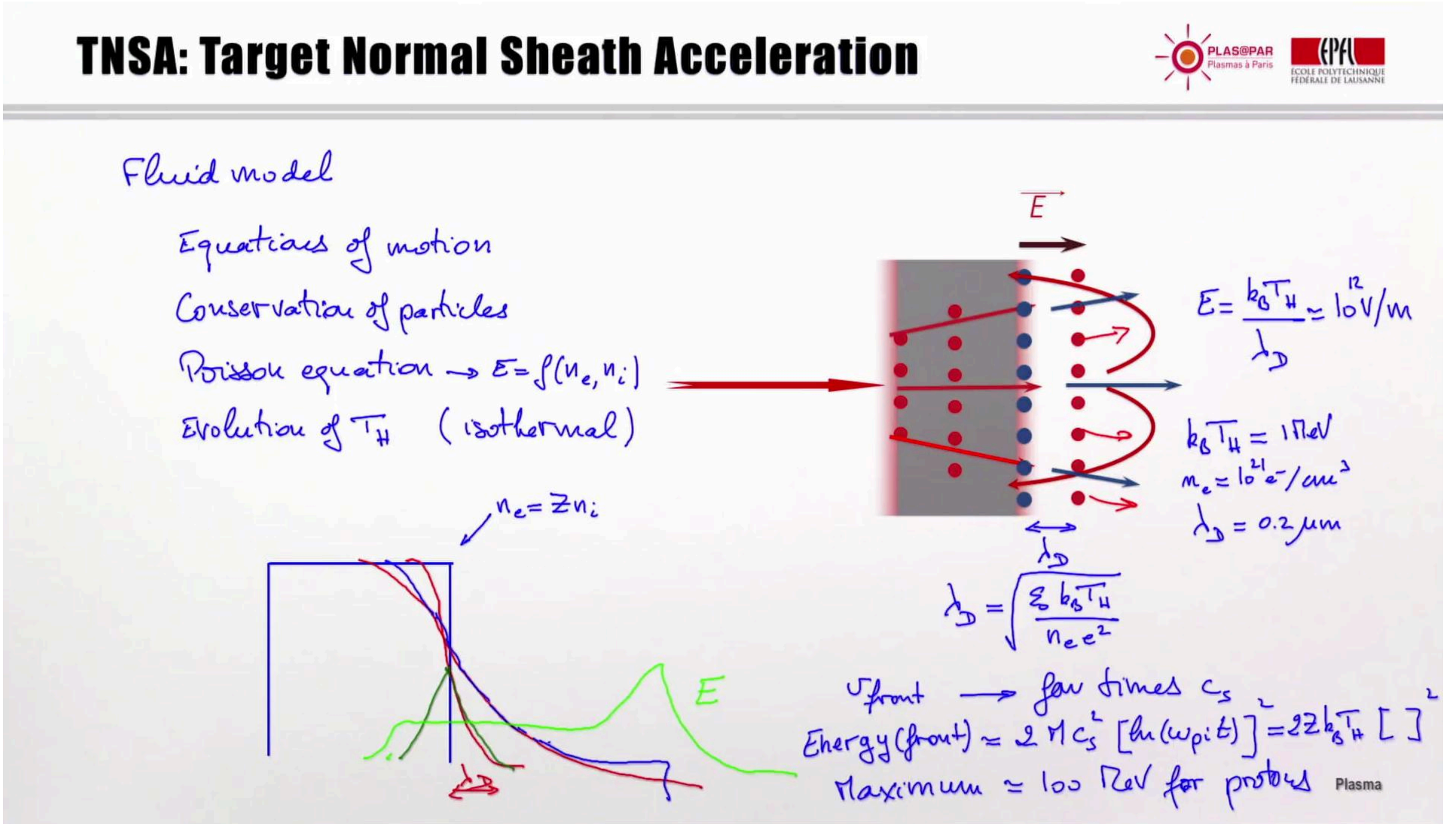


So the electric field obtained from plasma equation will look like that. After some time, the ions began to move so that the whole profile evolved. So the electron density profile becomes something like that, whereas the iron profile will be like this with the first region where the electron density is smaller than Z and i, a very long region where both densities are almost equal. And near what we call the iron font, you've got a little bit more ions in this region and less ions in this region. So the electric field will look like something like this, an almost constant electric field here. The electric field increases a bit before going again to zero. What's interesting is the velocity of this iron front and the energy of the irons at this front. So what we get is that the velocity of the iron font increases with time, of course, starting from zero and getting up to typically a few times the iron acoustic velocity. The corresponding energy, the energy of the front, after an initial transition is given by 2 times mass of the Einstein CS squared multiplied by a slow varying factor, which is log of Omega Pi Tau squared, which you can also write as 2ZkBTH and the same factor squared, where Omega Pi here is the iron plasma frequency.

Notes

Summary

9m 32s

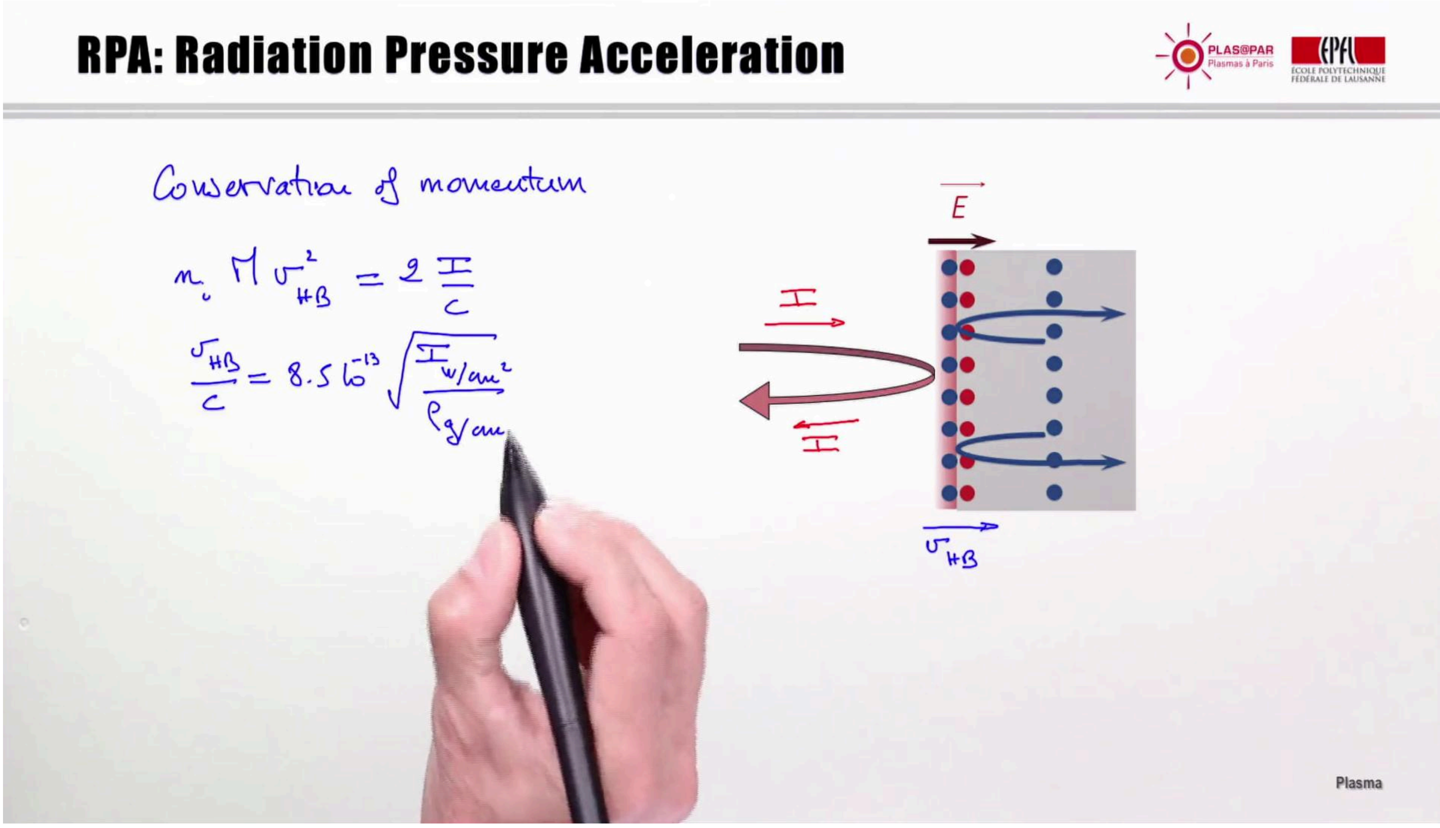


And T could be either the lifetime of the electrons in this region, or the duration of the laser pulse, which continuously accelerates new electrons. The maximum energy obtained to date is of the order of 100 MeV for protons. Using higher laser intensities, other mechanisms come into play that can lead to higher proton energies. And that is what we are going to look at now.

Notes

Summary

11m 57s

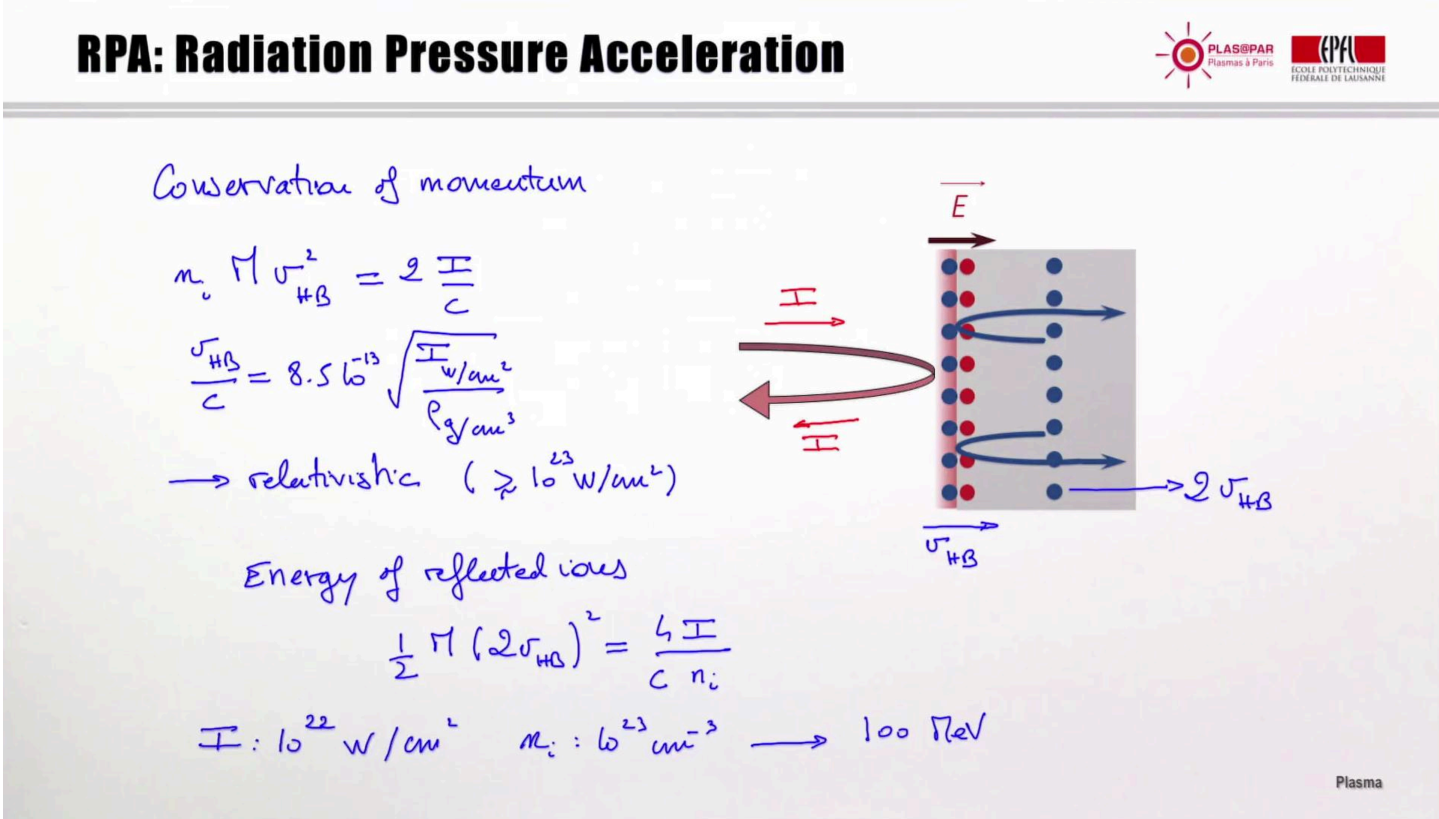


So in the radiation pressure acceleration mechanism, a high intensity laser, but with an intensity larger than before still irrigates a thin foil. So in this case, the laser beam pushes all the electrons from the front surface inside the target. And once again, the electric field, due to this charge separation here will drag the ions in this direction. And this whole structure here will propagate at the velocity that we call the hole-boring velocity. We can estimate this hole-boring velocity by taking into account the conservation of momentum. So on one side, you have the momentum of ions that propagate to the right. So on one side for one ion, the momentum would be mass times hole-boring velocity. You have to multiply by the density of the ions and once again by the velocity of the ions to have the flux of momentum. On the laser side, you've got an incident intensity I. And if the absorption is not too large, you have about the same intensity reflected by the target so that the transfer of momentum would be 2 times intensity divided by the velocity of light. From this, one can easily get the hole-boring velocity, which I divide by C, in this case, and we obtain this formula here.

Notes

Summary

12m 35s

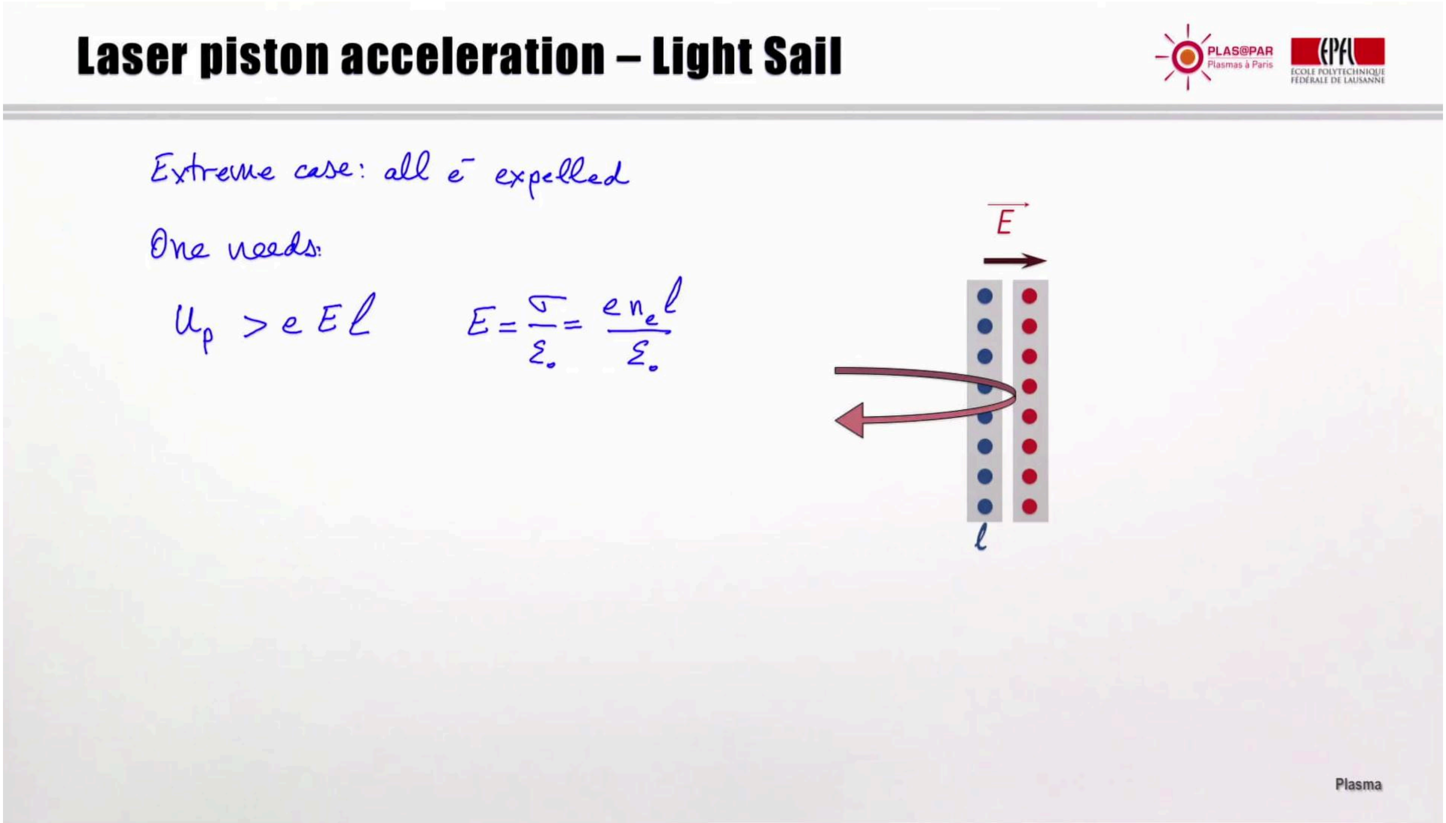


So where hole-boring velocity divided by C is something like 8.5 10 to minus 13 times the square root of the intensity in Watts per square centimetre divided by, now it's really the mass density, though in gramme per cubic centimetre. You can see that at very large intensities here, the intensity is of the order of 10 to 23 Watts per square centimetre or higher. This can become relativistic. So that was for the front surface. Now, you have to imagine that this whole structure propagates at the hole-boring velocity. Then ions from the back of the target will see the structure arriving on them. And so the ions will be reflected by this electric field here. And as the front moves at the hole-boring velocity, the ions will be reflected at twice this value, so 2 times hole-boring velocity. It means that the energy of the reflected ions will be given by one-half mass times velocity square, which, using this formula, can be expressed as 4 times intensity divided by velocity of light ni intensity. Taking some typical values for the intensity, something like 10 to 22 Watts per square centimetres, a density for the ions of 10 to 23 per cubic centimetres, we obtain an energy of 100 MeVs.

Notes

Summary

14m 43s

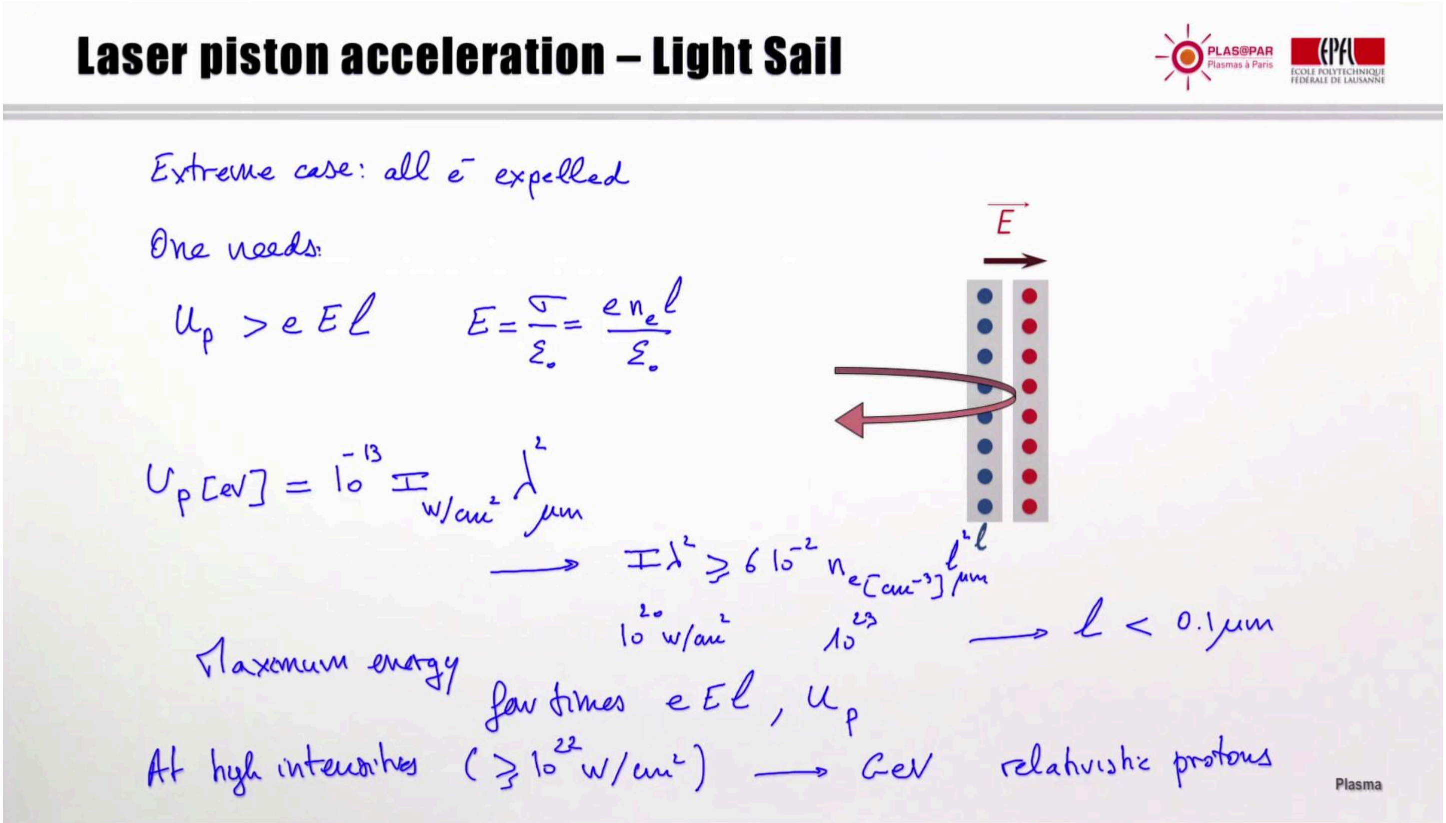


In the extreme case of a very, very high intensity in a very thin foil, all electrons could be expelled from the target as shown here. So you've got a region with only electrons and a region with only ions. To obtain this region, you need a given condition both on the intensity of the laser and on the thickness of the foil, which I'll call l. So for this, that is for the extreme case, where all electrons are expelled, you need that the energy of the electrons here, which I call, in this case, the [inaudible 00:17:39] potential, which is in fact the energy acquired by the electrons in the laser field has to be larger than the potential related to this electric field here, which I can find as electron charge times the electric field times the thickness of this region here, where the electric field is related to the charge surface density Sigma divided by Epsilon 0, and this charge surface density is simply, if all electrons are expelled, e times ne times l, so the electric field is e times ne times l divided by Epsilon 0.

Notes

Summary

16m 46s

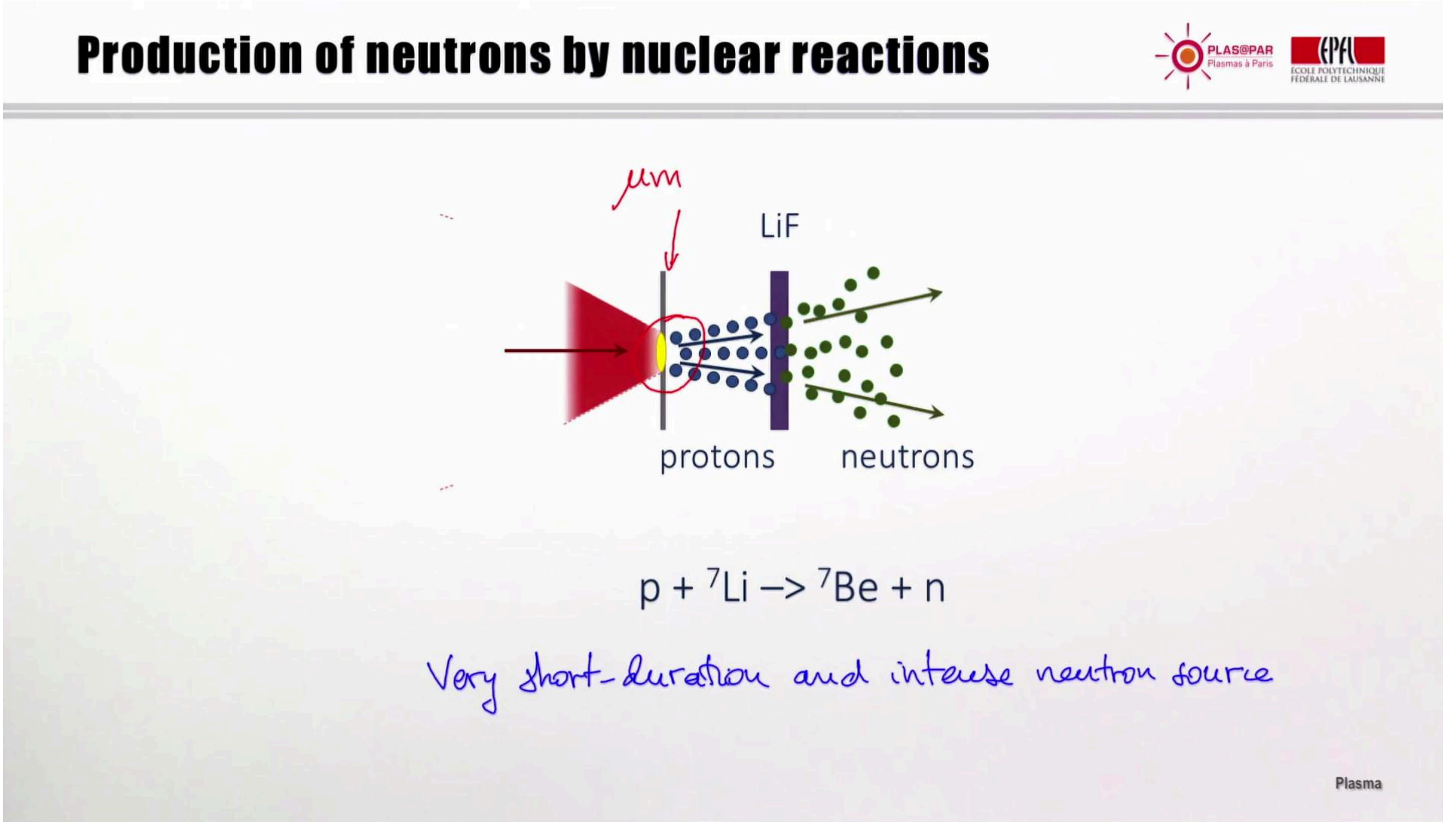


So taking the typical value for the energy of the electrons, which I can express as energy of electrons in electron volts is of the order of 10 to minus 13 times intensity in Watts per square centimetre times the square of the laser wavelengths in micron, it leads to the condition I Lambda squared, in these units, once again, has to be larger than 6 10 to minus 2 the electron density in electrons per cubic centimetres times l square, where l is expressed in microns. So assuming an intensity of the order of 10 to 20 Watts per square centimetres for wavelengths close to one micron, an electron density of 10 to 23 electrons per cubic centimetre, it leads to a target thickness, which should be less than 0.1 micron As this structure propagates, as long as the electron are pushed by the laser, the maximum energy required by the ions is a few times the potential here, which is e times electric field times l. Or it means it's a few times the typical energy of the electrons. So at very high intensities, once again, for instance, larger than 10 to 22 Watts per square centimetres, this maximum energy can reach GeV. And so you get relativistic protons if you have accelerated protons.

Notes

Summary

18m 32s

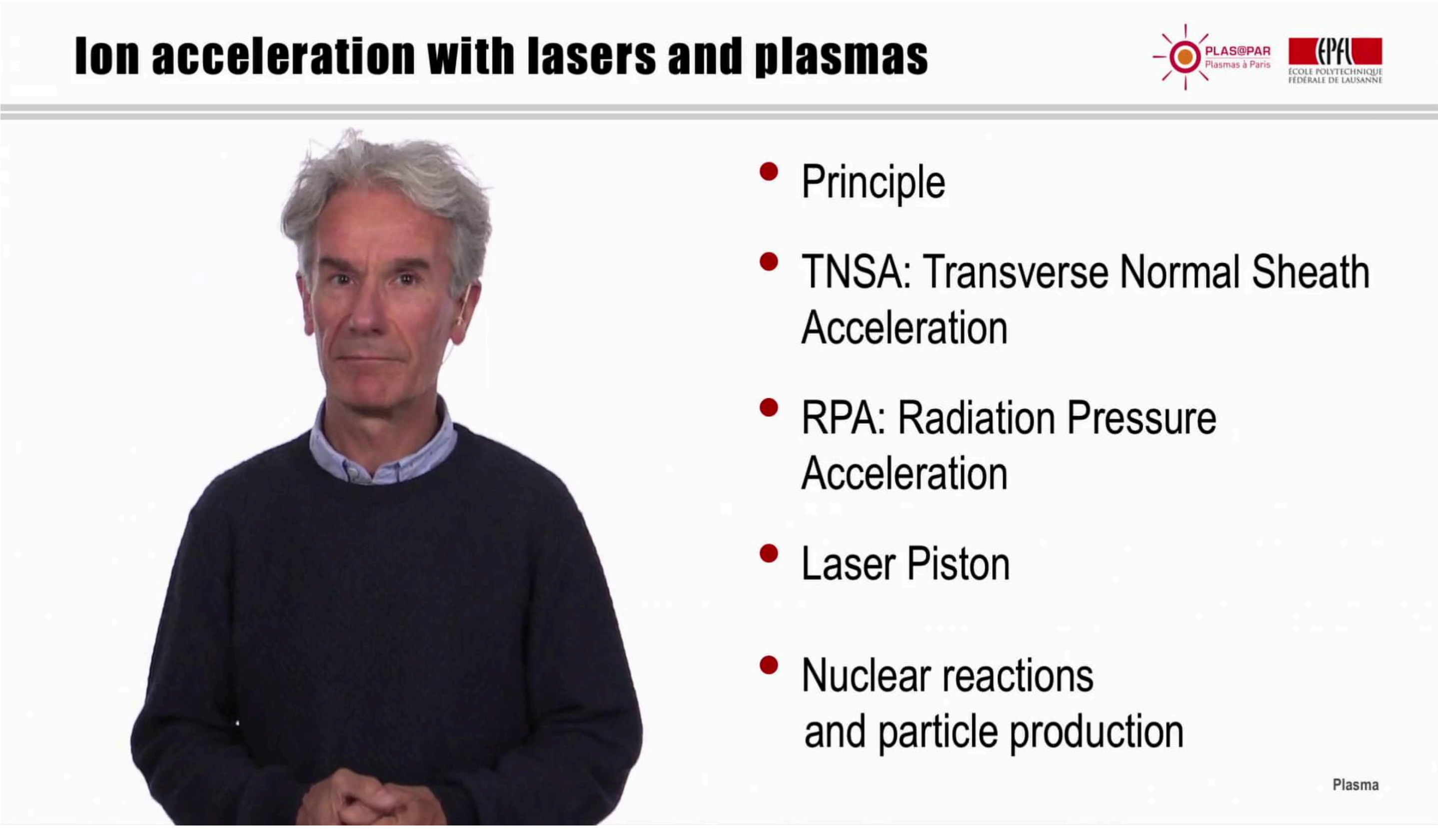


What is it possible to do with these high energy and intense proton sources? An example of application is shown in this picture. A high energy protein beam is generated by irradiation of a thin foil via intense and short duration laser pulse. So high energy protons propagate in this direction. We then add a secondary target, in this case, Lithium fluoride target, where high energy protons can induce nuclear reactions with Lithium nuclear. In this case, the reaction would be a proton reacts with Lithium 7 and produces a Barium 7 plus a high energy neutron. In fact, the largest part of the energy of the protons is transferred to the neutrons. In this scheme, we then get a very short duration and intense neutron source. It's a very short duration source because the proton source itself lasts for only picoseconds because it's been accelerated by a very short laser pulse in the centisecond to picosecond region. And the size of the emitting region here is only of the order of microns or maybe tens of microns. So on the secondary target here, not only the size is very small, but the number of neutrons can be very large. That is why you get a very short duration and intense neutron source.

Notes

Summary

21m 03s



In summary, we have seen in this lecture that lasers and plasmas can be used to generate ultra high space charge fields that can accelerate ions to high energies. And we have detailed three of these mechanisms, target normal sheets acceleration, TNSA, radiation pressure acceleration, RPA, and the laser piston. The maximum energy reach today is of the order of 100 MeV for protons mainly by TNSA. The development of the next generation of ultra intense short pulse lasers should lead to a significant increase of this maximum energy. I have also shown an application of these beans to the generation of secondary Newton sources through nuclear reactions.

Notes

Summary

23m 06s