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Scientific session of the Division of General Physics and Astronomy of the Russian Academy of Sciences (22 April 2002)

A scientific session of the Division of General Physics and Astronomy of the Russian Academy of Sciences (RAS) was held on 22 April 2002 at the P N Lebedev Physics Institute, RAS. The following reports were presented at the session:

(1) **Krokhin O N** (P N Lebedev Physics Institute, RAS, Moscow) "Laser fusion: state of the art and prospects";

(2) **Letokhov V S** (Institute of Spectroscopy, RAS, Troitsk) "Lasing in space".

An abridged version of the reports is given below.

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Laser fusion: state of the art and prospects

O N Krokhin

Within the span of the four decades that elapsed since the advent of the first laser and nearly as many years since the first proposals that lasers should be employed to induce the reaction of nuclear fusion, the attitude toward the feasibility of a laser fusion (LF) program has been changing. Clearly, the technical difficulties arising in the path of implementation of this program are extremely hard to overcome despite the initial simplicity of the idea: there is the requisite power density of the light flux, and there is a highly ignitable fuel — a deuterium – tritium mixture. And the energy scale of a laser pulse required to initiate the reactions is not in itself too large and could well be realized. However, even today the LF problem involves tackling the question of how to realize the conditions appropriate for the 'ignition' of a fusion target.

Beginning with the 70s of the past century, the concept of compressing spherical fusion targets to high densities of the order of 100 times the initial density of liquid or solid DT was adopted as the basic 'strategic' avenue of LF research. Given, say, a deuterium – tritium globular target with a radius of 1 mm and a liquid-state density (0.2 g cm^{-3}, i.e., with an atomic number density $n = 5 \times 10^{22}$ cm^{-3}), no more than 0.1 MJ of energy is required to heat it to a temperature of 2 keV. In this case, the ignition criterion $n\tau \sim 10^{14}$ (where τ is the expansion time) will be fulfilled because, assuming an expansion velocity of the order of 10^8 cm s^{-1}, τ will approximate 10^{-9} s. (In LF, it is more common to use the criterion ρr in lieu of $n\tau$; $n\tau = 10^{14}$ corresponds to $\rho r \sim 5 \times 10^{-2}$ for a deuterium – tritium mixture.) This is seemingly feasible. But here the laws of physics come into play — is it possible to add the energy, the way we would like it to be added, to the DT plasma?

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One of the main obstacles is the impossibility of introducing laser radiation into a high-density plasma. The laser radiation is too soft, i.e., low-frequency, for our purposes. For instance, radiation with a wavelength of 1 μm (a neodymium-glass laser radiates at a wavelength of 1.06 μm) has a cyclic frequency $\omega = 2 \times 10^{15}$ rad s^{-1}. The frequency of an electromagnetic wave propagating through the plasma should exceed a certain value termed the Langmuir frequency $\omega_p = (4\pi ne^2/m)^{1/2}$, where e and m are the electron charge and mass. The plasma density whereby the condition $\omega = \omega_p$ is fulfilled is referred to as the critical density. For $\lambda = 1$ μm, the critical number density is 10^{19} cm^{-3}, i.e., is three orders of magnitude lower than the liquid hydrogen number density.

Therefore, on the one hand, the direct heating of a high-density plasma seems to be problematic. On the other hand, the reaction rate, proportional to n^2, for a low material density is also low — in this case, additional plasma confinement is also required. And for the fusion reaction to proceed in the mode of free material expansion (inertial confinement), we must find a way of increasing the plasma density.

This concept has been pursued since the early 1970s. It proceeds from the compression of spherical targets due to irradiation of their exterior surface by high-intensity laser beams, which results in the evaporation (ablation) of the outer part of the spherical target and the consequential building up of pressure on the target surface, which brings about an inward target compression. This concept is logically closed and can undoubtedly be implemented. This brings up the only question: what is the price to be paid? What is the requisite minimum of expensive laser energy?

This approach has a very useful immanent property: the higher the degree of compression, the lower the energy required for initiating the reaction (in inverse proportion to the square of the degree of compression). However, there are also disadvantages and difficulties. In my opinion, the weakest point of this approach is the low coefficient of energy transfer: the energy that goes into the ablation-driven compression accounts for only 10% of the total quantity, the remaining energy being wasted in the expanding plasma. Another significant point is the necessity to simultaneously provide a high degree of compression and the heating of the DT volume at the center of the target in the final stage. This problem is solved by choosing the proper design of the target (as a rule, they are thin shells with a DT layer frozen on the inside of the wall) and by selecting the rate of laser radiation energy delivery to the target surface. However, the compression process is subject to the Rayleigh–Taylor instabilities whose development defines the state of the material at the final compression stage. This sets limits on the plasma parameters, both in density and in temperature ('smearing' them and mixing the material), in comparison with those which would be expected under ideal cumulation.

The above circumstances cast some doubt upon the correctness of choosing this line of implementing ignition. This brings up the natural question: is it warranted to expend so highly organized a form of energy as laser radiation for a 'brute-force' approach? That is why I believe that alternative schemes and techniques should be contrived, which may prove to be more efficient.

I feel certain that the last word in the field under discussion has not yet been uttered and there exist routes that lead beyond the province of the scheme now being elaborated. A long time ago, we considered at the P N Lebedev Physics Institute (Moscow) the possibility of directly heating frozen DT, enclosed in a heavy shell, with the aid of a short laser pulse fed through tiny openings in the shell. Later on there emerged proposals for a target design which has come to be known as a 'greenhouse', wherein laser radiation is delivered to a low-density material layer. Lastly, six years ago scientists (including scientists from our P N Lebedev Physics Institute) came up with the idea that the processes of compression and heating should be 'separated'. This approach is now referred to as 'fast ignition' and implies the ignition of a compressed target with a very short, well-focused laser pulse. The latter deserves attention and invites thorough investigation, especially so because it involves new physics, though with a yet uncertain outcome.

The heart of the concept developed at LLL (Livermore) is as follows. For extremely high flux densities, in a thin channel through which laser radiation is propagated, one might expect the formation of conditions that favor a deep penetration of the light energy into the above-critical high-density plasma.

It is anticipated that electrons together with ions would be forced out of the light beam due to the ponderomotive forces directed opposite to the gradient of the laser field amplitude squared. Furthermore, a tremendous force also acts on the electrons in the longitudinal direction. There forms a reduced-density channel (the so-called self-focusing) and it is reasonable to expect that the density would be subcritical and the energy would be delivered to the dense precompressed target core. The absorbed light energy would heat the material, thus causing ignition.

This concept is now being experimentally investigated in model conditions. The fundamental fact discovered is the production of a large number of fast electrons with energies ranging into the hundreds of kiloelectron-volts, which are ejected from the field localization region. These data, however, are as yet insufficient for a definitive prediction.

The optimistic view on the solution of the LF problem may, I belive, be based upon the fact that we are witnessing an impetuous (without exaggeration) advancement in generation techniques of high-power laser radiation. Two fundamental advances were made in this field approximately five-to-six years ago, which will undeniably have a strong impact on the future development of the LF program as well as on other fields of laser application. I have in mind, first, the implementation of semiconductor pumping (by means of injection semiconductor lasers) of crystal and glass lasers. It is likely that the total efficiency will be as high as 30 – 35%, and this has already been reached at a level of several kilowatts of continious wave (CW) output power.

Second, it has been possible to realize the mode of ultrashort (femtosecond range) pulse lasing. Few-cycle laser pulses have been produced (few wavelengths in space). Furthermore, impressive energy flux densities were produced in the focal region — up to 10^{18} W cm^{-2}. The feasibility of designing a laser facility with an energy ranging into the hundreds of kilojoules and a pulse duration of several tens-to-hundred femtoseconds is being considered in all seriousness!

Should these projects be realized, the LF program will have unique instruments at its disposal, which would call for a reconsideration of present-day approaches and invite the development of new ideas. One possibility involves going over to ultrarelativistic conditions, when the energy of electron oscillations in the electric field exceeds mc^2. This occurs at energy flux densities higher than 10^{18} W cm^{-2} (for radiation with a wavelength of 1 μm). Under ultrarelativistic conditions the plasma oscillation frequency decreases with an increase in the electron 'mass', resulting in the plasma transparence cutoff shift to higher densities. Moreover, the response of the medium becomes strongly nonlinear, which should be accompanied by rescattering of the laser radiation to high-order harmonics. In any case, going over to a very short pulse duration would allow a more efficient employment of laser radiation energy.

Needless to say that the above considerations are not a simple prediction for the future, but I have been greatly impressed by the fact that 42 years after the first implementation of optical lasing we are witnessing a major 'breakthrough' in the realm of practical laser applications. When did optical fiber communication lines make their appearance? When did compact disks emerge, which ousted mechanical and magnetic recording? Or semiconductor-pumped lasers, which have found use in various technologies? and so on. We have seen all this in recent years, and the results have been achieved owing to the combination of new ideas and technologies. That is why I believe that unexpected and maybe quite simple solutions will emerge in the realm of laser fusion.

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Lasing in space

V S Letokhov

Lasing in a CW mode is implemented under selective or preferential excitation of any appropriate excited quantum level, resulting in disturbance of the equilibrium with the production of inverse population and amplification. With positive feedback, the active medium transforms to a laser [1], but in the absence of the feedback it remains a laser amplifier of both its intrinsic spontaneous radiation and an external light signal. Though making a pulsed-mode laser proved to be an easier task than making a CW laser [2], in the astrophysical conditions of an interstellar medium (nearstellar medium, stellar atmosphere) all characteristic equilibrium-disturbance times are much longer than the characteristic relaxation times for level populations of a quantum system (atom, ion, molecule). That is why in astrophysical conditions the case in point is possible in a CW mode of a maser or laser.