Optimized boron fusion with magnetic trapping by laser driven plasma block initiation at nonlinear forced driven ultrahigh acceleration

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(RECEIVED 4 April 2014; ACCEPTED 23 April 2014)

Abstract

Fusion reactions of solid density boron-11 with protons after initiation of a fusion flame by very powerful picosecond laser pulses were derived for plane geometry. The problem of lateral energy losses with laser beams was solved by using spherical geometry, where however the gains are limited. The other elimination of losses now available by cylinder-axis symmetric 10 kilotesla magnetic fields is possible needing laser powers in the exawatt range. Estimations are presented by varying parameters for reducing the necessary laser pulse powers to lower values by up to a factor 100.

Keywords: Exawatt power; Initiation of flame; Laser driven fusion; Picoseconds laser; Solid boron-proton fuel

Ultrahigh acceleration in the range above $10^{20}$ cm$^2$/s$^2$ of plasma blocks was numerically predicted by laser pulses of ps duration and intensities of $10^{18}$ W/cm$^2$ (Hora, 1981) where a non-thermal direct conversion of optical energy into macroscopic plasma motion was determined by nonlinear (ponderomotive) forces using the dielectrically modified Maxwellian stress tensor. This was experimental verified at plane geometry laser-plasma interaction by Doppler effect line shifts (Sauerbrey, 1996) using 350 fs laser pulses of $3.5 \times 10^{17}$ W/cm$^2$ pulses from a KrF laser. These accelerations were 100,000 times higher than ever measured before in a laboratory and reproduced (Földes et al., 2000) in agreement with the theory of the nonlinear force (Hora et al., 2007).

Necessary condition was that the contrast ratio had to be $>10^7$ for cutting off prepulses in order to avoid relativistic self-focusing. Another essential condition is to work with single mode laser pulses. This was fulfilled in the experiments (Sauerbrey, 1996; Földes et al., 2000) with the KrF lasers. This condition is not fulfilled in most other lasers where the results could not be reproduced. In retrospect, it confirms the extreme high quality of the Titan-sapphire single mode laser of Zhang et al. (1998) used in the experiment where from anomalously low X-ray emission it could be concluded, how relativistic self-focusing was avoided for the plane geometry interaction process supporting the ultrahigh acceleration.

Thanks to the now available 3 PW laser pulses (Li et al., 2013; Chu et al., 2013) on the way to exawatt (Mourou et al., 2013), the initiation of a fusion flame in solid density deuterium-tritium (DT) fuel by interpenetration of very fast picoseconds plasma blocks (Hora, 1983; Hora et al., 2005) could be studied numerically (Hora, 2009) where fusion energy from the extremely difficult $^{11}$B (HB11) reaction with protons changed into the level of the conditions of DT.

After the fusion results were manifested for infinite plane geometry, the problem was the problems of cylindrical lateral energy losses when working with finite diameter laser beams. One way out was to use spherical geometry (Hora et al., 2014) where, however, the fusion gains are limited by fuel exhaustion if not laser pulses above exawatt are used. Another way is to use cylinder-parallel magnetic fields (Hora et al., 2012) (Fig. 1) where fields up to 100 Tesla were not sufficient (Moustaizis et al., 2013). This situation changed dramatically after the recent laser operated 10 kilotesla magnetic fields were developed (Fujioka et al., 2013), resulting in high gains, however still needing exawatt laser pulses (Lalousis et al., 2014). The computations use the multi-fluid code as used before (Lalousis et al., 2013; Hora...
et al., 2014a; 2014b) based on the general genuine two-fluid plasma hydrodynamics (Lalousis et al., 1983; Hora et al., 1984). From a series of cases with each irradiation of ps laser pulses of 248 nm wave length and 10^{20} \text{ W/cm}^2 intensity at an interaction diameter of 0.1 mm radius on solid density HB11 for initiation of fusion, Figures 2 and 3 show the resulting densities of the electrons \( N_e \), protons \( N_h \), and boron nuclei \( N_b \) along the radial coordinate \( r \) at times 100 ps and 1000 ps, respectively, of the figures. From the initial radius of 0.1 mm, the plasma has expanded showing depletion at the cylinder axis up to the radius but with some compression at higher radius. Above 0.4 mm the plasma has the untouched densities. Figure 4 shows at 100 ps the magnetic field which is 10^4 \text{ T} in the axis-parallel \( z \)-direction while the curve on the left-hand side is the density \( N_a \) of the generated alpha particles centered inside the plasma. The fact of the ignition can be seen in Figure 5 where the density of the generated alpha particles is shown increasing on time.

All these calculations are similar to the DT fusion as binary reactions. The secondary reactions of the 2.9 MeV alphas when hitting a boron nucleus and transferring about 600 MeV energy at central collision are not included in the computations (Hora et al., 2013). The gyro radius of the alpha particles at 10 kilotesla magnetic fields is 42.5 \( \mu \text{m} \) and their mean free pass for collective stopping at solid state density is nearly independent on the electron
temperature in the range of 60 μm at solid state density such that an avalanche multiplication is resulting in an exponential increase of the fusion gain until fuel depletion. Similar estimations as for spherical geometry (Hora et al., 2014a) show how a laser energy input into the block for the initiation of the flame of 30 kJ can produce alpha energy of 1 GJ. By this way, the requested fusion gain for DT of 10,000 postulated by Nuckolls et al. (2002) for a power station with its relativistic electron beam fast ignition arrives at comparable values for HB11. It is remarkable that the alpha-avalanche process is arriving at comparable values with clean HB11 fusion compared with DT, but without the neutrons produced by DT and their difficulties with the generation of radioactivity (Tahir et al., 1997).

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