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Production of exotic states of matter with the use of X-rays generated by focusing a petawatt laser pulse onto a solid target

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Abstract. **The possibility is discussed of using optical laser radiation with an intensity of $> 10^{20}$ W cm^{-2} to create an ultraintense X-ray source capable of producing polychromatic radiation with a power flux of 10^{19} W cm^{-2} or higher. X-ray radiation of so high an intensity permits not only transforming a condensed matter of the target into a plasma state but also obtaining an exotic plasma state with a high density of hollow ions. Currently not yet in wide use and available in only a few laboratories in the world, lasers with a radiation intensity of about 10^{20} W cm^{-2} are more compact and less expensive than free-electron X-ray lasers or lasers used for the indirect heating of fusion targets. The source under discussion can produce by far higher X-ray intensities than plasma X-ray lasers of a similar scale.**

Investigations into the interaction of superintense electromagnetic radiation with matter, when the aggregate state changes under irradiation, commenced, in essence, in the second half of the 20th century. This research was initiated by the advent of high-power lasers and was strongly motivated by inertial thermonuclear fusion proposals. Since high-power laser systems that existed until recent times operated only in the optical or infrared ranges, investigations of the radiation–matter interaction referred almost completely to the electromagnetic radiation with these wavelengths, i.e., to the situation where the energy of laser photons is much lower than the ionization potential of atoms (molecules) of the target material. In this case, the laser radiation is absorbed by free electrons produced from atomic outer-shell electrons due to multiphoton and tunnel effects (dielectrics) or from conduction electrons (metals). As the free electrons are heated, collisional ionization of deeper atomic shells becomes possible, resulting in the production of a high-temperature plasma of multiply charged ions. To state it in different terms, the laser energy initially goes into the heating of free electrons and only thereafter into the increase in the energy of heavy particles (ions). The wealth of highly interesting experimental and theoretical results obtained to date pertains to precisely the case of high-power electromagnetic radiation interaction with a matter. The modern state of research in this field was reflected, for instance, in recent reviews [1–6].

It was not until very recently that it became possible to carry out laboratory research involving matter irradiation by high-intensity fluxes of photons with energies comparable to the ionization energy of inner atomic shells. We emphasize that the case in point is highly intense fluxes which change the aggregate state of the matter upon its irradiation. This research became possible in connection with the development of ultraviolet and X-ray lasers, both free-electron lasers (see, for instance, Refs [7–9]) and plasma ones (see, for instance, Refs [10–13]). Although this research is still in its infancy [14–22], it has already yielded several unexpected results. For instance, X-ray ablation thresholds turned out to be far lower than optical ones [23–26].

The key feature of high-energy photon–matter interaction is that the photons are absorbed due to the ionization of inner atomic shells. As this takes place, on the one hand, the internal ion energy increases simultaneously, and, on the other hand, the outgoing free electron acquires appreciable kinetic energy even in one elementary interaction event. In other words, in this case, the initial excited state of matter is inherently different from the state obtained under optical radiation heating. Naturally, different relaxation processes will eventually have the effect that the resultant plasma state will hardly depend on the incident radiation wavelength for the same specific energy input. However, in the most topical cases of pico- and femtosecond laser pulses, these times, perhaps, will not be of particular interest, while the description of processes that proceed for several femtoseconds (and even picoseconds) will call for consideration of the peculiarities of laser photon absorption.

Known to date are two types of laboratory sources of high-power short-wavelength electromagnetic radiation fluxes: free-electron lasers [7–9], and plasma lasers [10–13]. To generate coherent ultraviolet or X-ray radiation in the former case, use is made of the energy of an electron beam accelerated to relativistic energies. To produce lasing in the latter case, advantage is taken of the energy stored in a high-temperature plasma, most often in a laser-produced plasma. In principle, a laser-produced high-temperature plasma is always a very bright source of incoherent short-wavelength radiation. When use is made of a laser with a very high pulse energy (several dozen or hundred kilojoules) for a duration not exceeding 1 ns, even thermal X-ray radiation is powerful enough to produce a thermonuclear plasma. This approach is employed in the indirect plasma heating in hohlraum type targets; however, it necessitates the exploitation of unique superhigh-energy laser facilities: the National Ignition Facility (NIF) [27], OMEGA [28], and the Laser MégaJoule (LMJ) [29]. With the use of even high-power lasers, the

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intensity of incoherent X-ray radiation proves to be obviously insufficient for substantially heating condensed targets. In recent years it has been shown, however, that this radiation may be validly employed for radiographic applications [30–37].

As shown recently in Ref. [38], with the use of lasers producing an optical radiation intensity of $> 10^{20}$ W cm^{-2}, it is possible to devise an X-ray source that provides a polychromatic X-ray flux density of at least 10^{19} W cm^{-2}. X-ray radiation of so high an intensity permits not only transforming a condensed target into a plasma state but also obtaining an exotic plasma state with a high density of so-called hollow ions, whose properties are the concern of recent review [39]. Despite the fact that the high-energy lasers with an intensity on the order of 10^{20} W cm^{-2} are not commercially available so far, even now they operate in many laboratories in the world, largely because such lasers are not huge and extremely expensive facilities, unlike free-electron X-ray lasers or lasers employed for indirect fusion target heating. Furthermore, the source under discussion can provide a substantially higher intensity of X-ray radiation than plasma X-ray lasers of a comparable scale.

It is pertinent to note that the resultant X-ray radiation source has a tiny size, and the high X-ray radiation fluxes mentioned above may be realized only in the immediate vicinity of the source. While the source itself is created at the focal spot of the laser beam and, accordingly, is micrometer-sized (from a few to several dozen micrometers), plasma heated by it is produced in the same target in the spatial regions within several focal radii of the optical axis, which will not exceed several dozen micrometers. Naturally, energy will be delivered to this plasma both from the laser beam and from the X-ray source located at the focal spot. Since the intensity of laser radiation decreases exponentially with distance from the axis, while the intensity of the X-ray radiation decreases according to a power law, beginning with some distance the X-ray radiation will play the dominant role in plasma heating. The exotic plasma state mentioned above will be produced at precisely this place. When the X-ray radiation intensity is high enough, this state may be additionally characterized by a significant feature.

To wit, many properties of high energy density plasmas (examples are provided by the plasma of inner stellar regions, the plasma core of a giant planet [40], hot inertial confinement plasmas [41]) are determined by the kinetics of its constituent ions. All kinetic processes may be divided into two groups: those whereby the internal energy of the ions decreases, and those whereby the ion internal energy increases. For instance, such processes as collisional deexcitation and radiative decay belong to the first group. Collisional excitation and ionization, photoexcitation, and photoionization belong to the second group. In the overwhelming majority of laboratory plasmas of multiply charged ions, the second group is dominated by collisional processes. It has been the kinetics of precisely such plasmas that have primarily been studied over many years, both experimentally and theoretically. Meanwhile, there are natural objects in which the opposite is true: the ionization and excitation of ions in these objects proceed primarily due to radiative transitions. Among these objects are, in particular, the nuclei of active galaxies and binary X-ray stars [42].

The dense plasma of multiply charged ions dominated by radiative excitation mechanisms is quite difficult to experimentally reproduce in laboratory conditions, because this requires X-ray sources of extremely high power. For instance, according to the estimates by Colgan et al. [38] (for more details, see below), for photoexcitation/photoionization mechanisms to prevail in the production of hollow ion configurations with a charge of ~ 10, the X-ray photon flux must exceed 5×10^{18} W cm^{-2}. It turns out that the X-ray source considered in Ref. [38] satisfies even this strict requirement.

The main idea advanced by Zhidkov at al. [43] is as follows. High-power laser radiation is focused onto a target, which is a thin metallic foil. The valence electrons are field-ionized [44] and then accelerated to a high energy (on the order of several MeV), when the laser flux provided is high enough. During foil irradiation by a highly intense laser pulse, some of these hot electrons oscillate and pass through the foil [45, 46], emitting X-ray photons of widely different energies, up to γ-ray radiation (see, for instance, Refs [46–50]). The emission mechanisms comprise the Thomson scattering of the incident and scattered laser radiation, as well as the Bremsstrahlung in the strong laser field at the foil boundaries. According to the estimates [38], when the intensity of optical laser radiation exceeds 10^{20} W cm^{-2}, these processes may result in the generation of an X-ray photon flux with an energy of several keV and an intensity of about 10^{19} W cm^{-2}. The conception proposed in Ref. [38] is schematized in Fig. 1.

It is pertinent to note that the X-ray source is polychromatic in this scheme, while modern free-electron X-ray lasers produce bright monochromatic X-ray beams of coherent radiation. The coherence of X-ray laser radiation permits using them for various topical applications, like X-ray interferometry. As recently shown experimentally in Ref. [51], these beams may be focused onto a spot 1 μm in diameter, which makes it possible to obtain even now an extremely high X-ray radiation intensity, at a level of $(1-6)\times 10^{17}$ W cm^{-2} [21, 51]. It goes without saying that the source proposed in Ref. [38] may be employed only when the coherent properties of X-ray radiation are insignificant for the problem at hand. In this case, the main advantage is that, with the aid of existing laser facilities, it is possible to generate X-ray radiation with a flux density of up to 10^{19} W cm^{-2}, which is more than an order of magnitude

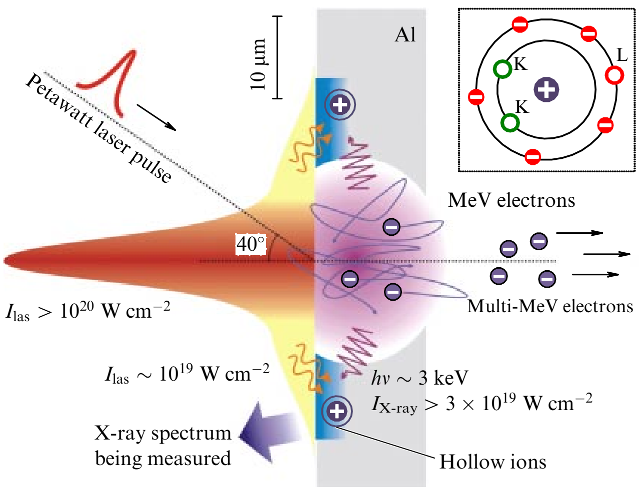

Figure 1. Schematic for the creation of an ultrabright X-ray source in a relativistic laser plasma, whose action on the ambient matter gives rise to a hollow ion plasma [38].

higher than the record high value attained for a free-electron laser [51].

This conception was experimentally realized with the aid of the Vulcan petawatt laser facility (Rutherford Laboratory, UK), which generated a 0.8-ps long pulse at a wavelength of 1.054 μm. The laser contrast ratio was equal to 10^9 for a pulse energy of up to 160 J; the laser irradiation intensity attained a maximum (3×10^{20} W cm^{-2}) at a focal spot 8 μm in diameter, which contained about 30% of the total laser energy. The pulse was p-polarized; the angle of laser radiation incidence on the target was equal to 40°. For a target, use was made of aluminum foils 1.5 and 20 μm in thickness.

The plasma created was diagnosed from its X-ray emission spectra. The spectra in the 7.0–8.4 Å wavelength range (photon energies of 1.47–1.77 keV) were recorded with a high-resolution spectrometer with a spherically bent mica crystal. The selected spectral range contained the K-spectra (i.e., the spectral lines arising from transitions of an optical electron to the K-shell) of multiply charged ions, as well as of neutral aluminum atoms. First of all, we emphasize that the central diagnostic idea was to record the spectra of hollow ions [39], which were also expected to fall into this spectral range. The X-ray spectra emitted by the foils of different thicknesses were traced for different parameters of laser pulses. The results are exemplified in Fig. 2.

As is clear from Fig. 2, lowering the pulse energy from 160 to 64 J leads to appreciable changes in the emission spectrum. For the lower laser energy, the spectrum contains primarily the He_α and Ly_α resonance lines, along with their dielectronic satellites. For the highest laser energy, the spectra are radically different: 'ordinary' spectral lines no longer dominate the observed spectrum, and the emission intensity is highest in the 7.3–7.7 Å and 7.9–8.3 Å spectral regions.

The former spectral range is, as shown in Ref. [38], associated with transitions in the aluminum ions that have two K-shell vacancies and one or several vacancies in the L-shell, i.e., with transitions in hollow ions. It is noteworthy that such hollow ions (one of the possible configurations is schematically shown in the inset to Fig. 1) are significantly different from the previously considered hollow atoms with

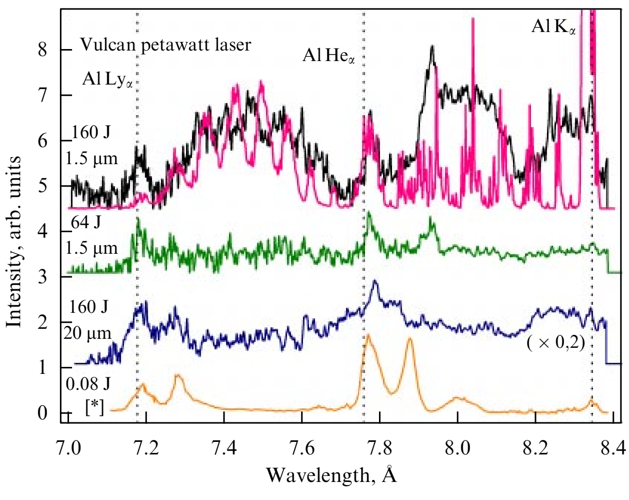

Figure 2. (Color online). X-ray spectra emitted by foils of various thicknesses for different energies of a heating laser pulse (according to data from Ref. [38]). The Ly_α, He_α, and K_α spectral line positions for immobile aluminum ions are marked by vertical dotted straight lines.

LM transitions [52]. The summary spectrum is due to ions of many charge multiplicities, from Al III to Al X. For all of these ions to exist, the density must be high (at a level of 10^{23} cm^{-3}), whereby a three-body recombination will efficiently counterbalance the ionization by X-ray photons and prevent them from ionizing the plasma completely.

The longer-wavelength emission (7.9–8.3 Å) is similar to the radiation considered above, with the only difference being that it arises from transitions in the ions with one K-shell vacancy. This part of the spectrum is emitted at a somewhat later time, when not only the electron plasma density becomes lower but also the intensity of heating X-ray radiation significantly reduces.

As noted above, the pump laser radiation emerges when the electrons oscillating in the laser field pass through the foil. With an increase in foil thickness, such a process becomes progressively less efficient. This is the main reason why the lines of hollow ions disappear from the spectrum observed at a foil thickness of 20 μm (see Fig. 2, blue line).

Shown in Fig. 2 for comparison is a spectrum (the lowest curve) obtained for a lower laser flux, 5×10^{17} W cm^{-2} (for a pulse energy of 80 mJ) [53]. This spectrum is typical for a solid target plasma produced by a high-contrast laser pulse of moderate intensity, when there is no additional heating by X-ray radiation. It is easily seen that hollow ion spectra are not observed in this case as well.

The discrepancy in emission spectra shows that the physical picture of plasma production and heating for a large energy input, which is characteristic of the experiments reported in Refs [38, 54], is different from that observed for lower intensities. In this case, initially rapid field ionization of the valence electrons of the target occurs [43]. These electrons are then accelerated in the strong electromagnetic laser field and their ponderomotive energy amounts to 10 MeV for intensities above 10^{20} W cm^{-2} [55]. The thin aluminum foil is virtually transparent to such accelerated electrons [43], but these electrons rapidly lose their energy due to bremsstrahlung [56] and nonlinear Thomson scattering [57, 58]. The dependence of the generated X-ray emission power on the laser field intensity may be estimated by invoking the radiative friction force [44]. Estimates [38, 54] suggest that this force increases in proportion to the high power of laser amplitude (the 4th or the 6th, depending on the radiative process type and the plasma density); for a laser intensity of about 5×10^{20} W cm^{-2}, it may amount to about 10^{19} W cm^{-2}, with the average photon energy falling in the kiloelectron-volt range.

These X-ray photons interact with the ions and atoms of aluminum to produce vacancies in the K and L inner shells. It is significant that the photoionization cross section for deeper shells is larger than for more outer ones. We also note that keV-energy photons are much more efficient in removing K-electrons than are electrons of the same energy [39]. In Ref. [50], where a laser of similar power was employed for plasma heating but use was made of thicker targets, it was discovered that hollow ions were produced due to ionization by fast electrons, but the efficiency of this process was extremely low.

To produce a rather high population of K^2 type hollow ion states [i.e., with a double vacancy in the K-shell (see the notation of hollow ions in Ref. [39])] comparable to the population of ordinary autoionization states (i.e., levels with one vacancy in the K-shell), photoionization must be the main decay mechanism of the autoionization states. Let Q_K

be the population rate for the state with one K-vacancy, then the population rate Q_{K^2} for the state with two K-vacancies is expressed as $Q_{K^2} = Q_K W_{ph}/(\Gamma_K + A_K + W_{ph})$, where W_{ph}, Γ_K, and A_K are the photoionization, autoionization, and radiative decay probabilities, respectively. Since the decay probabilities of the states K and K^2 are of the same order of magnitude, their population ratio will be defined by the population rate ratio Q_{K^2}/Q_K, i.e., by the quantity $W_{ph}/(\Gamma_K + A_K + W_{ph})$, which is close to unity provided $W_{ph} > \Gamma_K + A_K$. Since $W_{ph} = (I_{\text{X-ray}}/\hbar\omega_{\text{X-ray}})\,\sigma^{ph}$ (where $I_{\text{X-ray}}$ is the pumping X-ray radiation flux with a photon energy $\hbar\omega_{\text{X-ray}}$, and σ^{ph} is the photoionization cross section) and $\Gamma_K > A_K$, this signifies that the condition $(I_{\text{X-ray}}/\hbar\omega_{\text{X-ray}})\,\sigma^{ph} > \Gamma_K$ should be fulfilled. For Al XII ions and $\hbar\omega_{\text{X-ray}} \sim 2$ keV, the K-shell photoionization cross section is equal to 5.5×10^{-20} cm^2 and the autoionization probabilities are about 10^{15} s^{-1}. And so, for the hollow ions to be prevalent in the plasma, the condition $I_{\text{X-ray}} > 10^{19}$ W cm^{-2} must be fulfilled, which corresponds to the estimates made above.

To obtain quantitative estimates, kinetic simulations were made in Refs [38, 54] of the spectra of hollow ions using the ATOMIC code [60]. A nonstationary calculation was initially performed in the framework of a simplified atomic model, which permitted determining the characteristics of the main part of the plasma. The calculated data evidenced that the stationary mode is attained very quickly for the high electron density under consideration. The simulation was carried out with the inclusion of all elementary atomic processes which could proceed in the plasma (photoionization, collisional ionization, autoionization, collisional excitation, photoexcitation and deexcitation, radiative and three-body recombination).

After that, stationary simulations were made in the framework of a detailed atomic model, which permitted determining the emission spectrum as a function of the electron temperature T_e, density N_e, and radiation temperature T_r. In doing so, it was taken into consideration that the electron distribution function could be non-Maxwellian, and its high-energy part was described by a hot-electron temperature T_h. The radiation field acting on the plasma was assumed to be blackbody radiation with a temperature T_r. The atomic and ionic structures were calculated using the Los Alamos atomic physics code package, as were the cross sections for collisional processes. Ion state populations were determined by solving the system of stationary kinetic equations for different values of T_e, N_e, T_r, and T_h. Self-absorption effects were included in the framework of the Biberman–Holstein escape factor. The calculated populations were utilized to determine the emission spectrum. In so doing, advantage was taken of the mixed-Unresolved-Transition-Array model developed earlier [61].

To correctly model the exotic plasma state under study, it was necessary to include over 16,000 atomic configurations of aluminum ions, in which up to five electrons were transferred from the inner K- and L-shells to the external M-, N-, etc. shells. It turned out that the inclusion of multiply excited states is extremely important for the adequate description of the observed spectrum. It was found, in particular, that L–K transitions, many of which are quite weak by themselves, can produce clearly defined peaks in the observed spectrum owing to summation of a huge number of transitions which differ only in outer-shell configurations and are therefore quite close in wavelength.

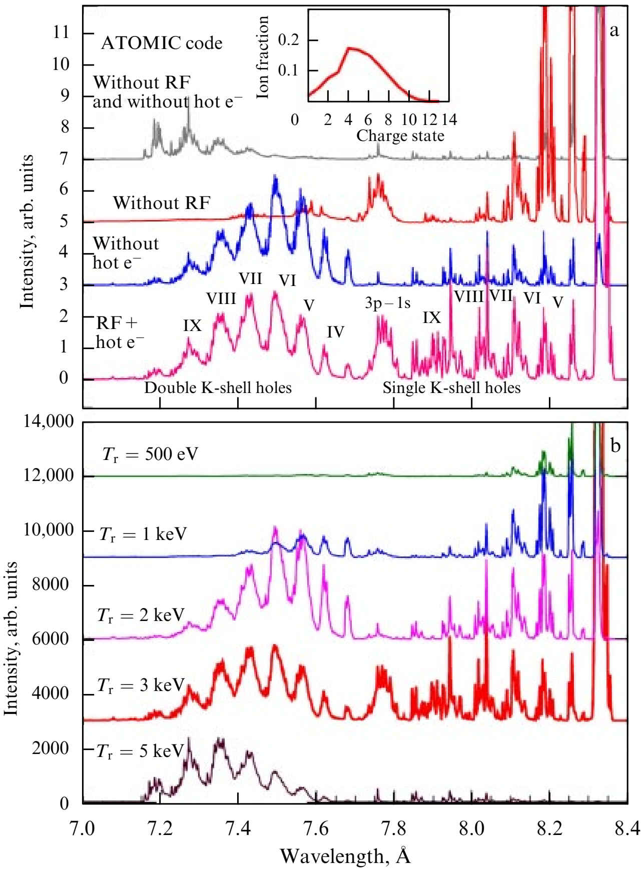

Figure 3. (Color online). Plasma emission spectra of solid aluminum targets [38] (calculated by the ATOMIC code package [60]), which demonstrate the dependence of the spectrum on: (a) the presence or absence of fast (hot) electrons in the plasma and/or an intense source of X-ray keV radiation (radiation field – RF); (b) the radiation temperature of the X-ray source in the range between 0.5 and 4 keV (with the inclusion of the simultaneous action of the hot electron flux).

The pink curve in Fig. 3a is plotted for the simulated spectrum [38] of plasma exposed to a radiation field (RF) with a temperature $T_r = 3$ keV. The electron density is $N_e = 3 \times 10^{23}$ cm^{-3}; it contains a small fraction (5%) of hot electrons with $T_h = 5$ keV, while the bulk of electrons is characterized by a temperature $T_e = 55$ eV. One can see that transitions from the hollow configurations of aluminum ions with different charge multiplicities clearly show up in the calculated spectrum. A comparison with experimental data (the black and pink curves) discloses that the kinetic simulation reproduces quite well almost all features of the observed spectrum. It was found, in particular, that transitions in K^2-hollow ions resided in the 7.2–7.7 Å domain manifest themselves in the observed spectrum for all ion charge multiplicities, from Al IV to Al IX. Interestingly, the total intensities of transitions associated with one ion or another are in agreement with the ion charge state distribution over degrees of ionization shown in the inset to Fig. 3a. The emission lines were identified [38, 54] for the states with 2–6 electrons removed from the K-and L-shells.

Observed in the 7.7–8.3 Å spectral range are transitions from the states with one L-shell vacancy, i.e., so-called dielectronic satellites, which are emitted primarily by lower-density plasma domains produced due to the expansion of the initially produced solid plasma.

For conclusive confirmation that it is precisely the external radiation field which is responsible for the excitation of K^2-hollow ions, Fig. 3a displays the results of simulations (the red and grey curves) in the absence of the source of photopumping. One can see that no hollow-ion spectra are evidenced in this case, including those located in the 7.2–7.7 Å range. The red curve shows that adding of hot electrons with $T_h = 5$ keV does not improve the situation. Whence, it follows that it is precisely the external radiation field which entails the abrupt change in the spectrum observed.

The blue curve evidences the role of photopumping in conditions when there are no hot electrons in the plasma. One can see that the hot electrons contribute to the excitation of hollow ions in the presence of photopumping, but their contribution is negligible.

Figure 3b illustrates the role of the temperature of the external radiation field. It is evident that the photopumping cannot excite an appreciable number of hollow ions for as long as $T_r < 500$ eV, because the photoionization and photoexcitation probabilities are not high enough and the plasma kinetics are determined, as usual, by collisional processes and spontaneous radiative decay. On raising T_r to 1 keV, a small number of new lines appear in the spectrum. But it is not until $T_r = 2$ keV that an abrupt change occurs in the emission spectrum, associated with a transition from collisional kinetics to primarily radiative ones. A further increase in T_r initially brings about a better agreement between the simulated and experimental data (for $T_r = 3$ keV), but then (for $T_r = 5$ keV) the agreement deteriorates.

A comparison of the simulated and experimental data suggests that the only way to explain the results obtained at the Vulcan facility consists in the inclusion of an external radiation field with a characteristic photon energy of about 3 keV. Recall that the cause of the emergence of this field, which was discussed in the foregoing, is due to the following two factors: (1) the employment of a laser with a radiation intensity of up to 3×10^{20} W cm^{-2}; (2) the use of a thin (1.5 μm) foil as the target. When at least one of these conditions is not fulfilled, the ultraintense X-ray source does not emerge and, as a consequence, a plasma of hollow ions is not produced.

As noted above, the intensity of this X-ray radiation source is much higher than that of present-day free-electron X-ray lasers. This brings up the question of how efficiently the energy of a laser pulse is converted to X-ray radiation energy in this source. First of all, it is pertinent to note that the laser-to-X-ray radiation conversion coefficient depends on the intensity of laser radiation and may range, according to simulations, up to 30% in power for a laser radiation power of 10 PW [46]. In the experiment under our consideration, the laser pulse was absorbed at a focal spot 8 μm in diameter. For the laser intensity of 3×10^{20} W cm^{-2} in use, this gives a figure of about 1.5×10^{14} W for the power of absorbed laser energy. The X-ray radiation will be generated mostly in the direction parallel to the target surface (i.e., perpendicular to the direction of acceleration of the hot electrons), and the X-ray flux will pass primarily through the side surface of a cylinder whose base is the focal spot and the height is the hot-electron oscillation amplitude, which must be no less than the target thickness. For the measured X-ray radiation flux equal to $\sim 10^{19}$ W cm^{-2} [38], we thus obtain an X-ray radiation power of 3.8×10^{12} W. That is, in this case, the conversion coefficient was equal to about 2.5%.

From the results of work [38], we mark out two implications which are the most topical, in our view.

The first of them has to do with the implementation of a relatively compact laboratory X-ray source with a power sufficient for producing the new exotic plasma state by short-wavelength irradiation of a solid body. This source may be used in experimental research that, until recently, could be conducted exploiting free-electron X-ray lasers, which are unique expensive facilities of very limited accessibility. For instance, this source may be employed in research aimed at the realization of highly excited discrete ion states in strongly coupled plasmas, which have recently aroused vivid interest [20].

It is noteworthy that such a source will be an extremely bright source of γ-ray radiation when use is made of laser fluxes of an ultrahigh intensity exceeding 10^{22} W cm^{-2} [46–48]. As follows, for instance, from the calculations [46], with the employment of a 10-PW laser with a pulse duration of 30 fs, it is possible to generate a γ-ray radiation pulse with photon energies on the order of 20 MeV and a power of about 2.75 PW, i.e., quite comparable to the power of a pump laser. In this case, hollow ion plasmas may be produced for the heaviest elements of the Periodic Table.

The second implication is related to the possible diagnostics of this exotic plasma state. Reference [38] confirmed the assumption made in Ref. [39] that the spectra of hollow ions will be the most appropriate diagnostic tool in the investigation of the effect of short-wavelength irradiation of a matter at high energy densities.

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