FEMTOSECOND LASER PLASMA: REVIEW OF INVESTIGATION AND CALCULATIONAL MODEL

N. Bugrov, S. Kholod, N. Zaharov
CIPT DM RF, Russia

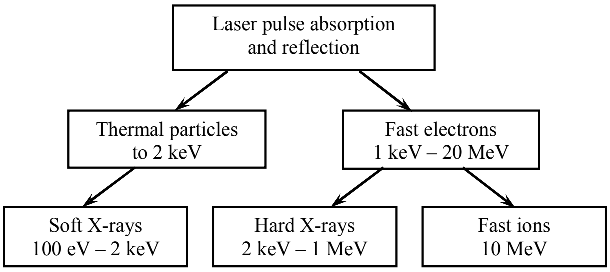
Review of experimental and theoretical investigation of physical processes in femtosecond laser plasma is presented. Such effects, as X-ray and electric-magnetic wave emission, high energy electron and ion beams are described. It is shown that ultrashort laser pulse with duration comparable to period of wave oscillation (less than a few femtoseconds) is absorbing by inner electrons in contrast to absorption of more lasting laser pulses by outer electrons. The problem of mathematical modelling of these processes and corresponding computer code development is observed. Technological applications, such as production of high power X-ray and particles plasmas sources, laser precision shaping and machining of different materials are discussed.

PASC 52.38.-r; 52.38.Mf; 52.38.Ph; 52.50.Jm

PROCESSES OF INTERACTION OF LASER RADIATION WITH SUBSTANCE

The increasing amount of the works devoted to femtosecond laser plasma physics in last time, indicate to new achievements in this area, both regarding to theoretical researches, and regarding to development of applied problems.

Effects of interaction of ultrashort laser radiation with the condensed environment can be illustrated by following circuit.



At interaction of a intense ($q = 10^{16}$-10^{20} W/cm^2) femtosecond laser pulse with condensed matter, the thin layer of solid density plasma (~ 0,1-1 mm), cold ions and hot (more 1 keV) electrons is formed. Therefore it is necessary to take into account mechanisms of plasma formation and absorption of laser radiation in this layer of plasma.

PLASMA OPTICAL PROPERTIES

Researches show [1], that absorptive ability formed near-surface plasmas depends on intensity, length of a wave and polarization of laser radiation, angle of its falling on a target and characteristics of the target. The value of absorption coefficient is from 20 % to 60 % and has the maximum for the p-polarized laser radiation falling under a angle ~ 60°. So, at fig.1 the dependence of reflection coefficient Al-plasma versus angle of laser pulse falling is shown.

GENERATION OF X-RAY RADIATION

Fast electrons, due to the big length of free run, are capable to penetrate into cold target area before front of a thermal wave. Thus, as bremsstrahlung at collision with cold ions, as ruled radiation at knocking-out of electrons from K-shells is formed.

The bremsstrahlung turns out as a continuum in an interval 0,1 keV – 1 MeV and depends on laser intensity and parameters of plasma whereas radiation from K- and other internal nuclear shells can have energy 1 – 100 keV and depends on nuclear number of a target [2].

Soft X-ray emission occurs both in lines, and in a continuous spectrum of bremsstrahlung, and can occupy time, much greater (~ 20 times), than duration of a laser pulse. For example, in experiments with the XeCl-laser ($\lambda = 0.308$ μm, $q = 10^{17}$ W/cm^2) and metal targets, X-ray pulses with energy more than 200 eV and duration about 7 ps have been received, whereas duration of a laser pulse was equal 500 fs.

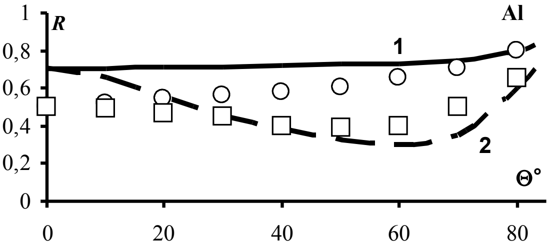


Fig. 1. Reflection coefficient of Al-plasma versus angle of laser pulse falling ($q = 2{,}5{\cdot}10^{15}$ W/cm^2, $\lambda = 0{,}248$ μm, $\tau_p = 200$ fs, 1 – s-polarization, 2 – p-polarization, lines – calculation, points – experiment)

Generation of hard X-ray is carried out during of the most laser pulse inside of a small angle from a direction of fast electrons movement. The output of hard X-ray depends on charging number of target atoms as $Z^{3/2}$ (see figure 2) while the temperature of electronic component formed in plasma poorly depends on structure of a target and at intensity of laser radiation and is ~ 4 keV for $q \sim 10^{16}$ W/cm^2 and various materials: from Si (Z = 14) up to Te (Z = 73).

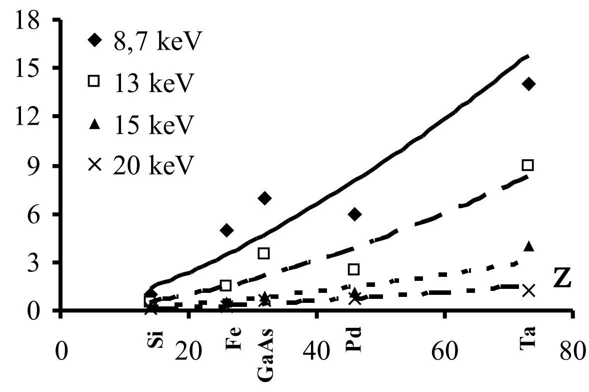


Fig. 2. Dependence of X-ray output from charging number of target atoms

ELECTROMAGNETIC PULSE GENERATION

Taking off from a target fast electrons create electromagnetic fields which aspire to return them back.

Electron's movement in the self-coordinated electromagnetic fields outside of a target can lead to dipole radiation of an electromagnetic wave with ultrashort duration. In [3] performed calculations for factor of fast electron energy transformation to electromagnetic wave $10^{-1} – 10^{-3}$ and spot radius $r_0 = 5 – 20$ μm. The main part of electrons is locked by an electric field in area with the characteristic size about 1 micron near to an irradiated surface. Most high energy electrons overcome the specified area and are turned back to a target at the further movement. Thus the part from them achieves a surface and is absorbed by it.

Result of such non-uniform (along an axis 0*z*) movements of electrons is generation of an electromagnetic wave. In a considered case there are all necessary conditions for dipole radiation.

GENERATION OF FAST PARTICLES BEAMS

At laser pulse interaction with the condensed matter the fast ions beam is formed. The main mechanism is an acceleration of ions by induced electrostatic fields in plasma of targets. Thus fast electrons will move into vacuum and accelerate ions by means of ambipolar fields. The calculations [1] show, that at increase of femtosecond laser intensity more than 10^{17} W/cm^2 the ponderomotive pressure of a laser beam starts to exceed pressure of plasma, and ions get a component of speed directed into solid.

ENERGY DISTRIBUTION

The part of the laser energy, expended to formation of electronic and ionic beams, X-ray and electromagnetic radiation, is estimated for various parameters of a laser pulse. It is shown that the factor of transformation of laser radiation to fast electrons is about 10 % and ~ 1-3 % of laser energy are capable to be transformed to energy of ions. The factor of conversion of laser radiation to soft X-ray can achieve 2 %, and to hard X-ray – 0,1 %. In turn, the factor of transformation of energy of fast electrons in dipole electromagnetic wave can achieve 10 %.

It is experimentally established [4], that the ionic beam is defined at first by atoms of the impurity on a material surface (the pollution, adsorbed gases: $\mathbf{C}^+$, $\mathbf{C}^{+2}$, $\mathbf{H}^+$).

ULTRAFAST LASER PULSE ABSORPTION

Process of absorption of laser pulses which duration τ_p, comparable to the period of a laser electromagnetic wave (less several femtoseconds) has quantum character. The main influence in this case, renders such parameter, as the ratio of laser pulse duration to a cycle time of electron on an orbit τ_p/τ_e (Fig.3). The value τ_p/τ_e is less, the probability of absorption of radiation quantum by electron is less. Therefore practically only nearest to a nucleus electrons can interact with ultrashort laser pulses. The exhaustive model of such abnormal absorption of radiation till is not developed now.

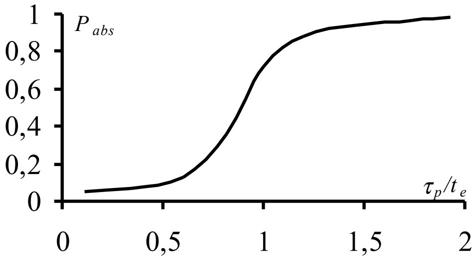


Fig. 3. Probability of absorption of 1 fs laser pulse by electrons of carbon

TECHNOLOGY APPLICATIONS

Examples of technology applications are drilling ultra small apertures, precision processing of surfaces, creation of ultra-thin films, production of high power X-ray and particles plasmas sources.

REFERENCES

1. V.M. Velichko, V.D. Urlin, B.P. Yakutov // *Kvantovaya electronika.* 2000, v.30, № 10, p.889-895.
2. A.A. Andreev, A.I. Zapysov, A.V. Tcharuhshev, V.E.Yashin // *Izvestiya AN. Seriya fizicheskaya*, (63), 1999, p. 1239.
3. I.A. Litvinenko, V.A.Lykov // *Pis'ma v ZhTF.* 1998, v.24, N5, p. 84-88.
4. P.L. Shkolnikov, A. E. Kaplan, A. Pukhov et al. // *Appl. Phys. Lett.* 1997, v.71, p.3471.

ФЕМТОСЕКУНДНАЯ ЛАЗЕРНАЯ ПЛАЗМА: ОБЗОР ИССЛЕДОВАНИЙ И ВЫЧИСЛИТЕЛЬНАЯ МОДЕЛЬ

Н. Бугров, С. Холод, Н. Захаров

Представлен обзор экспериментальных и теоретических исследований физических процессов, происходящих в фемтосекундной лазерной плазме. Описаны такие эффекты, как рентгеновское и электромагнитное излучение, высокоэнергетичные электронные и ионные пучки. Показано, что ультракороткий лазерный импульс длительностью, сравнимой с периодом колебания волны (меньшей, чем несколько фемтосекунд), поглощается внутренними электронами, в отличие от более продолжительных импульсов, которые поглощаются внешними электронами. Рассмотрена задача математического моделирования этих процессов и создания соответствующего компьютерного кода. Обсуждены технологические аспекты, такие, как создание мощных источников рентгеновского излучения и плазмы, формирование лазерного пучка и обработка различных материалов.

ФЕМТОСЕКУНДНА ЛАЗЕРНА ПЛАЗМА: ОГЛЯД ДОСЛІДЖЕНЬ І ОБЧИСЛЮВАЛЬНА МОДЕЛЬ

М. Бугров, С. Холод, М. Захаров

Представлено огляд експериментальних і теоретичних досліджень фізичних процесів, що відбуваються у фемтосекундній лазерній плазмі. Описано такі ефекти, як рентгенівське й електромагнітне випромінювання, високоенергетичні електронні й іонні пучки. Показано, що ультракороткий лазерний імпульс тривалістю, порівнянною з періодом коливання хвилі (меншою ніж декілька фемтосекунд), поглинається внутрішніми електронами, на відміну від більш тривалих імпульсів, що поглинаються зовнішніми електронами. Розглянуто задачу математичного моделювання цих процесів і створення відповідного комп'ютерного коду. Обговорено

технологічні аспекти, такі, як створення могутніх джерел рентгенівського випромінювання і плазми, формування лазерного пучка й обробка різних матеріалів.