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MODES OF TRANSILLUMINATION OF THE DENSE PLASMA LAYER VIA ELECTROMAGNETIC BEAM

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Interaction of the powerful electromagnetic ray of the limited radius with a dense plasma layer was studied via computer simulation using the PIConGPU software package in 3D geometry. The characteristic modes of channel formation in the barrier (namely laminar and turbulent) are described. Turbulent mode can be associated with the fast transillumination, observed in laboratory experiments. The channel formation time as a function of the incident beam power and the plasma layer density is studied. Information transparency is also observed at the third harmonic of the incident wave.

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INTRODUCTION

The problem of waves' propagation through plasma barriers, which are opaque for them, is of interest from the point of the general problem of wave propagation in inhomogeneous plasma, considering nonlinear and kinetic effects [1 - 13]. This effect is of practical interest in relation to the problem of space radio communication (in particular, communication with spacecraft during the landing phase, when it passes through the lower layers of the atmosphere), the problem of microwave diagnostics of plasma formations for transillumination, and so on. A special case of the problem of wave transfer through dense plasma barriers, when these barriers are partially destroyed, is related to the problem of plasma target dynamics when it is irradiated with powerful lasers in controlled fusion reactors [14].

In our previous work [15], the preliminary simulation results of the powerful electromagnetic ray interaction with a dense plasma layer, done in 2D geometry, were presented. These results do not confirm the existence of most of the mechanisms of so-called "fast" transillumination proposed in other studies, when time of the wave appearance in the trans-barrier region is much shorter than the time required for the channel formation in the plasma.

This article presents simulation results in three-dimensional geometry, which qualitatively correspond to real laboratory experiments. Two main transillumination modes (depending on the incident beam power and the plasma layer density) are described, which are conventionally referred as laminar and turbulent ones.

1. MODEL DESCRIPTION AND SIMULATION PARAMETERS

The PIConGPU package [16], based on the particle-in-cell method, was used for 3D simulation. Note that electrons and ions collisions are not taken into account in this package, but the electrons scattering by thermal fluctuations of electric field are taken into account.

The simulation area looked like a cylinder with borders covered with an absorber. An electromagnetic plane-polarized (electric field was directed along the y-axis) ray fell on the plasma layer on the left side (Fig. 1).

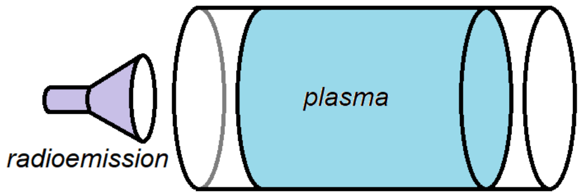

Fig. 1. Simulation area scheme (proportions are not respected)

The following simulation parameters were used: fully ionized hydrogen plasma, density – $4 \cdot 10^{12}$ cm^{-3} (electron plasma frequency – 18 GHz); plasma temperature – 0.5 eV (isothermal plasma); the plasma layer thickness – 56 cm, radius – 23 cm; incident wave length – 3.33 cm (frequency – 9 GHz, i.e. plasma is opaque for this wave); pulse duration – 7.1 ns; ray radius (at half maximum) – 5 cm; the electric field amplitude – $1.93 \cdot 10^6$ V/cm (weak wave), $3.86 \cdot 10^6$ V/cm (moderate wave) and $7.71 \cdot 10^6$ V/cm (strong wave). But during simulation the electric field amplitude varied over a wide range. Plasma density and ion mass were also varied.

2. MODES OF TRANSILLUMINATION

Note that three-dimensional simulation results are not fundamentally different from those obtained for the two-dimensional case [15].

Simulation results analysis allows us to identify several characteristic modes of interaction of the electromagnetic beam with the plasma layer.

Fig. 2 shows the instantaneous electromagnetic field components distributions, the electrons and ions density when a weak electromagnetic ray falls on a plasma. In this case, transillumination was not observed – at least during the simulation time. There are fluctuations on the plasma boundary at the electromagnetic beam incidence point. Over time, a conical cavity is formed in this area. In addition, there is the thin ray generation on the incident wave third harmonic (the plasma layer is transparent for this frequency). Over time, this beam forms a thin channel in the plasma.

The third harmonic generation and its subsequent passage through the plasma barrier can be classified as information transparency [13].

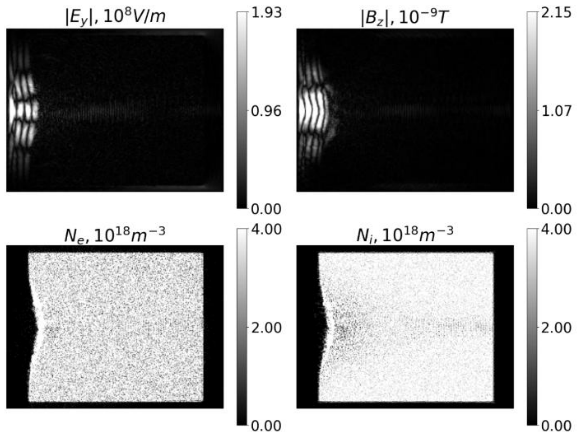

Fig. 2. Electromagnetic field components, electrons' and ions' density distributions when a weak electromagnetic ray is falling on plasma at the time point 6.3 ns ($\omega_p t = 712$)

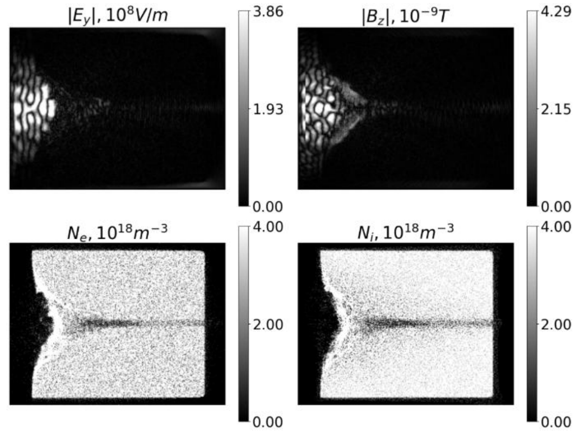

Fig. 3. Electromagnetic field components, electrons' and ions' density distribution, when a moderate electromagnetic ray is falling on plasma at the time point 6.3 ns ($\omega_p t = 712$)

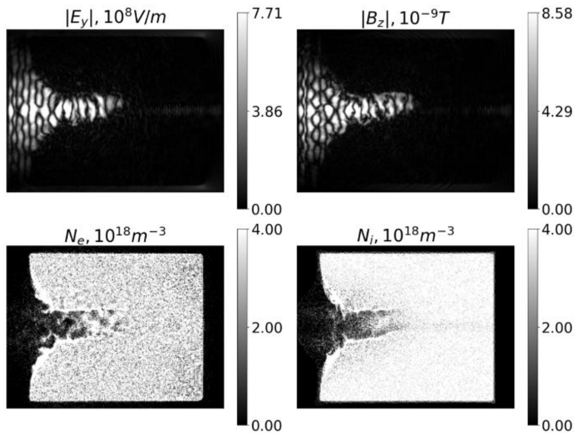

Fig. 4. Electromagnetic field components, electrons' and ions' density distributions when a strong electromagnetic ray is falling on plasma at the time point 3.5 ns ($\omega_p t = 396$)

Fig. 3 shows the simulation results of a moderate electromagnetic ray falling on a plasma. In this case, the plasma layer transillumination process can be divided into two stages. At the first stage, the beam propagation into the plasma is accompanied by its self-focusing. The penetration area has a conical shape.

On the second stage, this focused beam propagates deep into the barrier. Thus, in the propagation area decrease of density is observed (at first for electrons, and then for ions), i.e., the channel whose shape is close to cylindrical is formed. This mode can be referred as laminar because no vortices are observed in plasma.

Finally, Fig. 4 shows the simulation results of a strong electromagnetic ray falling on a plasma. In this case, the third harmonic generation is also observed. The main channel, as in the moderate ray case, is formed in two stages – beam self-focusing and channel formation, whose shape is close to cylindrical. In this mode, from the very beginning of the beam incidence, the plasma motion becomes turbulent. As a result, there is a local electron density redistribution – non-stationary increases and decreases in density appear. This redistribution can be associated with the fast plasma transillumination phenomenon, which was observed in laboratory experiments [8, 11 - 12].

Channel deviation from the system axis can be related with the plasma turbulent dynamics (this effect can be seen in Fig. 4).

3. MODEL PARAMETERS INFLUENCE ON THE TRANSILLUMINATION

Fig. 5 shows the dependence of the channel formation time on the incident electromagnetic ray power and the plasma density. As expected, the time decreases with increasing beam power and decreasing plasma density. The time increases with the increase of plasma ions' mass.

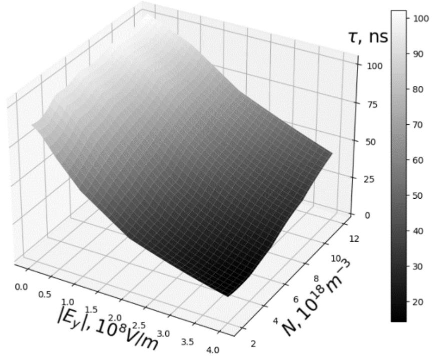

Fig. 5. The channel formation time dependence on the incident beam power and the plasma barrier density

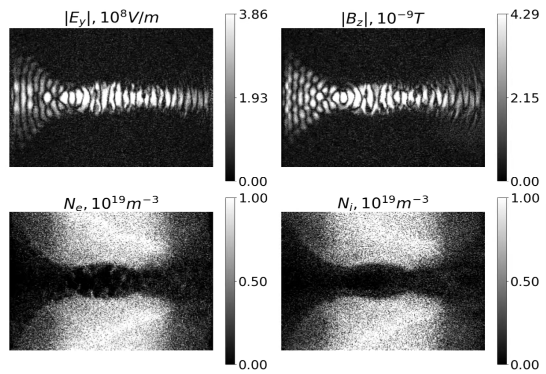

Fig. 6. Channel with non-monotonic change of radius along the length when a moderate electromagnetic beam is falling, plasma density – 10^{13} cm^{-3}, time point 50.6 ns ($\omega_p t = 9030$)

The dependence of the channel formation time on the initial plasma electrons temperature was not observed.

Width of the channel formed at the second stage of transillumination increased as the incident wave power increased. In some cases, a non-monotonic change in the channel radius along its length was observed (Fig. 6).

CONCLUSIONS

1. Simulation results for 3D and 2D geometry are well consistent.

2. Characteristic modes of the dense plasma layer transillumination by the powerful electromagnetic ray were revealed.

3. In the laminar mode, the beam is self-focused and a conical area with a reduced plasma density is formed. Then a cylindrical channel is formed in the depth of the plasma.

4. In the turbulent mode, the plasma motion in the electromagnetic ray field becomes turbulent from the very beginning. As a result, a local electrons' density redistribution takes place, which can cause fast transillumination for moderate thickness barriers.

5. The channel formation time increases with increase of the electromagnetic ray power and with decrease of the plasma density.

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РЕЖИМЫ ПРОСВЕТЛЕНИЯ БАРЬЕРА ПЛОТНОЙ ПЛАЗМЫ ПУЧКОМ ЭЛЕКТРОМАГНИТНЫХ ВОЛН

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Путем компьютерного моделирования с применением программного пакета PIConGPU в трехмерной геометрии исследовано взаимодействие мощного электромагнитного пучка ограниченного радиуса с плоским слоем плотной плазмы. Описаны характерные режимы формирования канала в барьере – турбулентный и ламинарный. Турбулентный режим можно связать с так называемым быстрым просветлением, которое наблюдалось в лабораторных экспериментах. Исследована зависимость времени формирования канала в зависимости от мощности падающего луча и плотности плазменного слоя. Также наблюдался перенос сигнала через барьер на третьей гармонике падающей волны.

РЕЖИМИ ПРОСВІТЛЕННЯ БАР'ЄРА ЩІЛЬНОЇ ПЛАЗМИ ПУЧКОМ ЕЛЕКТРОМАГНІТНИХ ХВИЛЬ

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Шляхом комп'ютерного моделювання за допомогою пакета PIConGPU у тривимірній геометрії досліджено взаємодію потужного електромагнітного променю обмеженого радіусу з плоским шаром щільної плазми. Описано характерні режими формування каналу в бар'єрі – турбулентний та ламінарний. Турбулентний режим можна пов'язати з так званим швидким просвітленням, що спостерігалося в лабораторних експериментах. Досліджено залежність часу формування каналу в залежності від потужності падаючого променя та густини плазмового шару. Спостерігалося також перенесення сигналу через бар'єр на третій гармоніці падаючої хвилі.