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A novel fusion reactor with chain reactions for proton–boron11

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Research Article

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Abstract

Using a combination of laser–plasma interactions and magnetic confinement configurations, a conceptual fusion reactor is proposed in this paper. Our reactor consists of the following: (1) A background plasma of boron11 and hydrogen ions, plus electrons, is generated and kept for a certain time, with densities of the order of a mg/cm^3 and temperatures of tens of eV. Both the radiation level and the plasma thermal pressure are thus very low. (2) A plasma channel is induced in a solid target by irradiation with a high power laser that creates a very intense shock wave. This mechanism conveys the acceleration of protons in the laser direction. The mechanisms must be tuned for the protons to reach a kinetic energy of 300–1200 keV where the pB11 fusion cross section is significantly large (note that this value is not a temperature). (3) Those ultra-fast protons enter the background plasma and collide with boron11 to produce three alphas. Fusion born alphas collide with protons of the plasma and accelerate them causing a chain reaction. (4) A combination of an induction current and a magnetic bottle keeps the chain reaction process going on, for a pulse long enough to get a high energy gain. (5) Materials for the background plasma and the laser target must be replaced for starting a new chain reaction cycle.

Introduction

Nuclear fusion is the origin of energy in our sun and in the stars. The nuclear fusion in our sun (e.g., four protons combine into an alpha) is a weak interaction. Thus, the sun's hot plasma confinement is made possible due to the gravitational force of the sun's large mass. In a terrestrial laboratory, between the possible existing reactions, the first choice for controlled fusion energy is the deuterium–tritium (DT) strong interaction creating an alpha and a neutron with the release of 17.6 MeV per reaction. The DT has been chosen since the cross section and the rate of this process are the largest for the lowest practical temperatures of the order of 10 keV. The problem with the DT reaction is that it produces the undesired neutron that can activate radioactive materials.

The cleanest fusion reaction that avoids the neutron problem is the fusion of protons with ^{11}B (pB11) that creates three alphas (Hora *et al*., 2017 and references therein). Using lasers, the first p–^{11}B 1000 reactions, just above the level of sensitivity, were measured (Belyaev *et al*., 2005). A combination of highly intense proton beams of energies above MeV produced by picosecond laser pulses intercepting a plasma created by a second irradiated laser beam produced more than one million pB11 reactions (Labaune *et al*., 2013). At Prague PALS facility, the few hundred joules-nanosecond time duration iodine laser interacting with targets containing high boron concentration doped in silicon crystals produced one billion alpha particles (Picciotto *et al*., 2014) and in an ELI meeting, more than 10^{11} alphas were reported per laser shot (Giuffrida, 2018).

The main problem in solving the energy problem with fusion on our planet for mankind is the difficulty to create it in a controllable and economical way with a positive energy balance. Two different distinctive schemes have been investigated in the past 60 years: (1) Magnetic confinement fusion (MCF) based on high-intensity magnetic fields (several teslas) confining low-density (10^{14} cm^3) and high-temperature (~10 keV) plasmas for long or practically continuous times. (2) Inertial confinement fusion (ICF) based on rapid heating and compressing the fusion fuel to very large densities (Nuckolls *et al*., 1972) and very high temperatures, larger than 5 keV for the DT fusion reaction. In order to ignite the fuel with less energy, it was suggested (Basov *et al*., 1992; Tabak *et al*., 1994) to separate the drivers that compress and ignite the target. First, the fuel is compressed, then a second driver ignites a small part of the fuel while the created alpha particles heat the rest of the target. This idea is called fast ignition (FI). The FI problem is that the laser pulse does not reach directly the compressed target; therefore, many schemes have been suggested (Guskov, 2013) including proton–boron fusion (Martinez-Val *et al*., 1996; Eliezer and Martinez Val, 1998).

The novel scheme described here can be used for combinations such as (Eliezer and Mima, 2009) helium3–deuterium (He3–D), deuterium–lithium6 (D–^{6}Li), and proton–lithium6 (p–^{6}Li), proton–lithium7 (p–^{7}Li). In this paper, we suggest the clean (i.e., without neutrons) proton–boron11 fusion yielding 3α,

$$p + {}^{11}B \rightarrow 3\,{}^4He + 8.9\,MeV \tag{1}$$

This new approach to fusion is given schematically in Figure 1. Our reactor consists of a background plasma with densities of the order of a mg/cm^3 of boron11 and hydrogen ions. A plasma channel or a solid target is irradiated by a high power laser that creates a shock wave containing proton particles with a flow energy (of the protons) in the domain of 300–1200 keV that enters the background plasma. Fusion boron alphas collide with protons of the plasma and accelerate them causing a chain reaction. The number of the alpha particles N_α created in this process is given by

$$N_\alpha \sim 3N_{\alpha 0}(e^{\tau/\tau_A} - 1)$$
$$\tau_A \equiv \frac{1}{n_0\langle\sigma v\rangle} \tag{2}$$

"Fusion cross section (σ) times relative pB11 velocity (v)" is denoted by $\langle\sigma v\rangle$ (in the range of 10^{-16} cm^3/s to few times 10^{-15} cm^3/s), N_α is the number of the alpha particles created during the chain reaction for an initial number of alphas $N_{\alpha 0}$. τ_A is defined as the chain reaction time (also defined as avalanche time, Eliezer *et al.*, 2016*a*; Hora *et al.*, 2017). In our background, plasma n_0 is of the order of 10^{19} cm^{-3}, $\langle\sigma v\rangle \sim 10^{-15}$ cm^3/s implying a time $\tau_A \sim 10^{-4}$ s. During an interaction time $\tau \sim 1$ ms, we get an increase factor to the originally produced alphas by a factor of the order of 10^4. In order to keep the chain reaction going, our reactor contains a combination of an external electric field and a magnetic mirror confinement device for a pulse long enough to get a high energy gain.

In "The confinement and the chain reactions", the confinement and the chain reactions are described. The conceptual design of the fusion reactor is given in "The New Reactor". We end "Conclusions" with a short conclusion.

The shock wave initiating mechanism

In this system, two (or more) shock waves are created by very high irradiance lasers. The desired shock waves are semi-relativistic with a shock wave velocity of the order of 0.1 c, where c is the speed of light. The formalism of these shock waves was recently described in the literature (Eliezer *et al.*, 2014, 2017). *The laser-induced shock wave acts as an accelerator* that accelerates fluid particles inside the shock wave domain (see Fig. 2) with proton and boron number densities n_p and n_B in a volume V. In our scheme, in this paper we consider two possibilities to create a laser induced shock wave: one for a solid target and the other for a gas target the shocked matter to velocities where the center of mass of p–B11 energy so that its "fusion cross section (σ) times relative pB11 velocity (v)" $\langle\sigma v\rangle \sim 10^{-15}$ cm^3/s gets large values. One case is the laser irradiates a solid that contains hydrogen and boron (Picciotto *et al.*, 2014; Giuffrida, 2018) in the entrance channel of Figure 1, or the other case is the laser creates a shock wave in the background gas.

The physics of shock waves is excellently summarized in Zeldovich and Raizer's book *Physics of Shock Waves and High Temperature Hydrodynamic Phenomena* (Zeldovich and Raizer, 1966). The interaction of a high power laser with a planar target creates a one-dimensional (1D) shock wave (Fortov and Lomonosov, 2010; Eliezer, 2013). The theoretical basis for laser-induced shock waves analyzed and measured experimentally so far is based on plasma ablation. For laser intensities of 10^{12} W/cm$^2 < I_L < 10^{16}$ W/cm^2 and nanoseconds pulse duration, a hot plasma is created. This plasma exerts a high pressure on the surrounding material, leading to the formation of an intense shock wave moving into the interior of the target (Eliezer, 2002). In this paper, we are interested in the semi-relativistic shock waves for solid or gas densities. Shock waves induced by lasers with irradiances in this regime are described by relativistic hydrodynamics (Landau and Lifshitz, 1987). Relativistic shock waves were first analyzed by Taub (1948) and in the context of laser–plasma interactions by Eliezer *et al.* (2014).

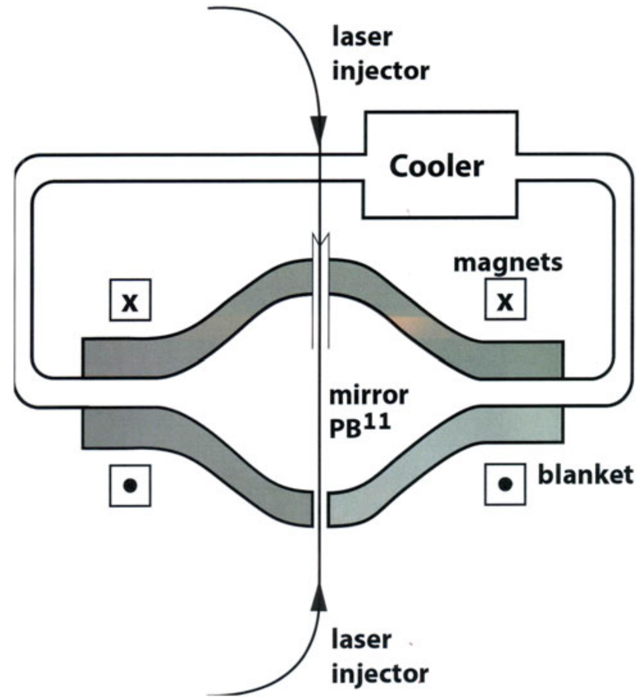

Fig. 1. The fusion reactor schematic model. The two injected high power lasers, in the magnetic field's mirror, trigger the pB11 fusion in the vessel. The created alphas heat the target which flows into a cooler that recirculate the plasma fluid with a density of the order of 1 mg/cm^3. The deposition of the energy is done continuously from the cooler, while the created alphas are confined by an external magnetic field.

In the following, we use the shock wave equations relevant to Figure 1. The relativistic shock wave Hugoniot equations in the laboratory frame of reference are given by

$$(i)\,\frac{u_p}{c} = \sqrt{\frac{(P_1 - P_0)(e_1 - e_0)}{(e_0 + P_1)(e_1 + P_0)}}$$
$$(ii)\,\frac{u_s}{c} = \sqrt{\frac{(P_1 - P_0)(e_1 + P_0)}{(e_1 - e_0)(e_0 + P_1)}}$$
$$(iii)\,\frac{(e_1 + P_1)^2}{\rho_1^2} - \frac{(e_0 + P_0)^2}{\rho_0^2} = (P_1 - P_0)\left[\frac{(e_0 + P_0)}{\rho_0^2} + \frac{(e_1 + P_1)}{\rho_1^2}\right] \tag{3}$$

P, e, and ρ are the pressure, energy density, and mass density accordingly, the subscripts 0 and 1 denote the domains before and after the shock arrival, u_s is the shock wave velocity and u_p is the particle flow velocity in the laboratory frame of reference, and c is the speed of light. We have assumed that in the laboratory the target is initially at rest. The equation of state (EOS) taken here in order to calculate the shock wave parameters is the ideal gas EOS

$$e_j = \rho_j c^2 + \frac{P_j}{\Gamma - 1}; \quad j = 0, 1. \tag{4}$$

where Γ is the specific heat ratio. We have to solve these Eqs (3) and (4) together with the following piston model equation (Esirkepov *et al.*, 2004; Eliezer *et al.*, 2014),

$$P_1 = \frac{2I_L}{c}\left(\frac{1 - u_p/c}{1 + u_p/c}\right) \tag{5}$$

It is convenient to use the following laser irradiance and pressure dimensionless variables in the solutions of the above equations

$$\Pi_L \equiv \frac{I_L}{\rho_0 c^3}; \quad \Pi = \frac{P_1}{\rho_0 c^2} \equiv \frac{P}{\rho_0 c^2} \tag{6}$$

In the transition domain between relativistic and nonrelativistic shock waves, we get the following solutions for the shock wave parameters

$$\begin{aligned}
\frac{u_p}{c} &= \sqrt{\frac{\Pi(2+\Pi)}{(1+\Pi)(\Gamma+1+\Pi)}} \approx 2\frac{(\Pi_L)^{1/4}}{(\Gamma+1)^{3/4}} \\
\frac{u_s}{c} &= \sqrt{\frac{\Pi(\Gamma+1+\Pi)}{(1+\Pi)(2+\Pi)}} \approx \sqrt{2}\frac{(\Pi_L)^{1/4}}{(\Gamma+1)^{1/4}} \\
\Pi &= 2\Pi_L\left(\frac{1-u_p/c}{1+u_p/c}\right) \approx 2\sqrt{\frac{\Pi_L}{\Gamma+1}}
\end{aligned} \tag{7}$$

The compression $\kappa = \rho/\rho_0$ as a function of the dimensionless pressure $\Pi = P/(\rho_0 c^2)$ is given in Figure 2a for $\Gamma = 5/3$. In order to see the transition between the relativistic and nonrelativistic approximation, one has to solve the relativistic equations in order to see the transition effects like the one shown in Figure 2a. The numerical solutions shown in Figure 2b give the dimensionless shock wave velocity u_s/c and the particle velocity u_p/c in the laboratory frame of reference *versus* the dimensionless laser irradiance $\Pi_L = I_L/(\rho_0 c^3)$ in the domain $10^{-4} < \Pi_L < 1$. For the practical proposal, the inserted table shows numerical values in the area $10^{-4} < \Pi_L < 10^{-2}$.

Furthermore, the speed of sound in units of speed of light, c_S/c, as a function of the dimensionless laser irradiance $\Pi_L = I_L/(\rho_0 c^3)$ and the rarefaction velocity, c_{rw}, is given by

$$\begin{aligned}
\frac{c_s}{c} &= \sqrt{\left(\frac{\partial P}{\partial e}\right)_S} = \left(\frac{\Gamma P}{e+P}\right)^{1/2} = \left[\frac{\Gamma(\Gamma-1)\Pi}{\Gamma\Pi + (\Gamma-1)\kappa}\right]^{1/2} \\
c_{rw} &= \frac{c_S + u_p}{1 + \left(\frac{c_S u_p}{c^2}\right)}
\end{aligned} \tag{8}$$

The time τ_{rw} that the rarefaction wave reaches the shock front, for the case that the laser pulse duration is τ_L, is

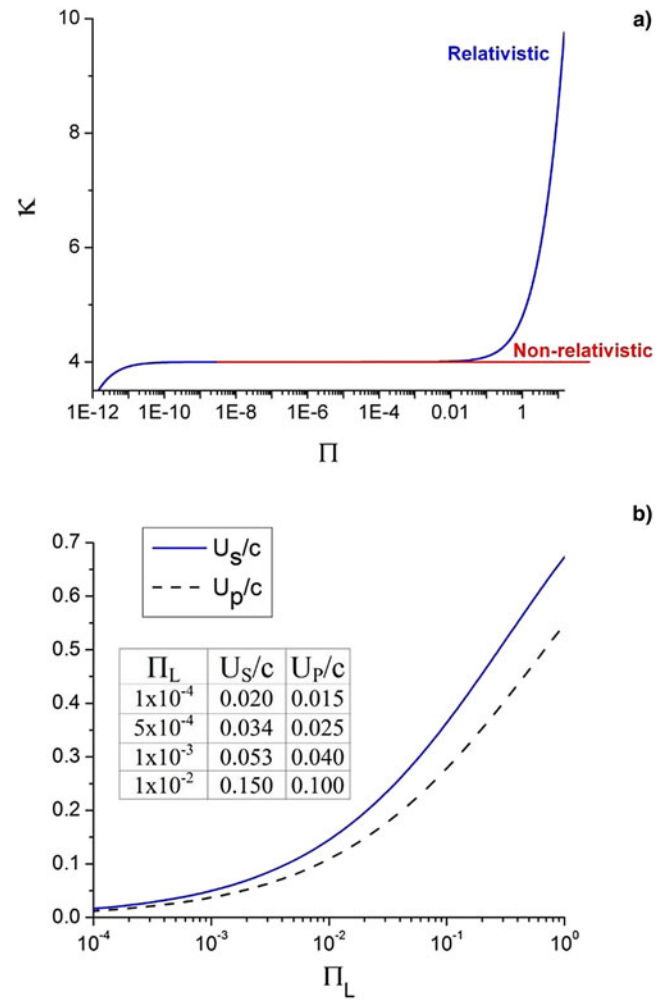

Fig. 2. (a) The shock wave compression $\kappa = \rho/\rho_0$ as a function of the shock wave dimensionless pressure $\Pi = P/(\rho_0 c^2)$ is presented. The numerical values are obtained for $\Gamma = 5/3$. The semi-relativistic domain is defined on the red line. (b) The dimensionless shock wave velocity u_s/c and the particle velocity u_p/c in the laboratory frame of reference are given *versus* the dimensionless laser irradiance $\Pi_L = I_L/(\rho_0 c^3)$ in the domain $10^{-4} < \Pi_L < 1$.

$$\tau_{rw} = \frac{c_{rw}\tau_L}{c_{rw} - u_s} \tag{9}$$

As a numerical example, we take a laser dimensionless irradiance Π_L yielding the desired velocities necessary for our scheme (see Fig. 2)

$$\Pi_L = I_L/(\rho_0 c^3) = 8.3 \times 10^{-4} \Rightarrow$$

$$\left\{\begin{array}{l}
\beta \equiv u_p/c = 0.035; \rightarrow u_p = 1.05 \times 10^9\,(\text{cm/s}) = 4.77\left(\frac{e^2}{hc}\right) \\
u_s/c = 0.0465; \rightarrow u_s = 1.40 \times 10^9\,(\text{cm/s}); \\
c_s/c = 0.0226; \rightarrow c_s = 0.69 \times 10^9\,(\text{cm/s}); \\
c_{rw}/c = 0.0573; \rightarrow c_{rw} = 1.72 \times 10^9\,(\text{cm/s}); \\
\Pi = P/(\rho_0 c^2) = 1.61 \times 10^{-3} \rightarrow \\
P[\text{bar}] = 1.45 \times 10^{12}\left(\frac{\rho_0}{1\,\text{g/cm}^3}\right)
\end{array}\right. \tag{10}$$

As an example for the shock wave created in the background plasma, relevant for our next section, we use

$$\rho_0(\mathrm{g/cm^3}) = 10^{-3} \Rightarrow \begin{cases} I_L(\mathrm{W/cm^2}) = 2.24 \times 10^{18} \\ P[\mathrm{bar}] = 1.45 \times 10^9 = 1.45\,\mathrm{Gb} \\ \tau_{rw} = 5.3\tau_L \end{cases} \quad (11)$$

For a given laser irradiance I_L and energy W_L, we estimate now the laser pulse duration τ_L for our scheme in order to have a reasonable 1D shock wave. I_L is a function of the flow velocity u_p (fixed by $\Pi_L = 8.3 \times 10^{-4}$) and the medium density ρ_0, implying

$$\begin{aligned} &I_L\,(\mathrm{W/cm^2}) = 2.2 \times 10^{18}\left(\frac{\rho_0}{10^{-3}\,\mathrm{g/cm^3}}\right) \Rightarrow \\ &S\,(\mathrm{cm^2}) = \pi R_L^2 = 4.5 \times 10^{-7}\left(\frac{10^{-3}\,\mathrm{g/cm^3}}{\rho_0}\right)\left(\frac{W_L}{1\,\mathrm{kJ}}\right)\left(\frac{1\,\mathrm{ns}}{\tau_L}\right) \\ &R_L\,(\mu\mathrm{m}) = 0.12\left[\left(\frac{1\,\mathrm{g/cm^3}}{\rho_0}\right)\left(\frac{W_L}{1\,\mathrm{kJ}}\right)\left(\frac{1\,\mathrm{ns}}{\tau_L}\right)\right]^{0.5} \\ &R_L(\mu\mathrm{m}) \gg u_s\tau_L(\mu\mathrm{m}) = 1.40 \times 10^4\,(\mu\mathrm{m/ns})\,\tau_L(\mathrm{ns}) \end{aligned} \quad (12)$$

To solve Eq. (12), we substitute the symbol $\gg$ by a factor of 5 equality, i.e., a laser diameter larger by a factor of 10 relative to the shock wave length during the pulse duration, $u_s\tau_L$, we get

$$\tau_L\,(\mathrm{ns}) = 1.2 \times 10^{-3}\left[\left(\frac{10^{-3}\mathrm{g/cm^3}}{\rho_0}\right)\left(\frac{W_L}{1\,\mathrm{kJ}}\right)\right]^{1/3} \quad (13)$$

Namely, for our scheme where $I_L = 2.2 \times 10^{18}$ W/cm^2, we need a laser pulse duration of 1.2 ps if the laser energy is 1 kJ.

The confinement and the chain reactions

In order to avoid proton and alphas losses to the wall of the vessel, we use a magnetic mirror confinement. For a longitudinal magnetic field inside the vessel, the transverse radius of the fuel container is at least $2R_\alpha$, where R_α is the alpha Larmor radius R_α, is

$$R_\alpha = \frac{\gamma\beta_\perp M_\alpha c^2}{2eB}; \quad \beta_\perp = \frac{v_\perp}{c}; \quad \beta = \frac{v}{c}; \quad \gamma = \frac{1}{\sqrt{1-\beta^2}} \quad (14)$$

M_α is the alpha rest mass, e is the elementary charge, B is the applied longitudinal magnetic field, and $v_\perp$is the perpendicular velocity to the magnetic field. In our case, M_α is about four times the proton mass and its kinetic energy is about 2.9 MeV, implying $\beta = 3.87 \times 10^{-2}$, $\gamma - 1 = 7.5 \times 10^{-4}$ and for a magnetic field of 25 T, we get R_α about 1 cm. The volume is controlled (Eliezer *et al.*, 1987) by its maximum and minimum magnetic fields B_{max} and B_{min} accordingly where one of the important parameters is its mirror ratio R_m defined by

$$R_m = \frac{B_{max}}{B_{min}} \quad (15)$$

For $R_m = 1.5$, one gets a (minimum) vessel volume V_v given by

$$\begin{aligned} &V_v = \pi R^2 L = 16\pi R_\alpha^3 \\ &R = 2R_\alpha; \quad L = 4R_\alpha \end{aligned} \quad (16)$$

Therefore, our mirror confinement of alphas requires a minimum volume of about 50 cm^3. We can increase the volume to sustain an appropriate fusion energy so that the temperature in the vessel is not more than a few electron volt.

In our scheme, we use the chain reaction as was explained recently in the literature (Eliezer *et al.*, 2016*a*) and defined there as avalanche. This chain reaction is explained by the following elastic collisions: (1) the first collision is between the created alpha from the pB11 fusion (with an energy E_α) and a proton in the vessel under consideration, (2) in the second step, this alpha collides with another proton in the vessel that (3) meets a boron in the vessel to fuse into three alphas. Therefore, after the alpha particle with an energy E_α has its second collision with a proton and this proton collides with an ^{11}B one gets in their center-of-mass system of reference an energy $E_{cm}(\mathrm{pB}^{11})$

$$E_{cm}(\mathrm{pB}^{11}) = \left(\frac{11}{12}\right)\left(\frac{16}{25}\right)\left(\frac{9}{25}\right)E_\alpha \simeq 0.21E_\alpha \quad (17)$$

If the energy created in pB11 fusion is equally divided between the three alphas then $E_{cm}(\mathrm{pB}^{11})$ ~600 keV. In general, recent experimental data (Feng, 2020) give a large pB11 cross section for one alpha with energy about 6 MeV and the remaining 2.9 MeV is shared statistically by the other two alphas. The spectrum of alphas created in pB11 fusion does not change the concept of our fusion reactor. To evaluate the impact of this spectrum on the value of the number of the alpha particles created during the chain reaction N_α (for an initial number of alphas $N_{\alpha 0}$ created by the laser-induced shock wave), the value of $\langle\sigma v\rangle$is required. This value depends on the cross section spectrum of the fusion reaction as explained in Eq. (24).

This published approach (Eliezer *et al.*, 2016*a*) was criticized (Shmatov, 2016; Belloni *et al.*, 2018) and defended (Eliezer *et al*, 2016*b*). In this section, we show how to keep the chain reaction going for a time duration much larger than the laser pulse duration. This is achieved with an external magnetic field and an accelerating electric field (Bracci and Fiorentini, 1982) acting as a cyclotron for protons and alphas. These fields prolong the avalanche process by overcoming the Bethe–Bloch energy loss (Bethe and Ashkin, 1953) of the protons and the alphas confined in the external magnetic field.

The Bethe–Bloch stopping power dT/dx is given by

$$\begin{aligned} &\frac{dT_A}{dx}(\mathrm{erg/cm}) = -\frac{4\pi Z_A^2 Z_B e^4 n_0}{m_e c^2\beta^2}\left[\ln\left(\frac{2m_e c^2\beta^2\gamma^2}{I}\right) - \beta^2\right] \\ &\beta = \frac{u}{c}; \gamma = \frac{1}{\sqrt{1-\beta^2}} = 1 + \frac{T_A}{M_A c^2}; \\ &\text{Non relativistic (NR)}: T_A = \frac{1}{2}M_A c^2\beta^2 \end{aligned} \quad (18)$$

The projectile (e.g., proton in our case) with a mass M_A and a charge $Z_A e$ (e is the positive value of the electron charge) dissipates its energy into the medium (i.e., H_3B) via interactions with the electrons of the medium. T_A is the kinetic energy of projectile A, βc is the projectile velocity ($\beta \gg 1/137$), index B is the medium where its particles have a charge $Z_B e$. The medium density is n_0 (atoms/cm^3), m_e is the electron mass, and I (~10 eV) is a phenomenological constant describing the binding of the electrons to the medium. We write the stopping power in the following practical units

$$\frac{dT_A}{dx}(\text{eV/cm}) = -1.65 \times 10^7 Z_A^2 Z_B \left(\frac{n_0}{10^{22}\,\text{cm}^{-3}}\right)\left(\frac{0.04}{\beta}\right)^2 \quad (19)$$

For our case, $Z_A = 1$ (proton), $Z_B = 2$ (H_3B), $\beta = 0.035$ [see Eq. (10)] and for practical purposes, it is conceivable to take $n_0 = ^{1019}$ (cm^{-3}). The strength of the electric field is of the order of $(dT_A/dx)/(Z_A e)$, yielding an electric field of $E = 43$ kV/cm.

A pulsed and oscillatory field is preferable because here it is possible to reach higher peak values than in the static field. In particular, one can use the oscillating electric field in conjunction with a magnetic field B at the cyclotron frequency ω_c given by

$$\begin{aligned} \omega_c &= \frac{Z_A eB}{M_A c}(\text{Gaussian cgs units}); \quad M_A = AM_p \\ \omega_c(\text{rad/s, proton}) &= 9.58 \times 10^8 \left[\frac{B}{10\,[\text{Tesla}]}\right] \end{aligned} \quad (20)$$

The breakdown field E_{ac} for ac field is much higher than in the dc case and it is approximately given by

$$E_{ac} \approx \frac{m_e \omega_c c}{e} \approx 43(\text{kV/cm})\left(\frac{B}{25\,\text{Tesla}}\right) \quad (21)$$

The number density of the produced alpha particles n_α in the nuclear fusion of pB11 is related to the proton number density,

$$n_p = n_{p0} + \delta n_p; \quad \delta n_p = n_\alpha/3 \quad (22)$$

The appropriate number densities (cm^{-3}) of the boron11 and protons n_B, n_p are

$$\begin{aligned} \varepsilon &= \frac{n_B}{n_p}; \quad n_0 = n_B + n_p = (\varepsilon + 1)n_p \\ n_p &= 5.00 \times 10^{19}\left(\frac{\rho}{10^{-3}\,\text{g/cm}^3}\right)\text{for } \varepsilon = 1/3 \\ n_B &= 51.66 \times 10^{19}\left(\frac{\rho}{10^{-3}\,\text{g/cm}^3}\right)\text{for } \varepsilon = 1/3 \end{aligned} \quad (23)$$

We avoid the protons from decelerating with an external electric field [given by Eq. (21)] in the H_3B medium so that the chain reaction yields the number density of the produced alpha particles n_α,

$$\begin{aligned} \frac{dn_\alpha}{dt} &= n_B\langle\sigma v\rangle(3n_{p0} + n_\alpha) \\ n_\alpha &= 3n_{p0}\left[\exp(n_B\langle\sigma v\rangle t) - 1\right] \approx 3n_{p0}\left[\exp\left(\frac{t}{\tau_A}\right) - 1\right] \\ \tau_A &= \frac{1}{n_B\langle\sigma v\rangle} \approx 4.8 \times 10^{-5}\left(\frac{10^{-3}\,\text{g/cm}^3}{\rho}\right)\text{for } \varepsilon = 1/3 \end{aligned} \quad (24)$$

The new reactor

In this paper, we suggest a clean proton–boron11 fusion reactor (Martinez Val and Eliezer, 2019). The concept of this reactor is distinctly different from ICF and MCF reactors. In this scheme, the particles are accelerated by a shock wave to velocities of the order of 10^9 cm/s so that the fusion cross section gets its maximum value.

We consider the fusion $p + {}^{11}B \rightarrow 3^{4He}$ +8.9 MeV. Our reactor consists of a background plasma with densities of the order of a mg/cm^3 of boron11 and hydrogen ions. A plasma channel or a solid target is irradiated by a high power laser that creates a shock wave containing proton particles that enter the background plasma. Fusion boron alphas collide with protons of the plasma and accelerate them causing a chain reaction. The new created alphas are confined by external magnetic fields in the mirror vessel.

We use an existing fluid in our vessel filling the circuit shown in Figure 1. The ${}^{11}B_2H_6$ is the most popular and suitable compound with a density of 1.3×10^{-3} g/cm^3. The fluid can easily be compressed and reach higher densities if required. Therefore, for our numerical examples, we take $\rho = 0.001$ g/cm^3 and $\epsilon = 1/3$.

For the case of creating a shock wave in the background plasma in Figure 1, we use two PW lasers with irradiances of 10^{18} W/cm^2. The existence of these lasers is due to the chirped-pulse amplification technique developed more than 30 years ago (Strickland and Mourou, 1985; Mourou *et al*., 1998). Today, the laser intensity has increased presently to a maximum value of 10^{22} W/cm^2 at infrared wavelength (1.6 eV). Laser systems with an even higher power are worldwide under consideration and development, such as the ELI project in three countries (the Czech Republic, Hungary, and Rumania), XCELS in Russia, HIPER in the UK, and GEKKO EXA in Japan.

The Peta-Watt lasers create a semi-relativistic shock wave with flow velocities as given in "The Shock Wave initiating mechanism" and Figure 2b. The volume of this accelerated fluid is according to Eqs (10)–(12),

$$\begin{aligned} V &= S(\tau_L + \Delta t)u_s \approx 5.3\tau_L u_{sL} S \\ V(\text{cm}^3) &= 2.5 \times 10^{-6}\left(\frac{10^{-3}\,\text{g/cm}^3}{\rho_0}\right)\left(\frac{W_L}{1\,\text{kJ}}\right) \end{aligned} \quad (25)$$

Using Eqs (23)–(25), one gets

$$\begin{aligned} N_{p0} &= n_{p0}V = 1.25 \times 10^{14}\left(\frac{W_L}{1\,\text{kJ}}\right), \\ N_\alpha &= 3N_{p0}\left[\exp\left(\frac{t}{\tau_A}\right) - 1\right]; \quad \tau_A \approx 4.8 \times 10^{-5}\left(\frac{10^{-3}\,\text{g/cm}^3}{\rho}\right) \\ t \gg \tau_A &: N_\alpha \approx 1.65 \times 10^{14}\left(\frac{W_L}{1\,\text{kJ}}\right)\exp\left(\frac{t}{\tau_A}\right) \end{aligned} \quad (26)$$

As a numerical example, we calculate for the case where the energy of the proton–boron11 nuclear fusion of 8.9 MeV per reaction is mainly divided between the three alphas so that we can define the gain G in this case by the ratio of $W_\alpha N_\alpha$ to the laser energy W_L, where $W_\alpha = (8.9\text{ MeV}/3)$. For a reactor facility, a gain of 100 would be economically and technologically satisfactory. Using Eq. (26), we have

$$G = \frac{N_\alpha W_\alpha}{W_L} = 7.8 \times 10^{-2} \exp\left(\frac{t}{\tau_A}\right) \geq 100$$
$$\exp\left(\frac{t}{\tau_A}\right) \geq 1282 \rightarrow t[\mathrm{s}] \geq 7.15\tau_A = 3.0 \times 10^{-4}\left(\frac{10^{-3}\ \mathrm{g/cm^3}}{\rho}\right) \tag{27}$$

For each laser pulse, we need an electric field with a duration of 0.3 ms in order to receive our chain reaction process. For a 100 MW power reactor, we need the power of 100 laser pulses. This can be accomplished with 100 lasers operating with a frequency of 1 Hz or for example with two lasers of 50 Hz.

Conclusions

Using a combination of laser–plasma interactions and magnetic confinement, a conceptual fusion reactor is suggested in this paper. Our reactor consists of a background plasma with densities of the order of a mg/cm^3 and of boron11 and hydrogen ions. Since the temperature of this plasma is few eV, the well-known problem with a thermal plasma for pB11 is avoided, i.e., the radiation level is very low. The fusion process is started via a plasma channel or a solid target that is irradiated by a high power laser that creates a semi-relativistic shock wave. This accelerates a proton beam to reach a kinetic energy of 300–1200 keV where the pB11 fusion cross section is significantly large to produce three alphas

The fusion boron alphas collide with protons of the plasma and accelerate them causing a chain reaction as described in “The confinement and the chain reactions”. It is important to emphasize that in a thermal fusion reactor, the maximum possible theoretical gain is 8900/600∼15 (for the case where the alphas have equal energy); however, in our case, due to the chain reaction process, the maximum gain is (8900/600)*(chain reaction factor) where the chain factor is given by $\exp[t/(n_0\langle\sigma v\rangle)]$ [see Eqs (2) and (26)] and can be very large. In order to achieve this, a combination of an external electric field and a magnetic mirror confinement device keeps the chain reaction process going on for a pulse long enough to get a high energy gain.

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