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A NEW X-RAY AMPLIFIER PUMPED BY THE KINETIC ENERGY OF CLUSTERS

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Abstract. A new type of laser amplifier with high gain (80%) and high amplification in the visible and ultraviolet range will still provide sufficient amplification for wavelengths of 100 Angstroms or less by a sequence of injections of energetic solid particles (pellets or clusters). Based on the experimental fact that electrons are laterally emitted from the focus of a laser a free electron laser amplifier was proposed based on the inversion of this experiment. That consists in converting translational electron into optical and oscillation energy of the laser beam. An energy transfer can be expected only from the transient processes of laser pulses. The generalization of this free electron laser towards the injection of solid clusters or dust particles with synchronized and calibrated high kinetic energies and other diffraction properties leads to a very highly efficient (80%) laser with high gain even in the x-ray range. The transient switching process is then extended to the conditions of high density plasma clouds produced from the injected solid particles. In combination with this switching, it is the inversion of the ejection of plasma from the beam axis at nonlinear (ponderomotive) force self-focusing. The processes of the momentum transfer are then well understood and the deformation of phase fronts in plasma can be used for controlled bending, or focusing of x-ray beams, or for correcting of other insufficient beam quality. A proof of principle experiment is discussed.

1. Introduction

The conventional helical free-electron laser [1] is based on the synchrotron radiation emitted when a relativistic electron beam propagates in an undulating magnetic field. This field causes the electron to execute helical motion, and as a consequence, stimulated emission combines coherently to produce a lasing action at the expense of the kinetic energy of the electron beam. This process is dominated by the nonlinear force [2,3] interaction as has been shown by Sprangle et al [4].

Contrary to this conventional free-electron cases with nearly parallel electron and laser beams, an alternative free electron laser scheme consists of an electron beam being injected perpendicularly (or nearly) into an existing laser beam [5,6]. The basic principle of this scheme is that the electron beam is retarded by the nonlinear ponderomotive force [3] when injected radially. Thus kinetic energy is converted into oscillation energy which is then converted into optical energy at switching off of the laser beam. The laser pulse has to be optimized (this criterion will be discussed in more detail later) because if the laser pulse duration is too long, the electron is expelled (reflected or transmitted) from regions of high laser intensity with the effect that the kinetic energy of the electron remains the same. For too short laser pulses the transfer of kinetic into quiver energy is not completed. Thus we have a competition between the radial ponderomotive force and the forces exerted in the direction of the laser beam propagation. These ‘axial’ ponderomotive forces will impart axial momentum to the electrons and thus the laser beam must decrease in momentum to compensate for this change. The question we address in this paper is whether this energy change is negligible compared to the energy gain of the laser beam due to the radial ponderomotive forces. The decrease of the wave momentum of the wavepacket was initially based [5,6] on the work by Klima and Petrzilka [7,8].

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The motivation for such a free-electron laser scheme was provided by the experimental results of Boreham et al [9]. In this experiment a Q-switched neodymium glass laser pulse was focussed in $10^{-6}$ to $10^{-4}$ Torr Helium to a diameter of about 30 m with a maximum intensity of around $10^{15}$ W/cm$^2$ where a Debye-length discrimination appears as in the case of double layers [10,11]. The oscillation energy of the electrons (after ionization) was about 200 eV and in terms of translational kinetic energy of 100 eV [3,9]. This experiment showed that a collisionless absorption process occurs whereby optical energy is extracted from the laser beam and converted into translational kinetic electron energy.

Inversion of these processes leads to the laterally injected free electron laser (LIFEL). The problem, however, exists in the difference between the stationary mechanism of the conversion of the laser energy into the kinetic energy of the laterally emitted electrons in the case of the Boreham-experiment [9,12] to the necessarily non-stationary inverse mechanism. Stationarily, the injection of electrons into a laser beam will lead to a slowing down and a transfer of kinetic energy into oscillation energy [13] such that the electron is reflected if it does not reach the center of the laser beam or is transmitted by reaching finally the same kinetic energy (apart from scattering losses which are very small). LIFEL works only by a stationary-like lateral transfer of the energies as described, and by the subsequent switching-off of the laser pulse to convert the oscillation energy into optical energy as in the Klima-Petrzilka-process [7].

We briefly review the LIFEL process here and based on the resulting limitations conclude how these can be overcome by using condensed material (clusters, pellets or similar of velocities of 100 km/sec or more) to be injected laterally instead of electrons.

It should be noted that there is a connection to very fundamental problems. The axial (forward) momentum necessary for the Klima-Petrzilka-process requires a small axial component of the injected electrons (or clusters) which immediately is identical to the momentum of the gained optical energy [14] which in turn confirms both models: the Klima-Petrzilka-process and the LIFEL amplification. A further problem exists in the fact, that transversal electromagnetic fields with a radial decay theoretically arrive at the negative results. Only the Maxwellian exact electromagnetic field leads to the correct result where for the first time the exact laser field of a beam with the then necessary longitudinal components had to be derived and included [Section 12.3 of ref. 3]. A further problem appeared when the Boreham-experiment [9] was performed with extremely low laser intensities [15] where the multiphoton ionization resulted in an emission spectrum with characteristic maxima, contrary to the high intensity case without maxima and with the ionization by the tunnel-like Keldysh process [16]. An immediate explanation for the different regimes has been given: using a new criterion for a correspondence principle, the first case can be described as a quantum process (similar to the conditions of the Schwarz-Hora effect [17]) while the second case is in the classical regime. This all explains immediately, why most of the radio-wave phenomena are classical and why most of the optical phenomena (apart from those of very high laser intensities) are basically quantum processes [18].

2. Gain Formula for Electron Injection

A particle interacting with a spatially varying high frequency electromagnetic wave will experience the ponderomotive force [3]

$$f_p = -\frac{e^2}{4\pi \omega \epsilon_0^2} \nabla |\mathbf{E}|$$

(1)

as a special approximation of the general nonlinear force [2,19]

$$f_{NL} = \frac{1}{c} \mathbf{j} \times \mathbf{H} + \frac{1}{4\pi} \mathbf{E} \nabla \times \mathbf{E} + \left( 1 + \frac{1}{\omega \epsilon_0} \frac{3}{\nabla} \right) \mathbf{E} \times \mathbf{R} (R^2 - 1)$$

(2)

where $\mathbf{E}$ is the electric field, and $\mathbf{H}$ the magnetic field, and $\omega$ the (central) radian frequency of the laser. $\epsilon_0$ is the refractive index and $\mathbf{j}$ the electric current density. This force shows that the particle will be expelled from regions of high laser intensity to decreasing laser intensity. From a physical viewpoint this force acts on the oscillation-center of the particle trajectory, which in general, consists of a slowly varying drift (of the oscillation-center) and a high frequency motion about the oscillation-center.

In Eq. (2) the complete transient nonlinear force formula was given. Without time derivative, this formula was derived [2] as the complete result on the basis of momentum conservation showing that all terms in Eq. (2) and no others are the correct description. For the transient case, seven different formulations were derived mostly with some simplifi-
cations and approximations. Without having such a tool as the momentum conservation as in the stationary case for proving its generality, Eq. (2) seems to be the most general and probably the final formulation [19].

For the discussion of LIFEL it is sufficient to describe the lateral injection process by the stationary solution (as it was derived in a simplified form by Kibble [13], and to refer the transient process of the switching-on or -off to the Klima-Petrzilka-mechanism [7] since the agreement with the axial momentum transfer has been proved [14]. Any further discussion of the transient process has at least to result in these cases as an approximation before a more general and elegant transient solution can be discussed.

The gain in the LIFEL amplifier is principally very high, up to 90% or more if the fitting of the injection parameters with respect to pulse lengths injection energies etc. are fulfilled. Serious restrictions appear however, when practical electron beam current densities and energy spreads are to be taken into account for calculating the value of the optimized amplification A [5]. Using \( E_p \) as the translative energy of the laterally injected electrons, then it has to be taken into account that this is a center energy around which an energy spread is given by \( \Delta E_p \). Using Eq. (1), it follows that the amplification formula is

\[
A = \frac{2j \sqrt{n_{e}}}{e \pi n_{ec} \sqrt{\Delta E_p}} - \lambda^2
\]  

where the energy spread \( \Delta E_p \) of the electrons is in eV, \( j \) is the current density in Amp/cm\(^2\) and the cutoff density \( n_{ec} \) of the electrons is cm\(^{-3}\). Eq. (3) then becomes

\[
A = \frac{j}{n_{ec} \sqrt{\Delta E_p}} 9.47 \times 10^{10}
\]  

As one example, a CO\(_2\) pulse of \( 7.85 \times 10^4 \) J interacts with an electron beam of \( 10^6 \) Amp and \( \Delta E_p = 71 \) eV and the input energy \( E_p = 0.09 \) MeV, then the amplification \( A \) is 0.337%. After \( 10^3 \) round trips in the cavity, the laser pulse has reached 63.5 MJ while the interaction energy of the electron beam pulses has to be increased up to \( 2.1 \times 10^5 \) J.

3. Cluster Injection

We have shown from the results in the previous section and in [5,8] that \( A \) is only a few tenths of a percent if \( j \) is in the range of the highest available electron current densities of \( M \) Amp/cm\(^2\) for a laser wavelength of \( \lambda = 10 \) \( \mu \)m. While electron beams in the range of \( M \) Amp/cm\(^2\) are available [20] for electron energies of MeV, their slowing down in the laser pulse will generate very high electric fields which may limit the operation of the LIFEL. Because of the \( \lambda^2 \)-dependence, for longer wavelengths, e.g. for \( \lambda = 400 \) \( \mu \)m (or longer) wavelengths, reasonable conditions may be achievable if primary pulses in the GW range are to be amplified [6].

A radical change from the LIFEL is possible by dropping the concept of electron injection at all, in which case we no longer an FEL, and to use for injection condensed (solid or liquid) nearly neutral larger size particles. These types of particles e.g. hydrogen cluster [21,22] are available which contain \( 10^3 \) to \( 10^6 \) atoms and which can be accelerated up to energies of 1 keV per atom as it was realized for neutral injection of tokamaks. Similar clusters can also be produced from argon and a number of recently developed techniques are ascending into this direction. Another most important technique is the pellet generation pioneered by Hendricks [23] where solid spheres with \( 10^7 \) Hz repetition and a jitter in the size by less than \( 10^{-4} \) can be produced.

The inversion of this process, the plasma ejection, is a nonlinear absorption process (as it consumes optical energy without necessitating heating, just by dynamics only) as indicated as attenuation in Fig. 1 happening always at self-focusing in plasma. It is obvious, that the inverse process (Fig. 2) should be possible by injection of the clusters which plasmatisate in the outer parts of the beam and are decelerated by the radial nonlinear force similar to the plasma ejection at self-focusing. The switching process with a finite (optimized) duration of the laser pulse is necessary as in the case of LIFEL.

The cluster velocities have to be fixed with the laser beam geometry and power apart from the timing to be injected into the center of the pulse. At the switching-off of the pulse, the kinetic energy of the clusters is converted into optical energy as described before. Beam diameter, energy spread of the clusters, and beam duration have to be adjusted.
Figure 1. Scheme of the ponderomotive (nonlinear force) self-focusing with the ejection of plasma clouds from the center of the laser beam causing a collisionless transformation (absorption) of optical energy into kinetic energy of plasma.

Figure 2. Inversion of the self-focusing process by injection of plasmas into the center of a laser beam.

Figure 3. Box-like scheme of a laser pulse for the calculation of the amplification by lateral injection of clusters.
The amplification can be calculated according to Fig. 3 with a nearly rectangular laser pulse of length \( \tau_L \) and \( 2r \) diameter. For injected frozen hydrogen clusters, the amplification energy transferred per pulse is

\[
E_A = \frac{\rho_H \text{Vol}_{H_2}}{2} \frac{v_p^2}{\rho},
\]

where \( \rho_H \) is the hydrogen density and \( \text{Vol}_{H_2} \) the cluster volume of optimized size and \( v_p \) is the cluster velocity. Related to the energy \( E_L = P \tau_L \) in the laser pulse of power \( P \), the amplification is

\[
A = \frac{\rho_H \lambda^2}{\pi 2c^2}
\]

the analysis for other materials shows an independence of the atomic mass and of the velocity as long as it is optimized. The general amplification for solid state density is

\[
A = \frac{13.3}{(E/\psi)^2}
\]

where the energy \( E_\psi \) of the photons is in eV.

Losses occur by the ionization, by heating of ions and by emission of bremsstrahlung or scattering for which conditions of limitations were found. Gains of 80% or more are possible. High amplification results in the visible or near UV range, a fact which may be most interesting for laser fusion too.

What is most important, however, is that a reasonable amplification is possible even for very short wavelengths as e.g. of 100\( \AA \). The repetition by firing a sequence of clusters successively into the beam, is an easy procedure. Using some 1000 clusters, an amplification by 200 is possible for 100\( \text{\textmu} \) wavelength.

The description of the cluster injection laser amplifier (CILA) process as the inversion of the ponderomotive self-focusing indicates immediately another essential difference and an advantage to the LIFEL. The radial momentum transfer of the electrons in the LIFEL will lead to a divergence of the laser pulse which is to be amplified. In the case of the CILA, the high density plasmas produced from the injected clusters or other solid macro-particles will optically bend the wave fronts in the laser pulse as in the self-focusing process in favour of beam focusing and against defocusing. For a fully symmetric process, a synchronized cluster injection from various radial directions towards the same axial point in the center of the laser beam is necessary. Asymmetries would lead to a beam deflection which in special cases will be desired. This deformation of the phase fronts of the laser beam can be used actively (by feedback) for correcting and improving lower quality laser pulses.

It has to be noted that the efficiency (to distinguish from the amplification) at optimized conditions is 80% and more, and such high efficiencies together with the high amplification in the UV-range may drastically improve the scenario for laser fusion. The amplification per interaction for the KrF excimer laser of 250 nm wavelength is up to 0.5.

4. Design of Experiments

An experiment for demonstration of amplification has been designed. The short wavelength conditions can be simulated by the following experiment with readily available longer wavelength lasers: the pulse to be amplified is from a CO\(_2\) laser (200 J, 5 nsec) focussed to 1 mm diameter. The maximum oscillation energy of the electrons is about 80 eV, therefore sufficient for the mechanism.

The easiest way to accelerate the injected hydrogen to the needed velocities of 1.2 × 10\(^7\) cm/sec is to use lasers too. When firing the CO\(_2\) pulse through a coaxial tube of polyethylene of 3 to 5 mm diameter and some \( \mu \)m thickness, irradiation radially from outside by three Nd glass laser beams of 100 J, 5 nsec each, the imploding hydrogen-carbon plasma [25] will be injected with the optimized speed at the right time into the CO\(_2\) laser pulse. The density of the injected plasma has to be so much below the critical density that the collisional absorption by the CO\(_2\) laser pulse is small. The amplification can then be measured directly (Fig. 4).
Figure 4. Scheme for a proof-of-principle experiment for demonstrating the amplification process of a CO₂ laser beam.

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