Present state of research into the interaction between powerful laser radiation and high-temperature plasmas

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Research into the interaction between powerful laser radiation and plasma is reviewed in the context of laser fusion. Topics discussed include absorption and scattering of laser radiation by plasmas and the transfer of heat from the region in which absorption takes place to denser plasma layers. It is shown that parametric processes that lead to anomalous (nonclassical) absorption and scattering of laser radiation by plasmas do not prevent the attainment of laser energies of the order of kilojoules or dozens of kilojoules. The main problems that await investigation before existing data can be extended to the megajoule range that is necessary for the ignition of fusion reactions by lasers are reviewed.

1. INTRODUCTION

Inertial fusion (IF) has in recent years occupied a prominent place in fusion programs undertaken by the most advanced countries across the world. In the United States, IF funding is comparable with the funding of magnetic systems.[1,2] A similar situation has emerged in Japan. The European high-performance laser facility[3] has a component devoted to IF. Similar projects are being discussed in our own country.

The US inertial fusion program provides for the ignition of fusion reactions at the end of the present decade, i.e., before the year 2000.[1,2] The attainment of this goal will depend on the successful completion of an extensive range of construction and technological projects as well as the development of new high-power laser systems and new laser targets. Purely scientific studies of the laser/plasma interaction in IF targets and of the dynamics of plasmas in the field of an electromagnetic pulse will also be necessary. The scientific problems in laser-plasma physics as a whole were formulated 15–20 years ago, and there is now an extensive body of data in this field. However, the increase in the output of laser installations and in the size of plasmas available for power engineering has necessitated a constant re-examination of the data in the light of the relative importance of different processes, the interplay between them, the methods used for illuminating the targets, the target parameters, and so on.

The following appear to be the most important current goals for studies of the interaction between laser radiation and high temperature plasmas:[1-3]

1. Improved understanding of processes governing the absorption of powerful laser radiation by plasmas, of large dimensions and development of reliable scaling for the absorption coefficient at high laser intensities.

2. Development of methods for controlling stimulated Mandel'shtam–Brillouin scattering (SMBS) in low-density plasmas of large dimensions.

3. Studies of a range of topics involving stimulated Raman scattering (SRS) in plasmas, including the interpretation of low-threshold generation of SRS and the observed level of nonlinear saturation.

4. Studies and development of scaling for the conversion of laser radiation energy into electron beams and the development of methods for reducing the number of fast electrons to a level acceptable for IF.

5. Deeper theoretical and experimental studies of filamentation and self-focusing of laser radiation in plasmas of large dimensions, and elucidation of the interrelation between filamentation and other parametric processes such as SRS, SMBS, and parametric decay.

6. Studies of heat transfer in the plasma corona and the conversion of laser radiation into x-rays; development of methods for increasing the conversion efficiency and for controling the spectrum and duration of x-ray emission for different targets.

7. Development of methods for improving the uniformity of energy absorption and the compression ratio for targets of different design with a view to controlling the coherence (both spatial and temporal) and the profile of laser beams.

These are complex problems whose solution will depend mostly on advances in the experimental base. The major modern installation for laser fusion (LF) is the *Nova* at the Livermore National Laboratory in the United States. This system generates up to 100 kJ per nanosecond pulse at the wavelength of 1.06 μm and 50–60 kJ at 0.35 μm. This is the only installation that can produce plasmas with millimeter dimensions which are typical for targets in which thermonuclear fusion reactions can be ignited. However, experiments on the physics of the interaction (in so far as they have been published) have been confined to lower energies, namely, 2–4 kJ. Such experiments do not constitute a direct simulation of the ignition conditions and amount to an intermediate stage along the path to full-scale experiments.

Kilojoule laser pulses can also be produced in the Omega installation at Rochester University in the USA, the Vulcan System at the Rutherford Laboratory in England, and the Gekko-12 at the Institute for Laser Technology at Osaka (Japan). However, more or less systematic studies of the physics of the laser/plasma interaction have been carried out only at the Rutherford Laboratory. Moreover, a series of experiments on the interaction between laser radiation and

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plasmas at lower energies (a few dozen kilojoules) were performed at the Naval Research Laboratory in Washington (USA), the National Research Center at Ottawa (Canada), the National Laser Facility at the Ecole Polytechnique at Palaiseau (France), and the Institute of Basic Physics of the USSR Academy of Sciences in Moscow. They differ from previous work by greater experimental sophistication and a broader set of diagnostic facilities capable of yielding more detailed information on the interaction processes and of providing a means of scaling these interactions to higher energies.

Our aim in this brief review is to examine current work on the physics of the laser/plasma interaction and to identify the basic problems that will have to be solved in the next few years.

2. ABSORPTION OF LASER RADIATION BY TARGET PLASMA

The attainment of a high absorption coefficient for laser radiation in a plasma target has always been one of the most important problems in fusion research. The transition during the first half of the 1980s to lasers generating shorter wavelengths (0.25–0.35 μm) resulted in higher absorption coefficients, i.e., $\geqslant 80\%$. At the same time, the absorption process was largely confined to inverse bremsstrahlung, i.e., the classical mechanism. The absorbed energy was therefore transformed into the thermal energy of the plasma, and the number of accelerated particles was quite low. The accelerated electrons observed in these experiments were ascribed to stimulated Raman scattering which, together with stimulated Mandel'shtam–Brillouin scattering, was responsible for the reflection of the laser radiation.

Stimulated scattering plays an important part in modern experiments on the interaction between laser radiation and high-temperature plasmas. An analysis of the underlying processes is presented below. However, recent evidence suggests that there is appreciable nonlinear absorption of shortwave laser radiation in modern large-scale experiments.[4,5] Analysis of plasma emission spectra at the second-harmonic frequency (Fig. 1) provides convincing evidence for the presence of parametric instabilities near the critical density even for relatively low laser flux densities (less than 10^{14} W/cm^2), i.e., values below those necessary for the ignition of fusion. The importance of parametric processes in the region of the critical plasma density has again been raised in Refs. 4 and 5 in relation to the generation of hard electrons. This is in agreement with the view of Soviet workers who, more than a decade ago, emphasized the importance of parametric absorption near the critical and quarter-critical densities[6] and parametric absorption effects in plasma emission spectra at frequencies corresponding to the harmonics of the laser radiation.[7]

Parametric absorption transforms laser radiation into longitudinal plasma waves localized near the critical and quarter-critical plasma densities for which the following resonance conditions are met, respectively: $\omega_0 \approx \omega_{pe}$ and $\omega_0 \approx 2\omega_{pe}$, where ω_0 is the laser frequency, $\omega_{pe} = (4\pi e^2 n_e e/m_e)^{1/2}$ is the electron Langmuir frequency, e and m_e are the charge and mass of the electron, and n_e is the electron concentration. A parametric instability corresponding to the decay of a photon into a plasma-electron wave (plasmon) and an ion-acoustic wave (phonon) is excited near the critical density, and the decay of the photon into two plasmons occurs near the quarter-critical density.

The excitation and nonlinear saturation of parametric instabilities were examined in some detail in Ref. 8, but this discussion was confined to the idealized conditions prevailing in time-independent, homogeneous, and weakly-inhomogeneous plasmas. Because the plasmon group velocity is low even when the transformation coefficient is low, the corresponding electric-field amplitude may substantially exceed the laser field and may therefore lead to highly nonlinear effects such as the generation of accelerated electrons and laser-frequency harmonics, plasma density deformations, and so on.

Theoretical estimates[6] indicate that up to 10% of parametric absorption is possible under conditions typical for the ignition of thermonuclear fusion reactions. However, there are as yet no reliable measurements of the contribution of parametric absorption of laser radiation by plasmas. Such measurements present a very complex experimental problem, but it has become increasingly obvious that such experiments will have to be performed, especially in connection with the direct target compression method.[1] Recent publications[4,5] suggest that this is becoming one of the more important problems among those tackled by the LF program.

3. STIMULATED MANDEL'SHTAM–BRILLOUIN SCATTERING

In addition to parametric absorption in laser plasmas there are also important processes such as parametric (stimulated) scattering in which a laser photon decays into another, lower-frequency photon and a plasma oscillation, i.e., a plasmon (SRS) or photon (SMBS). Studies of stimulated scattering in laser plasmas are reviewed in Ref. 9.

SMBS is now regarded as a serious impediment to the efficient introduction of energy into plasma. Most of the radiation reflected by plasma is ascribed to it. The main danger

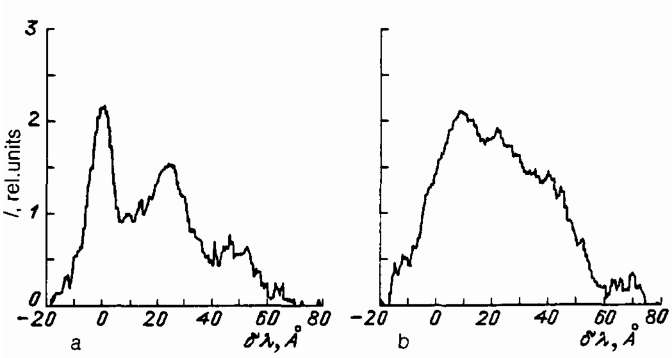

FIG. 1. Plasma generation spectra at the frequency of the second harmonic of the laser radiation, reported in Ref. 5 for a molybdenum target exposed to radiation flux density of 10^{13} (a) and 3×10^{13} (b) W cm^{-2}; normal incidence, detector at 45°. The peak at the unshifted frequency is ascribed to the linear transformation of the laser radiation to the second harmonic. The other peaks in (a) are due to the parametric decay instability (just above threshold). The broadening of the spectrum in (b) is due to plasma turbulization near the critical density.

with SMBS is that this parametric instability encompasses a broad region of plasma ranging from the critical density $n_e \approx n_c = m_e\omega_0^2/4\pi e^2$ to less than $0.01n_c$, i.e., $n_{e,\min} \approx n_c T_e/m_e c^2$ where c is the velocity of light and T_e is the temperature of plasma electrons. An increase in the target size and laser-pulse duration is accompanied by an increase in the size of the region in which SMBS is excited and, correspondingly, an increase in the fraction of reflected radiation. This applies equally to both direct and indirect target compression methods because, in both cases, the laser radiation must cross a relatively thick layer of low-density plasma before it reaches the absorbing region. It is possible that the generation of hard electrons and the inhomogeneity of energy release have more hazardous effects because the target is spatially separate from the absorption region, but the suppression of nonlinear reflection is a problem common to all types of target.

SMBS data at kilojoule levels are reported in Refs. 9 and 10 ($\lambda_0 = 0.53\,\mu$m) and Ref. 11 ($0.35\,\mu$m). The most important empirical fact is the relatively low level of SMBS reflection, ranging from 10% at $\lambda_0 = 0.53\,\mu$m and of the order of 5% at $\lambda_0 = 0.35\,\mu$m. At flux densities in excess of 10^{14} W/cm^2, the latter percentage remains practically constant. An increase in the flux density produces a change in the scattering pattern whereby backward scattering at low flux densities is replaced by 'lateral' scattering for flux densities $\geqslant 10^{15}$ W/cm^2 (Fig. 2).

In principle, an SMBS level of the order of 10% is acceptable for LF, but it is still not clear how it depends on the plasma inhomogeneity scale L. The values of L attained in the experiments reported in Refs. 10 and 11 amount to $\leqslant 400$ μm which is lower by roughly an order of magnitude than the values expected for the megajoule range. It is still not clear how an increase in L will affect the level of scattering since experimental data[10,11] cannot be compared with existing theories. The analysis reported in Ref. 11 shows that the observed SMBS threshold is close to theoretical predictions for homogeneous and infinite plasmas, and is appreciably lower than the predictions of the theory that takes into account density inhomogeneities and would therefore seem to be closer to reality. This is also indicated by preliminary results reported in Ref. 12 in which an ultrashort laser pulse,

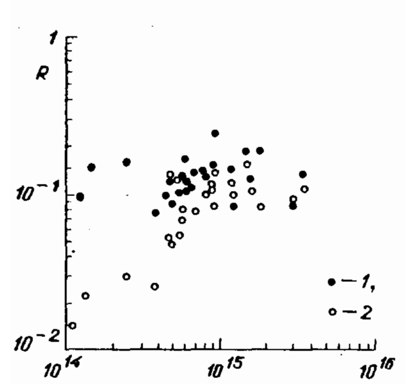

FIG. 2. SMBS reflection coefficient R as a function of q for $0.53\,\mu$m laser radiation (3.5 kJ per pulse; plasma dimensions $L \geqslant 1000\lambda_0$): *1*–backward scattering (180–150°); *2*–side scattering (150–90°). Gold foil target 5 μm thick, normal incidence, pulse length 1 ns.

10 ps long was used in order to minimize the influence of hydrodynamic motion on SMBS. These data suggest that an increase in the inhomogeneity scale leads to a reduction in the nonlinear scattering threshold and, possibly, an increase in reflection.

The theoretical explanation of this low SMBS threshold may be found in double SMBS (DSMBS) proposed in Ref. 13 and confirmed experimentally in Ref. 14 at low energies (of the order of 10 J).

DSMBS corresponds to two SMBS processes coupled coherently by a common ion-acoustic wave. One of them is initiated by a standing light wave and the other by a wave reflected from dense plasma layers. Since the incident and reflected light waves propagate in opposite directions, the ion-acoustic wave provides a distributed feedback loop between the scattered waves, and the DSMBS process cannot be described by convective amplification (as is usual in SMBS). It is in fact a generation process (absolute instability). In the plane-layer plasma model, the DSMBS threshold is much lower than the SMBS threshold. However, in practice, the density distribution in the laser plasma corona can be very complicated, so that the extension of these descriptions to the megajoule range will have to await further advances in the theory and a detailed comparison with experiment. The question of the magnitude of the nonlinear reflection coefficient and the mechanism responsible for SMBS stabilization have not as yet been finally resolved. Experimental data[11,14] suggest that SMBS undergoes a qualitative change for flux densities $\approx 10^{14}$ W/cm^2, i.e., there is a broadening of the scattered spectrum, the reflected light intensity undergoes small scale fluctuations, and the scattering region changes in the course of time and shifts in space. This suggests that SMBS assumes all the features of a chaotic process. Comparison of the data reported in Refs. 10–15 indicates that the saturation of scattering and chaotic scattering regime are related phenomena. Possible reasons for this interrelation are suggested in theoretical papers[16,17] that discuss SMBS saturation in terms of the nonlinearity of plasma-ion motion.

SMBS saturation in slightly nonisothermal plasmas, i.e., plasmas with $ZT_e/T_i \leqslant 10$ (Z is the mean degree of ionization and $T_{e(i)}$ is the temperature of electrons and ions), is due to the trapping of ions by the ion-acoustic wave field. This is accompanied by a reduction in the phase velocity of the wave, which leads to resonance with the ponderomotive force due to beats between incident and scattered waves, the resonant interaction length becomes shorter, and scattering becomes saturated. The change in the phase velocity of the ion-acoustic wave in space and in time, corresponds to a broadening of the SMBS spectrum and the onset of time-dependent and chaotic scattering. The results reported in Ref. 16 on the level and width of the SMBS spectrum are in qualitative agreement with SMBS experimental data obtained with the CO_2 laser in a prepared plasma at low energies.[18,19]

When the plasma is highly nonisothermal ($ZT_e/T_i > 10$), the few resonant particles present have no appreciable effect on the dynamics of the ion-acoustic wave. The nonlinearity of the ion sound is then due to the steepening of the wave profile, i.e., the generation of its higher harmonics. The analysis reported in Ref. 17 shows that the hydrodynamic nonlinearity leads to the formation of a periodic shockwave that is unstable and splits into a sequence of weakly-coupled independently-moving solitons. This evolution of ion sound results in plasma turbulization, a departure from the coherence of scattered waves, and chaotic SMBS with saturation at a relatively low level.

The above nonlinear SMBS saturation mechanisms are in qualitative agreement with experiment, but require further development for the creation of a complete SMBS model and the construction of the necessary scaling up to the megajoule range.

Control of scattering by a reduction in laser-beam coherence is also important in SMBS studies. The two methods for reducing coherence are the random phase procedure (RPP) proposed by Japanese researchers[20] and induced spatial incoherence (ISI) suggested in Ref. 21. In RPP a plate consisting of square elements is inserted into the beam before the focusing lens. One half of these elements shift the beam phase by 180° while the other half leave it unaltered. This splits the beam into several hundred or even thousand elements with different phases. This method can be used to smooth out large-scale beam inhomogeneites and instead produce a large number of small-scale inhomogeneities (usually smaller than 10 μm) and relatively small field amplitudes in the far zone. The results reported in Refs. 22 and 23 indicate that the SMBS can be reduced by a factor of 10–100 by applying RPP in the kilojoule range. The authors of Refs. 22 and 23 suggest that this effect is due to the suppression of filamentation of the laser beam in plasma, since in these experiments SMBS is largely due to regions of higher field strength, i.e., filaments. It is important to note that the suppression of SMBS by RPP is exclusively due to the fact that the target is located in far zone in which the individual

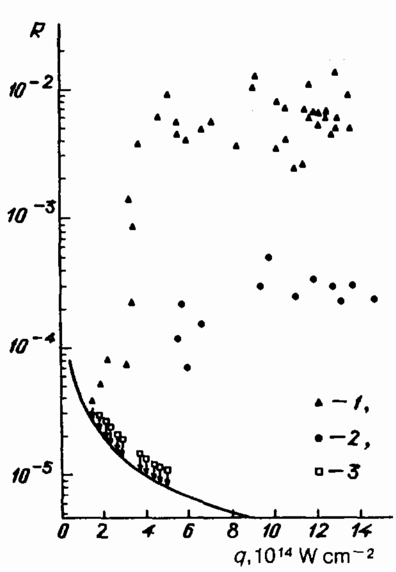

FIG. 3. SMBS reflection coefficient R as a function of q for laser radiation:[22] *1*–coherent laser beam, *2*–randomized phase beam (RPP method), *3*–reduced space-time coherence (ISI method). Solid curve–detection sensitivity threshold. The plasma was in the form of a cylinder 0.3 mm in diameter and 0.8 mm long. Its temperature and density was 0.5 keV and $0.08n_c$, respectively. The second harmonic radiation from a neodymium laser was focused along the axis of the cylinder (pulse length 0.6 ns, energy per pulse up to 500 J). A lens with a relative aperture of 1:10 was used in the case of the coherent beam and the ISI method. The corresponding figure for the RPP method was 1:2.5; the laser-beam correlation time in the ISI method was 2 ps.

beam elements are averaged out and superimposed. The suppression of SMBS is therefore observed provided the focusing lens has a sufficiently short focal length and a relative aperture of 1:5 or less.

A modification of RPP was proposed in Ref. 24 whereby the phase plate was replaced with a matrix of lenses with long focal lengths. This system produced a focal spot with a sufficiently uniform intensity distribution and sharp edges.

The disadvantage of RPP is that the small-scale interference pattern within the focal spot is practically independent of time. Laser beams with relatively short coherence time were suggested in Ref. 21 as a means of achieving averaging in time. In the ISI method, the spatial coherence of the beam is reduced by inserting into it two echelons before the focusing lens, which split the entire beam into several dozen or several hundred elements. The delay between the individual elements is greater than the laser correlation time, so that these elements become mutually incoherent. The interference pattern within the focal spot is then time-dependent. The ISI method is effective in suppressing small-scale filamentation of the laser beam if the laser coherence time is much shorter than the pulse length, but is comparable with the time necessary for the filaments to develop. According to Refs. 22 and 23, the ISI method can be used to reduce SMBS by more than three orders of magnitude, i.e., to the sensitivity limit of the detecting equipment (Fig. 3).

However, there is no evidence that the RPP and ISI methods will influence SMBS in the megajoule range because there are no data on the dependence of SMBS reflection on plasma dimensions.

4. STIMULATED RAMAN SCATTERING

In the currently available energy range (kilojoule range), SRS produces much less nonlinear reflection than SMBS, the factor being not more than 10^{-3}–10^{-4}. The main danger with SRS is that there may be collisionless damping of the electron plasma wave excited during this process and, consequently, undesirable generation of hard electrons. In principle, SRS is therefore more hazardous for direct compression and less hazardous for x-ray targets. Experimental studies of SRS have attracted considerable attention in recent years.[25-33] Advances have also been achieved in SRS theory.[34-41]

Important results were reported in, for example, Ref. 25 in which the correlation between SRS and the generation of accelerated electrons was studied in considerable detail. It was shown that the temperature of the hot electrons was 25–30 keV and was practically independent of the laser energy flux density. The number of fast electrons was directly proportional to the SRS intensity. There was also good correlation between temporal characteristics of the hard x-ray pulses and SRS. All these facts constitute serious evidence that it is precisely SRS that is mostly responsible for fast electrons, and contradict the hypothesis[34] that the SRS process is initiated by a beam of fast electrons. Moreover, the discussion presented in Ref. 35 and 36 shows that the experimental data are as yet insufficient for a positive identification of the mechanism responsible for SRS generation.

Another unresolved problem is the low SRS threshold (appreciable SRS is observed even at flux densities of 10^{14} W/cm^2) and the dependence of the threshold on the plasma inhomogeneity scale. There are reasons to suppose that the low SRS threshold is due to negative feedback loops between waves in the plasma[42] and (or) local density inhomogeneities.[41] SRS then acquires properties typical for absolute instability, and this has indeed been observed experimentally.[32] If these suggestions are confirmed, a further reduction in the SRS threshold can be expected with increasing plasma inhomogeneity scale and, consequently, greater SRS contribution as laser pulse energy increases.

The mechanisms responsible for the nonlinear saturation of SRS and the methods that can be used to control them present us with exceedingly important questions. Simple models[37,38] that relate fluctuations and SRS saturation with enhanced collisionless damping of plasma waves by electrons are in conflict with experimental data because they cannot explain the low level of saturation. An important factor responsible for SRS saturation is probably the enhanced ion-density fluctuation that leads to the randomization of Langmuir waves, their enhanced damping, and trapping in density voids. Secondary parametric instability of Langmuir waves excited during SRS and (or) the SMBS process could be the source of these enhanced fluctuations. This is indicated by numerical stimulations of SRS in the hydrodynamic approximation[39] and the particle-in-a-cell method.[40,43] Further evidence is provided by experimental data on the anticorrelation between SRS and SMBS in laser plasmas at wavelengths of 0.35 μm (Ref. 33). These data partially confirm previous results obtained with a CO_2 laser[44,45] and, in essence, show that SRS and SMBS are never observed at the same time (Fig. 4). However, experiments[44,45] in which the plasma is prepared in advance show that SRS occurs at the initial stage of the interaction and is followed by the slower SMBS process whereas SRS vanishes altogether. The reverse

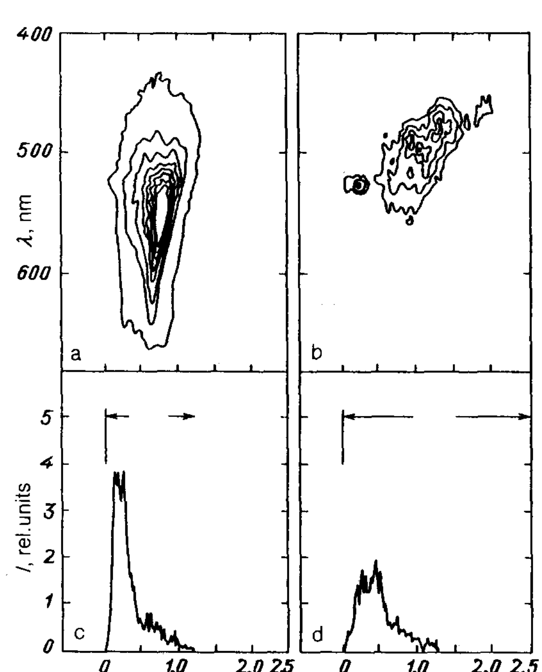

FIG. 4. SRS intensity level curves (a,b) and time dependence of SMBS intensity (c,d). Target–plastic film 3 μm thick. Laser beam at normal incidence, wavelength 0.35 μm, energy per pulse 1–2 kJ, beam spot diameter on the target surface 0.25–1 mm. The pulse length is indicated by arrows in (c,d). The SRS radiation appears only after the SMBS pulse.

situation was reported in Ref. 33, i.e., SMBS continued for less than 0.5 ns on the leading edge of the laser pulse and thereafter the SMBS intensity fell sharply and SRS was observed. It may be that the absence of SRS during the initial stage of the interaction in Ref. 33 was due to the fact that the plasma was formed in the presence of the laser pulse and a time of the order of 0.5 ns was necessary to ensure a greater inhomogeneity scale whilst the SRS threshold fell to the level of the acting laser field. This means that the possible interaction between SRS and SMBS under conditions typical for fusion reactions will require further experimental investigation.

According to Refs. 30 and 31, existing experimental data on SRS can be interpreted in terms of the interaction between three nonlinear processes, namely, additional damping of Langmuir waves by density fluctuations, possibly initiated by SMBS, additional excitation of Langmuir waves by an external source (e.g., an electron beam) or some other parametric instability, and a steepening of the plasma density profile by the pressure produced by the Langmuir waves. The relative importance of these three mechanisms is at present unclear. It seems that filamentation instability of the laser beam also plays a definite role in this connection. This is indicated by experiments[22,23] on the influence of laser-beam coherence on the level of SRS. It has also been shown that, as in the case of SMBS, the RPP technique can be used to reduce scattering by a factor of more than 1000.

Finally, we note that SRS is similar to other parametric instabilities in the sense that it displays chaotic properties, i.e., scattering is fluctuational in character, giving rise to bursts, time-dependent dimensions and position of scattering regions, and a variable scattered spectrum.[30,32] It is still unclear whether these are the properties of SRS itself or manifestations of the saturation mechanisms.

5. FILAMENTATION OF LASER BEAMS AND COUPLING BETWEEN PARAMETRIC PROCESSES

Filamentation instability, which is seen as a local enhancement of the laser field and the formation of filamentary beam structures, occupies a particular place in LF, especially in the direct compression method.[9] Filamentation is often said to arise from an inhomogeneity in the energy released by laser beams in plasma, which influences target compression symmetry, the excitation of secondary instabilities, e.g., SRS and SMBS in strong-field regions, and the turbulization of the low-density corona. As a rule, filamentation leads to the enhancement of inhomogeneites in powerful laser beams, which are already quite large because of inhomogeneities in the amplifying elements of the laser. An increase in the laser beam energy and, consequently, in plasma dimensions, produces a reduction in the self-focusing threshold, whereas a reduction in the radiation wavelength gives rise to more hazardous consequences because of the reduced separation between the absorbing regions and target evaporation.

Filamentation in a plasma with milimeter dimensions and its dependence on laser coherence was recently investigated[23,46,47] in the kilojoule range. In contrast to most previous studies, filamentation was observed by direct interferometry, and additional diagnostic procedures were employed to examine the effect of filamentation on SRS and SMBS.

It was shown in Ref. 46 that for energy flux densities in excess of 10^{14} W/cm^2 and wavelengths of 0.53 μm, the laser beam split into filaments with linear dimensions of $\leqslant 10\ \mu$m, and the maximum field intensity in the filaments was greater by a factor of seven than the average over the beam cross section. This is clearly unacceptable for LF because it leads to considerable compression assymmetry. Analysis of radiation transmitted by the plasma has produced information on the effect of reduced laser-beam coherence on filamentation. According to Ref. 23, the suppression of filamentation by RPP is due to a shift of the characteristic scale of laser beam inhomogeneity toward dimensions $\leqslant 5\ \mu$m which are more stable with respect to filamentation. The suppression of inhomogeneities with larger linear dimensions is in fact the principal aim of methods relying on reduced laser beam coherence. The RPP and ISI techniques can be used to raise the filamentation threshold to 10^{15} W/cm^2 at wavelengths of about 0.5 μm.

It is important to emphasize that, according to Ref. 23, the influence of laser-beam incoherence on SRS and SMBS is conveyed by filamentation. This conclusion is based on the fact that the characteristic laser-beam correlation time (about 2 ps) is greater by more than an order of magnitude than the scattered-field rise time for SRS and SMBS. However, we must emphasize that the results reported in Ref. 23 were obtained in experiments with tenuous plasma prepared in advance. The extension of these data to the plasma in fusion targets may not be satisfactory because there is then no reflected laser wave that could be responsible for the stimulation of filamentation and other parametric processes.[9,13]

6. HEAT TRANSFER IN THE CORONA OF LASER PLASMA

The particular feature of LF is that the laser-beam energy is absorbed in relatively tenuous layers of the plasma corona in which the electron density is $n_e \leqslant n_c$. Even for modern-short-wave lasers, such density values are lower by roughly two orders of magnitude than the density of a solid. Energy transfer from the hot absorbing region to the colder region in which the target material is evaporated is assured by electronic thermal conduction.

The positive consequence of the separation of the energy absorption region from the region of material evaporation is that this can be used to smooth out inhomogeneities in energy release since the heat transfer process is diffusive in character. However, experiments and numerical calculations show that this effect seems to be significant only for long-wave lasers ($\lambda_0 \geqslant 1\ \mu$m). For short-wave radiation ($\lambda_0 \approx 0.35$–$0.5\ \mu$m), the heat transfer length is insufficient for appreciable smoothing of absorption inhomogeneites for energy flux densities $q \geqslant 10^{14}$ W/cm^2. A negative consequence of the separation of absorption and evaporation regions is that the thermal conductivity of plasma is often inadequate to assure the transfer of the necessary amount of heat. There is as yet no unified and generally accepted model of heat transfer in the corona of the laser plasma.

The classical description of heat transfer by the heat transfer equation

$$n_e \partial T_e / \partial t = -\operatorname{div} \mathbf{Q}, \quad \mathbf{Q} = -\chi \nabla T_e,$$

where $\chi \approx n_e v_{te}^2 / \nu_e$, $v_{te} = (T_e/m_e)^{1/2}$ is the characteristic electron velocity, and ν_e is the collision frequency, is valid only for very smooth temperature and density inhomogeneities in which the scale L is greater by a factor of more than 100 than the electron mean free path $\lambda_e = v_{te}/\nu_e$. The thermal flux Q is no more than 0.01 of the maximum energy flux $Q_{fs} = n_e v_{te} T_e$ that can be transported by freely moving electrons. In laser plasmas with laser beam energy densities $q \geqslant 10^{14}$ W/cm^2, the condition $Q/Q_{fs} \leqslant 0.01$ is violated and the actual value of Q is less than the classical value. The result is that the absorption region becomes heated and there are steep temperature and density gradients in the neighborhood of this region.

The maximum heat flux density in laser plasma is commonly characterized by the thermal conductivity limiting factor f defined by $Q_{max} = fQ_{fs}$. Comparison of experimental and computed values shows that f ranges from a few hundreths to a few tenths.[48] Such a large spread in the values of f is probably due to the change in the relative importance of different mechanisms that limit thermal conductivity under different experimental conditions and the very crude conceptual basis used for the coefficient f.

One of the most frequently employed models of heat flux limitation relies on the replacement of the local classical expression for Q with a nonlocal expression corresponding to the "spreading" of the classical flux—$\chi \nabla T_e$ over a region of the order of the inhomogeneity scale.[49–51] However, the expressions for Q proposed in Refs. 49 and 50, and also the coefficient f itself, do not follow from the more rigorous transport description. Other mechanisms restricting thermal conductivity rely on nonlinear effects such as the excitation of oscillations in plasma under the influence of a high heat flux due to ion-acoustic[52] or Weibel[53] instabilities. The reason for the excitation of these instabilities is either a distortion of the electron distribution function, i.e., the onset of anisotropy, or a positive derivative in the region of the phase velocities of the ion-acoustic waves. In both cases, the distribution function becomes unstable with respect to the excitation of either magnetic or density fluctuations. The scattering of electrons by these fluctuations is indeed the reason for the limitation of the flow of heat.

Unfortunately, existing experimental data on laser plasmas do not as yet permit a choice between the different heat-transfer limiting mechanisms. This is why model experiments with large tenuous plasmas, in which steep temperature gradients are produced, are particularly important. The results of a recent detailed model experiment[54] suggest that the observed temperature profiles cannot be described by a single restriction coefficient f and that a complete heat transfer equation will be essential. However, because their parameters are significantly different, the results of model experiments cannot be extended to laser plasmas. It follows that special experiments designed to investigate heat transfer in laser plasmas will also be necessary.

7. CONCLUSION

We conclude that modern experiments on the interaction between kilojoule laser beams and plasmas demonstrate the presence of an acceptable level of absorption ($\geqslant 80\%$) for flux densities in the range 10^{14}–10^{15} W/cm^2 and wavelengths in the range 0.25–0.5 μm. The residual reflection, largely due to SMBS and SRS processes, is practically independent of the laser beam flux density. The fraction of energy removed by fast electrons is relatively small and does not produce a significant deterioration in compression parameters. The methods available for reducing laser-beam coherence (both in space and in time) can be used to suppress parametric processes and to ensure that the classical absorption mechanism will continue to operate up to energy flux densities 10^{15} W/cm^2. This is sufficient to produce pulsed thermonuclear fusion reactions with a positive yield.

However, direct extension of these relatively optimistic results from kilojoule to megajoule energies is unjustified and requires serious additional investigation. This is so because this extrapolation involves an increase in the characteristic scale of plasma by almost an order of magnitude and, at present, we have no inhomogeneity scaling for parametric processes. Moreover, the reasons for the anomalously low parametric threshold and the mechanisms responsible for their nonlinear stabilization are still not understood. It follows that an increase in the geometric dimensions of laser plasmas may lead to a qualitative change in the relative importance of the different parametric processes and the magnitude of the respective effects.

The above factors provide a basis for the systematic investigation of parametric processes in large-scale laser plasmas, including the determination of scaling data for important parameters such as the level of nonlinear SMBS and SRS reflection, the fraction of accelerated electrons, the influence of filamentation on target absorption and compression symmetry, and heat transfer and energy balance in targets of different construction. The solution of these problems will play a key role in successful realization of inertial fusion.

[1] Direct illumination of a spherical target by laser light is referred to as the direct compression method. A high degree of compression can be achieved by ensuring highly symmetric target illumination, which presents considerable technological problems. Less stringent conditions on the laser beam quality are demanded by the indirect compression method in which the target is compressed by x-rays. Laser to x-ray conversion is performed in a special cavity (containing the thermonuclear fusion target). Since the construction of a target for indirect compression is in many respects similar to the construction of a hydrogen bomb, most of the data on x-ray compression is not published in open literature.

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