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High efficient ultrahigh acceleration of plasma blocks by PW-ps laser pulses for producing fusion flames in DT and HB11 of solid state density

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Abstract. Ultrahigh acceleration of plasma blocks in the range of 10^{20} cm/s^2 has been confirmed experimentally after this was long predicted as a non-thermal direct conversion of optical energy into plasma motion due to dominating nonlinear (ponderomotive) forces [1]. The use of laser pulses of more than PW power and ps or shorter duration can ignite a nuclear fusion flame in solid density deuterium tritium because the necessary energy flux of $>10^8$J/cm^2 according to the theory of Chu [2] is available [3]. For the studies of the necessary velocities of the generated fusion flames above 1000 km/s the detailed processes can be analyzed by using the advanced genuine two-fluid hydrodynamic model [4] where it was surprising that the ignition of the fusion flame by the picosecond interaction needs a comparably long development in the nanosecond range before the thermal processes result in shock fronts similar to the Rakine-Hugoniot theory. For the evaluation of power generation the problem of lateral energy losses was studied by using very high pulsed magnetic fields. The recently produced 10 Kilotesla magnetic fields [5] are very promising for solutions.

1. Introduction

For the aim to produce controlled nuclear fusion reactions for generation of energy, the use of lasers for initiating and/or driving the reaction is followed up by a number of different schemes where the interaction process of the laser with the irradiated fusion fuel can depend on the duration of hte laser pulse. A basic difference for fusion energy generation was opened with the use of Petawatt-picosecond (PW-ps) laser-plasma interaction [6] initiated since 1986 [7] in contrast to laser driven spherical compression and thermal ignition needing more than 1000 times solid state densities deuterium-tritium (DT) for nanosecond laser pulses and where a breakthrough is expected [8]. In contrast to these thermal processes with unavoidable losses, delays, inefficiencies and instabilities, the new option with PW-ps pulses uses the efficient direct conversion of laser energy into motion of plasma blocks where the thermal processes are nearly fully avoided. In contrast to this scheme, The direct conversion of laser energy by the nonlinear (ponderomotive) force into motion of plasma blocks was evident after dielectric properties of plasmas with optical constants into the Maxwellian stress tensor was introduced permitting the generalizing of the ponderomotive force up to the nonlinear force for explaining measured MeV ion energies at laser-plasma interaction including self-focusing [9]. Computations of plane geometry interaction of ps laser pulses with 10^{18}W/cm^2 laser pulses arrived at ultra-high accelerations of plasma blocks above 10^{20}cm/s^2 within picosecond interaction, clearly demonstrating that the thermal processes were of very minor influence [10].

These ultra-high accelerations were first measured by Sauerbrey [11] where the values of 2×10^{20}cm/s^2 were in perfect agreement with the theory by inclusion of dielectric swelling [1]. These accelerations were reproduced [12] and were up to fife orders of magnitudes higher than the measured acceleration by thermal pressures using nanosecond laser pulses. The essential necessity was providing contrast ratios above 10^8 for suppression of relativistic self-focusing when using <ps laser pulses. This was supported by other independent measurements where plane wave front interaction was verified for confirming interaction with dielectrically increased skin layers [1]. When applying these results with ps laser pulses of powers above TW, PW (petawatt) and higher for igniting a

fusion flame in solid density uncompressed fusion fuel [13], the interesting results from plane geometry computations needed a solution how a section from the plane interaction with a cylindrical plasma can overcome lateral losses. For these purpose, a cylindrical magnetic confinemet was studied [14] by using magnetic fields up to 300 Tesla as reported in the following. This is a first evaluation with respect to the ignition of the fusion flame by plasma blocks produced by nonlinear force diven ps laser pulses. This is on the way to the recent generated magnetic fields above 10 kTesla [5].

2. Shock generation and penetration speeds of fusion flames

The system of equation describing the dynamics of the plasma particles interaction with electric and magnetic fields is based on the two fluid approximation. Fluid conservation equations for each plasma species plus Maxwell's equations are numerically computed using finite Volume Method (FVM). The computations are based on the plasma block acceleration from the dielectric increased interaction thickness of the laser irradiated skin depth given by optical properties. This differs from laser driven skind depth acceleration which is defined by plasma properties where the generation of separated electron and ion beams is essential [15]. The first computations on the ignition of a fusion flame in solid deuterium-tritium (DT) by a picoseconds energy deposition with an energy flux E* were performed using one-fluid hydrodynamics [2], improved later by two-fluid hydrodynamics [16]. The following resported results are based on a genuine two-fluid hydrodynamic code which was used [17][18] in order to study spatio-temporal details [19][20]. The ignition thresholds E* arrived in the range of 10^8J/cm^2 for DT gives ultrahigh acceleration of plasma blocks which are in the range above 10^{19}cm/s^2 [10][11][12] for incident ps laser laser pulses of intensities above 10^{18} W/cm^2.

The genuine two-fluid computations permitted to follow up the development of the electric field within the plasma for long times after the ps laser ignition had initiated the fusion flame but also the time dependence of the ion density showed the generation of the shock compression in agreement with the Rankine-Hugoniot theory [19], however with many more details than the analytical theory could cover. It was remarkable that the shock front did not build up immediately after the ps laser ignition of the fusion flame and it needed times of many hundred ps before the shock compression was generated. The very general code including thermal mechanisms with damping and equipartition between electrons and ions etc. led also to understand how the shock front depending on time was increasing its depth. The velocities of the shock front at ignition above the threshold were above 1000 km/s in DT at times of few ns after intiating the block ignition, decaying from initial velocites above 4000 km/s [20].

One example of the shock generation is shown in Figure 1 with the DT densities at a series of times as parameter. In this case a laser intenisty up to 10^{20}W/cm^2 from a KrF laser was used.

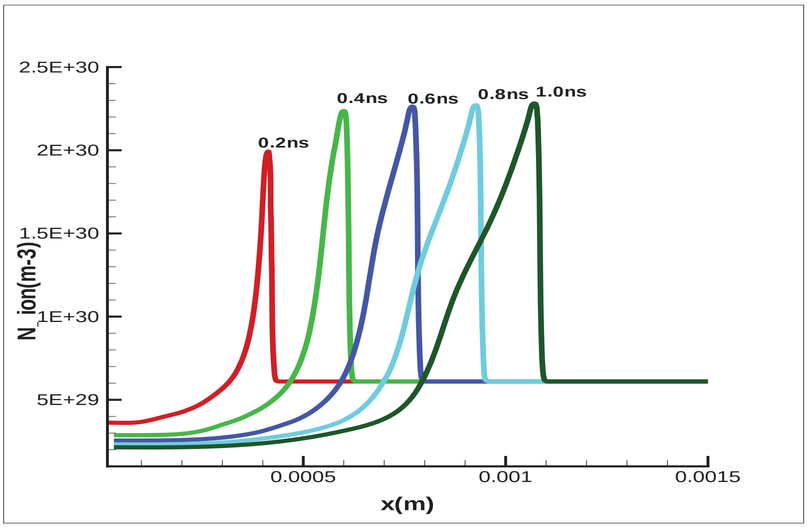

Figure 1. Ion density N_i depending on the depth X in the initially cold fuel at different times after the ps laser irradiation

The shock generation of four times the initial density as known form the Rankine-Hugoniot theory has not been reached at 0.2 nanoseconds after picosecond laser ignition of the fusion flame was irradiated. The generation of the increasing thickness of the shock front is the result of the complete thermal computation with separate electron heating, heating of the ions by equipartition and the dominating pressure by th ion fluid.

3. Elimnation of lateral energy losses

One critial point of the igniton by a fusion flame with nonlinear force driven ultrahigh acceleration of plasma blocks is the conversion of the results with plane geometry presumptions to real power station conditions. One has to select a cylindrical section of the nonlinear force ignition instead the infinite plane geometry. Taking out a cylindrical section for the plane wave geometry has the problem of the lateral losses of confinement for the cylindrical fusion fuel.

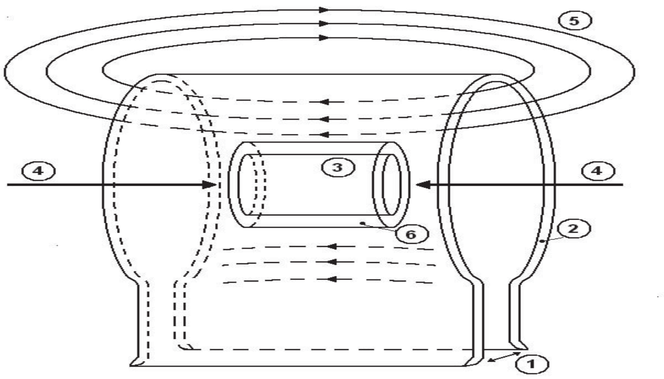

Figure 2. Production of a pulsed magnetic field 5 of 100Tesla if few nanosecond duration by a pulsed discharge 1 with the coil 2 for confining the cylindrical plasma 3 generated by ps laser pulse generated plasma blocks 4 from both sides in order to confine the plasma surface 6, according to [14].

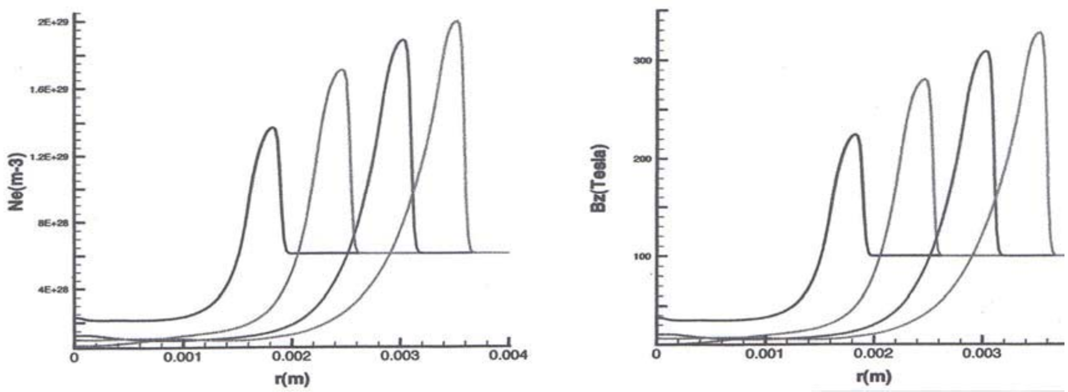

Figure 3. Computation of electron density N_e and axial cylindric magentic field B_z depending on radial cylindric coordinate r at times (from the left of the plots) 0.4, 0.8, 1.2 and 1.6 nanoseconds of a cylindrical solid density DT plasma of 1 mm radius at time zero located in an axially parallel magnetic field of 100 Tesla. At time zero a 10^{20} W/cm^2 KrF laser pulse of one ps duration produced a plama block for igniting a fusion flame.

Figure 2 describes the device for producing initially a magentic field of 100Tesla when a 10^{20} W/cm^2 KrF ps laser pulse initiates the nulear fusion flame in DT at the ends of the plasma cylinder. The ps interaction occurs in a fuel depth of 5 micrometer where the nonlinear force driven plasma block contains directed ions from the ultrahigh plasma block acceleration. Before the interaction, an external 100Tesla magnetic field is applied and results are plotted in Fig. 3 in the sequence of 0.4, 0.8, 1.2 and 1.6 ns. The genuine two-fluid hydrodynamic equations [16, 18] in contrast to the earlier computations [3] describe the motion [19] of the plasma by the electron density N_e which is nearly identical with the ion density showing how the plasma pressure is driving the magentic field out from the center while simultaneously the magnetic field is steepening up in the periphery to 300 Tesla. The whole dynamic is described including the time dependents of the electric field and of the axial magentic field and rotational plasma motion due to $\mathbf{E}\times\mathbf{B}$ term, showing a trapping of the radial alpha fluid expansion and the resulting fusion gain.

The computations show the limitation of radial-cylindric energy losses and conditions for generating fusion energy of this scheme. Alternative to this cylindrical magnetic scheme to control losses of the fusion reactions one can use spherical geometry. This will be improved when using initial magentic fields of more than 10 kTesla which are now being developed [5].

It is possibile to completly suppress lateral losses by the spherical geometry instead of the plane irradiation of the solid density DT fusion fuel, by producing spherical plasma blocks by ultrafast acceleration with picosecond laser pulses by lossless conversion of optical energy into mechanical compression producing a space charge neutralized DT ion block directed to the spherical center with 80keV ions. Working with the genuine two-fluid hydrodynamics [17][18][19][20] and the fluid of the generated alpha particle fluid, the spherical irradiation of 125PW laser power compresses the plasma to 20 times the solid state of DT at the center of the sphere at 14.4 ps after the ps laser pulse ignited the fusion flame. Then a rarefaction wave moves in radial direction.

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