CONFERENCES AND SYMPOSIA

Scientific session of the Division of General Physics and Astronomy of the Russian Academy of Sciences (30 December 1992)

Usp. Fiz. Nauk **163**, 85–88 (December 1993)

A scientific session of the Division of General Physics and Astronomy of the Russian Academy of Sciences was held on December 30, 1992 in the P. L. Kapitsa Institute of Physics Problems. Reports on the subject of *femtosecond pulses and their application in physics* were presented at the session:

1. *P. G. Kryukov.* Current trends in research on femtosecond pulses and applications of such pulses in experimental research in nonlinear quantum electrodynamics.
2. *E. M. Dianov, A. M. Prokhorov, and V. N. Serkin.* Nonlinear propagation of femtosecond pulses in fiber-optic waveguides.
3. *V. M. Gordienko, N. I. Koroteev, and V. T. Platonenko.* Generation of superstrong optical fields on the basis of high-power femtosecond laser systems with excimer amplification and experiments on the generation of ultrashort x-ray pulses.

A brief summary of one report is given below.

V. M. Gordienko, N. I, Koroteev, and V. T. Platonenko. *Generation of superstrong optical fields on the basis on high-power femtosecond laser systems with excimer amplification and experiments on the generation of ultrashort x-ray pulses.*

Progress in the technology of generation of high-power femtosecond pulses has led to the production of table-top terawatt laser systems with whose help intensities exceeding 10^{16} W/cm^2 and, correspondingly, light fields whose intensity exceeds intra-atomic fields can be produced with comparatively low pulse energies of 1–10^{-2} J.[1]

Under the action of femtosecond light pulses of such intensity a thin layer of hot plasma with unique parameters, which cannot be obtained by other methods, is produced on the surface of the target. The short duration of the plasma-producing pulse and the finite expansion time of the plasma create the conditions required for obtaining the regime of "inertial conservation" of plasma. The plasma temperature is limited mainly by heat transfer into the target and can be estimated in the diffusion-heat-transfer approximation according to the formula[2]

$$T \approx 2.5 \cdot 10^{-4} Q^{2/3} \tau^{-1/3},$$

where T is given in eV, Q is the energy (in J/cm^2) absorbed per unit surface area, and τ is the pulse width (in sec). For $\tau = 10^{-12}$–10^{-13} sec and intensities of 10^{16}–10^{19} W/cm^2 the temperature in the surface plasma is of the order of hundreds and thousands of electron-volts with electron density 10^3–10^{24} cm^{-1}, and pressure of 10–100 Mbar. Under these conditions the plasma is far from equilibrium and nonstationary and its lifetime is close to 10^{-12} sec, the plasma layer is thousands of angstroms thick, and the front of the layer is hundreds of angstroms thick. Intensities of 10^{18}–10^{19} W/cm^2 fall on the limit beyond which the light pressure exceeds the thermodynamic pressure realized in the plasma (the latter pressure increases with the intensity more slowly than does the light pressure). For intensities of 10^{19} W/cm^2 the motion of a free electron in the light field becomes relativistic. Thus a femtosecond surface plasma is a physical object with unique parameters, the study of which opens up a new direction in fundamental physical research. This refers primarily to questions concerning the following: the electrodynamics of the interaction of intense radiation with high-gradient, rapidly expanding high-temperature (almost collisionless) plasma front; the effect of superstrong fields (significantly exceeding intra-atomic fields $\sim 10^9$ W/cm) on the flow and cross section of elementary collisional processes; the physics of transport processes and hydrodynamic flows in a strongly nonequilibrium plasma in the presence of high gradients of different parameters; the initiation of phase transformations due to extreme dynamical pressures; and, so on.

Such a plasma is also a powerful source of x-rays, and this is one reason for the great interest in such plasma. The incoherent x-ray radiation from the hot surface plasma can have a duration of $\sim 10^{-12}$ sec at wavelengths of 10–60 Å.[1]

The femtosecond laser system, developed at Moscow State University (MSU) under the initiative of the late S. A. Akhmanov, enables obtaining, by focusing radiation on a target, intensities exceeding 10^{16} W/cm^2 in both the visible range 0.57–0.63 μm (a system based on dye lasers) and the UV range at 0.308 μm (system based on XeCl excimer molecules) with pulse durations of about 400 fsec. It consists of a triggering system based on an yttrium aluminate solid-state picosecond laser with hybrid mode-locking and combined feedback, a dye laser with synchronous pumping, a bank of dye amplifiers, a radiation frequency converter, and XeCl excimer amplifiers.[3–5]

With respect to the gain bandwidth excimer media are competitive with condensed media; with respect to saturation energy they are comparable to dyes ($\sim 10^{-3}$ J/cm^2) and they are not as good as solid state media (~ 1 J/cm^2). But the relative simplicity of the scaling of the amplifying cascades makes excimer systems competitive when used for amplifying $3 \cdot 10^{-13}$ sec pulses up to energies of 1–10 J.

Femtosecond laser systems employed for producing high-temperature surface plasma must satisfy the following requirements:

high power;

high energy contrast of the generated pulses; and,

high spectral and spatial quality of the beam, making it possible to focus radiation into a spot close in size to the diffraction limit.

The MSU system provides several gigawatts in the visible range and up to 100 gigawatts in the UV, energy contrast of about 100, and a close to Gaussian light beam. In Refs. 3–4 a scheme for a high-intensity (>1 GW/cm^2) narrow-band source ($\Delta\lambda \leqslant 0.5$ Å) of soft x-ray radiation ($\lambda \approx 40$ Å) was realized experimentally using matched focusing x-ray mirrors. It was shown that by optimizing and matching the parameters of the laser radiation, the target material, and the characteristics of multilayer focusing mirrors it is possible to create a source of powerful incoherent ultrashort x-ray pulses with controllable spectral-temporal and spatial characteristics.

Since the optical density of the surface plasma is low, a significant fraction of the energy in the x-ray radiation from the plasma lies in the region of the resonance lines of ions. This makes it possible to separate relatively narrow-band powerful x-ray pulses with the help of resonance (multilayer) x-ray mirrors. The characteristic lines of hydrogen- and helium-like ions of light elements with atomic numbers $A > 10$ are most effective.

We now briefly discuss the expected and realized (at MSU) characteristics of the x-ray radiation. The duration of the x-ray pulse is determined by the cooling and recombination time of the plasma as well as the de-excitation time of the excited ions. The de-excitation time can be estimated from the formula

$$\tau^{-1} = \frac{8\pi^2}{3} \frac{e^2}{mc\lambda^2} f,$$

where e is the electron charge, m is the electron mass, λ is the wavelength, c is the speed of light, and f is the oscillator strength. For strong lines of hydrogen- and helium-like ions $1 > f > 0.5$. Even for $\lambda \approx 50$ Å the de-excitation time of such ions is two to three picoseconds, and for $\lambda \approx 10$ Å it is close to 10^{-13} sec. The cooling time (owing to thermal diffusion and gas-dynamic expansion) does not exceed, in order of magnitude, the duration of the warming pulse. For this reason, when high-contrast laser pulses are employed, the duration of the x-ray pulses should not significantly exceed 10^{-12} sec.

For low contrast, when the energy density of the background radiation is sufficient for ablation of the material (~ 1 J/cm^2), the main pulse warms the expanding plasma produced by the preliminary pulse. In this case the duration of the x-ray pulse can be significantly longer.

In order to obtain high radiation intensity on resonance and helium-like ions a high concentration of such ions in excited states must be realized. The excitation and ionization cross sections of such ions decrease rapidly with increasing atomic number. Estimates show[2] that in the case of solid-state densities the elements with atomic numbers $A \leqslant 12$–13 can be almost completely ionized at temperatures $\leqslant 1$ keV within a subpicosecond time interval. This makes it possible to produce a high concentration of excited ions emitting at wavelengths of the order of 10 Å. The production of a high concentration of excited hydrogen- and helium-like ions of elements with $A > 15$ within subpicosecond time intervals is problematic.

Estimates show that conversion of laser radiation into the resonance lines of hydrogen- and helium-like ions of elements with $A \leqslant 12$–13 can be quite high. It can be conjectured that at the stage of recombination of a completely ionized plasma each ion gives one photon of characteristic radiation with energy $h\nu = 0.25$ keV ($\lambda = 40$ Å). Then a 500 Å thick surface layer of plasma[2] with initial density $5 \cdot 10^{22}$ cm^{-3} emits energy with density 10 J/cm^2. For the typical energy densities $\geqslant 10^3$ J/cm^2 of laser radiation in experiments of this type this corresponds to conversion of the order of 1%. Total ionization of elements with $A = 5$–6 at solid-state densities and temperatures of hundreds of electron-volts occurs over short times $\sim 10^{-13}$ sec. An accurate solution of this problem, of course, requires computer calculations.

The experiments performed at MSU employed radiation from a femtosecond XeCl excimer system with on target intensity exceeding 10^{15} W/cm^2 and energy density $\sim 5 \cdot 10^2$ J/cm^2. A flat target on a moving micrometric stand, calibrated pin diodes with bandpass filters, a pinhole camera for measuring the diameter of the emitting x-ray source together with a system for introducing the image, and an x-ray streak camera with temporal resolution of 5 psec were placed in the vacuum interaction chamber.[3] Multilayer x-ray mirrors were placed at a distance from the target equal to twice the focal length. The target materials were B_4C, Si, and Fe. The intense x-ray source employed narrow spectrally bright characteristic lines of hydrogen- and helium-like boron ions together with spectrally matched multilayer x-ray mirrors, developed by S. V. Gaponov's group (Institute of Applied Physics, Russian Academy of Sciences). With their help it was possible to separate from the radiation emitted by the laser-produced surface plasma (B_4C target) the following lines: $\lambda = 48.6$ Å, $1s^2S$–$2p^2P^0$; $\lambda = 60.3$ Å, $1s^1S$–$2p^1P^0$. The duration of the x-ray pulse was estimated with the help of an x-ray streak camera and was limited by the camera's time resolution of 5 psec. The conversion of optical radiation into x-rays was $\eta \approx 2\%$ at a wavelength of $\lambda = 48.6$ Å and $\eta \approx 0.2\%$ at $\lambda = 60.3$ Å.[6,7] The experimental data enabled estimating the lower limit of the intensity of the laser-plasma x-ray source of ultrashort pulses: $\sim 5 \cdot 10^9$ W/cm^2 for the brightest boron line ($\lambda = 48.6$ Å) with an ionization potential of 340 eV for the hydrogen-like ions.

The investigations show that a laser-produced surface plasma can be an effective source of intense incoherent x-rays. The intensity of x-ray sources of this type can be increased both by increasing the electron temperature T_e and by decreasing the wavelength. Assuming the plasma is absolutely black, the maximum intensity I_X of an x-ray source with a matched mirror, collecting radiation in a solid angle $\Delta\Omega$ and having a reflection coefficient R and spectral width $\Delta\lambda$, can be estimated in the region of the resonance line:

$$I_X \leqslant \frac{hc}{\lambda^4} \frac{1}{\exp(hc/\lambda T_e) - 1} \frac{\Delta\lambda}{\lambda} R.$$

For on-target femtosecond laser radiation intensity of the order of 10^{18} W/cm^2 the electron temperature reaches values of the order of 1 keV and the maximum intensity of the x-ray source is $I_X \approx 10^{12}$ W/cm^2 with $R=30\%$, $\Delta\Omega=0.2$ sr, $\Delta\lambda/\lambda=2\cdot 10^{-2}$, and $\lambda=25$ Å. Thin films (~ 1000 Å) make promising targets for producing effective sources of ultrashort hard x-ray pulses. In this case the main mechanism for removing heat from the target surface is "switched off," and this lowers the stringent requirements imposed on the intensity of the "warming" beam.

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Translated by M. E. Alferieff