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Application of High Current Density Ions from PW-PS Laser Pulse Nonlinear Force Driven Plasma Blocks for X-ray Lasers

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The use of CPA laser pulses of less than 50 fs duration and power above 30 TW may permit conditions for x-ray lasers where in solid state dense heavy nuclei materials K-shell electrons are emitted by irradiation of 5 MeV protons with subsequent transition of L-shell electrons into the K-shell level. Alternatively, if the L-shell emission dominates, M-L-x-ray laser operation may be interesting. The CPA laser pulses are used to produce plane plasma blocks of several wave length thickness where space charge neutral 5 MeV proton beams of 10^{11} Amps/cm^2 current densities are moving co-axially into the heavy nuclei material.

1. Introduction

The L-K shell x-ray laser was discussed before under several aspects [1-5]. There may be the possibility that ions with energy above 5 MeV per nucleon penetrating targets are emitting electrons from the K-shell of the target nuclei with higher probability than other interactions including bremsstrahlung generation. After this K-shell ionisation, there is preference than an electron from the L-shell of the targets is filling up the K-shell under emission of precise line x-rays in the range of above keV photons. If these photons could be led to stimulated emission, x-ray lasers with wave lengths of 10 Angstrom or less would be possible. The spontaneous L-K-shell transition was estimated to be 100 fs [1-5]. The aim is then to work under conditions shorter than this time. This can well be done by several longer duration schemes for which examples are well known [4, 5]. Further possibilities are available now by using laser pulses, which chirped pulse amplification CPA [6] where laser pulses up to Petawatt (10^{15} W) are available.

The interaction of these pulses led to never seen phenomena as the generation of new isotopes from the ps very intense 10 MeV gamma pulses [7, 8] including the transmutation of long lived radioactive waste [9], electron acceleration to several 100 MeV energy [10]. The possibilities for Exawatt and Zetawatt pulses are discussed [11] where pair production in vacuum may be envisaged [12]. In the case of preferential electron emission from L-shells the before mentioned considerations may apply for an M-L-transition laser. Without discussing what preference is to be considered, the following study is about consequences which are provided now by the application of the CPA laser pulses of less than 50 fs duration to conditions of a M-L-K-shell x-ray laser, where the generation of proton beams of current densities of 10^{11} Amps/cm^2 in space charge neutralised plasmas may be applied [13-17].

2. Acceleration of Plane Plasma blocks

One of the new phenomena observed is the laser acceleration of blocks of plasmas with measured acceleration above 10^{18} g (g=gravitational acceleration) where ps or shorter laser pulses of TW or higher power were used. After the first observation of these accelerations spectroscopically from the Doppler shift in the back scattered light [13], the measurements of a drastic decrease of the maximum ion energy form targets irradiated by ps-TW pulses was a problem, where Cu^{+13} ions did not reach 22 MeV energy as known from experiments after relativistic self-focusing, but only about 0.5 MeV [14].

The number of fast ions did not change when the laser intensity was changed by a factor 30. The explanation was that the suppression of a laser prepulse by a factor 10^8 (contrast ratio) avoided relativistic self-focusing and there was only a plane geometry interaction within the fixed skin depth volume by the nonlinear (ponderomotive) force [15]. The acceleration of the plasma blocks is due to the nonlinear force which is given by the plasma ω_p, the laser radian frequency ω and the dielectrically modified amplitudes of the electrical and magnetic laser fields E and H respectively by [16, 17]

$$f_{NL} = -(\omega_p / \omega)^2 \nabla E^2 / (8\pi) \tag{1}$$

$$f_{NL} = -(\partial / \partial x)^2 \left(E^2 + H^2\right) / (8\pi) \tag{2}$$

Where the first expression is the ponderomotive force into which the general nonlinear force [17] is reduced and the second expression is the algebraically identical with the first one but better demonstrated how the force densities are gradients of energy densities. The generation of two very collinear plasma blocks, one against the laser light and one into the plasma was measured [16] with ion current densities of at least 10^{10} A/cm^2 in agreement with the theoretical expectation [15, 17].

The advantage of this block acceleration for use to the L-K-shell laser consist in the fact that the blocks are parallel beams of space charge neutralised ions whose lateral expansion is given only by the rather low thermal motion at the basically non-thermalising nonlinear force interaction.

Even if the lateral thermal motion has to be compensated, the target surface in the focus may be a little bit spherically bent such that a fully parallel beam of 5 MeV protons may be produced with a current density above 10^{11} A/cm^2. It should be noted that the alternatively generated 5 MeV proton beams [18] after relativistic self-focusing [19] are essentially divergent. The relativistic self-focusing channel reduces the plasma density, such that the electrons are accelerated by the direct Lorentz force – as confirmed by comparison with experiments [10] – and are accelerated into a cone with subsequent acceleration of the ions.

In contrast to this, the plasma blocks following the conditions just described have the high cut-off density. Indeed to achieve our 5 MeV plane intense blocks of proton beams, the laser intensity for Ti: sapphir laser has to be close to 6×10^{19} W/cm^2 or less by the factor of maximum dielectric swelling [19]. What is important is that the Debye length for these blocks with protons at the neodymium glass laser wave length of 2.3×10^{-5} cm is more than ten times smaller than the thickness of the blocks if only the vacuum wave length is used in case than there is no dielectric swelling at all with usual radiation pressure interaction.

In the case of swelling with several vacuum wavelength thick blocks the relation to the Debye length is even less effective. Since the energy transfer to the blocks as a kind of collisionless nonlinear absorption is well known and even turning out as one of the rare analytical solutions of an integral equation [20] which method was proposed by Shank [21] for measuring the pulse lengths and energy transfer of sub-picosecond laser pulses. This all has to be taken into account when we are now looking into a special x-ray laser scheme.

3. Applications to an L-K-shell or M-L-shell laser mechanism

The x-ray laser scheme is based on the studies of F.P. Schafer [1] and Harry Paul et al. [2] where the option was discussed [3, 4] that there may be a very high cross section of K-shell ionisation for ions with energies above 5 MeV/nucleon compared to Coulomb collisions of the MeV ions with electrons or lighter bound electrons than those in K-shells.

There is also a relation to the gas lasers with neutron pumping from nuclear reactors [22]. The high ionisation probability of atoms by irradiation with MeV ions was confirmed also by Ulrich et al [23]. If the probabilities are better for an M-L-shell laser this may be considered as an analogy.

The laser mechanism may first hand be based on the transition of an L-shell electron into the K-shell, which was emptied by the 5 MeV protons [2]. The spontaneous transition of this kind was estimated by Schafer to be within 10^{-13} seconds [5]. While a 5 MeV proton produces a trace in a cloud chamber of few cm, we have to use heavy atoms in a metal of about 10-g/cm^3 density for our purpose, such that about 10^4 ionisation along a trace of 10 μm will be generated corresponding to an ionisation

$$n^* = 2\times10^{21}\ excited\ \ states / cm^3 \tag{3}$$

This is sufficient for a laser in the range of keV photons. The only condition is along the 10-μm trace that instead of super-radiance recombination radiation the one going into the direction of the trace passes this length in a shorter time than the spontaneous recombination time. This condition is fulfilled just by a factor 10 and it can be expected that from all the 10^{11} A/cm^2, 5 MeV protons in the nonlinear force driven plasma block hitting the heavy atom density metal behind the skin layer, at least 1% may have produced a laser emission along the traces. The laser property of this x-rays is confirmed by the directivity of the x-ray beam. A further proof and an access to study the details of this process is given by application of magnetic field in the range of Tesla perpendicular to the traces bending the otherwise straight traces. Since the photons at the stimulated emission cannot follow the bent curvature, the x-ray emission will then become isotropic and not longer directed. This method of magnetic field bending of traces e.g. of alpha particles or reaction products in low energy nuclear reactions in solids [1] could be used as proof whether the emission of x-rays in the keV range from solid density alpha emitters or similar cases is laser emission or not. However in these cases the direction of the traces is random, while the ion beams for the skin layer generated blocks for MeV ion excited x-ray lasers are primarily leading to parallel traces and a collinear laser beam.

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