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

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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/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 3.5×10^{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

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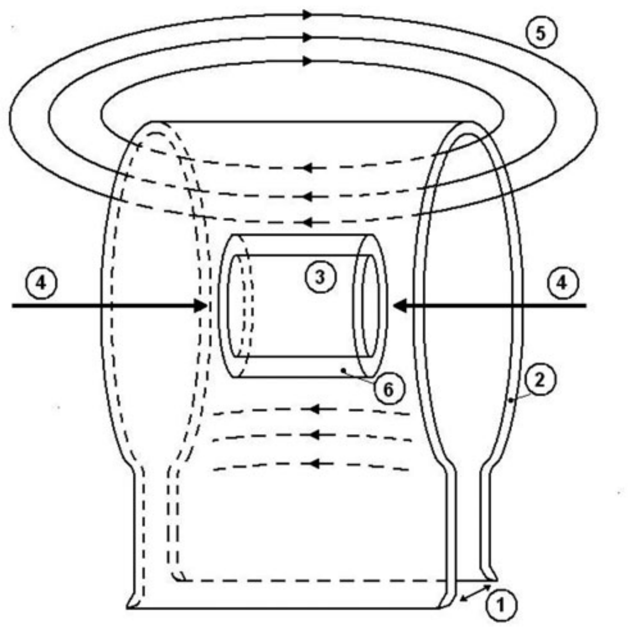

Fig. 1. Magnetic trapping of a cylindrical nuclear fusion volume: (**1**, **2**) is the loop for generating a magnetic field, (**3**) is the fusion fuel for one or two sided irradiation (**4**) of ps laser pulses to initiate a fusion flame, (**5**) is the magnetic field parallel to the cylindric symmetry, and (**6**) is the complete fuel not directly irradiated by the laser.

et al., 2014*a*; 2014*b*) 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} 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 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 μm and their mean free pass for collective stopping at solid state density is nearly independent on the electron

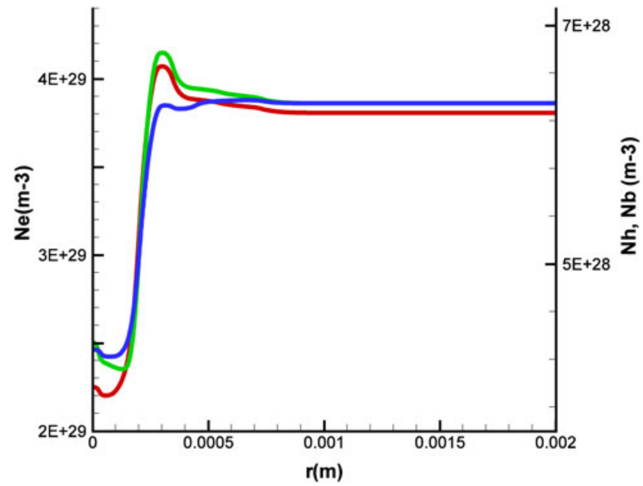

Fig. 3. (Color online) Same as Figure 2 at time 1000 ps.

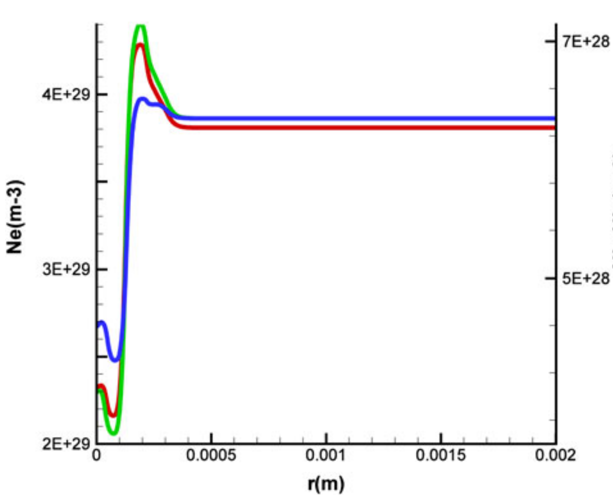

Fig. 2. (Color online) Dependence on the radius r of the electron density N_e, the proton density N_h, and the ^{11}B nuclear density N_b (maxima decreasing respectively) at time 100 ps for solid state HB11 fuel at an irradiation radius of 0.1 mm of a 248 wave length laser pulse of 1 ps duration.

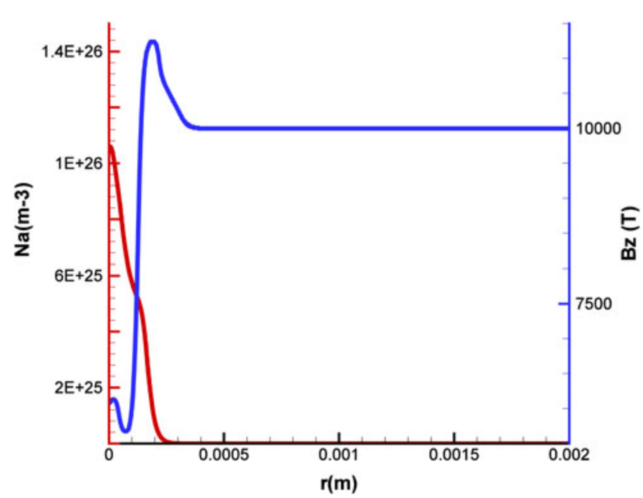

Fig. 4. (Color online) Same case of Figure 2 with the magnetic field B_z parallel to the cylindrical axis z merging into 10 kilotesla above the radius 0.3 mm, with the curve at the left showing the density of the generated alpha particles N_a.

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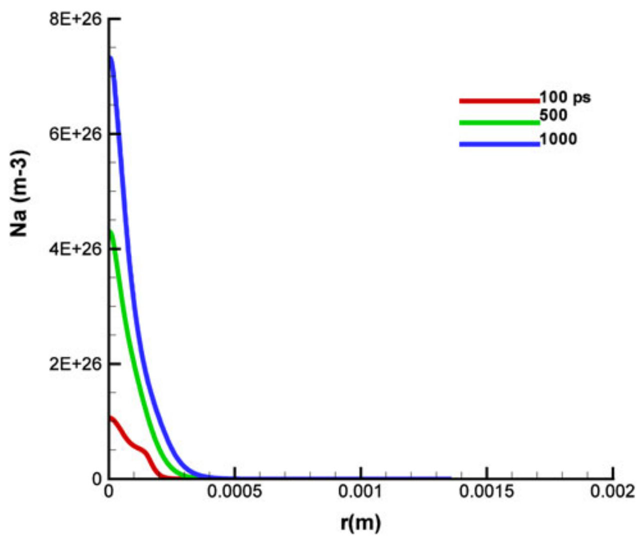

Fig. 5. (Color online) Alpha density N_a depending on the radius r at different times showing ignition from the increase of the curves on time.

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*., 2014*a*) 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 his 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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