



Laser-optical path to nuclear energy without radioactivity: Fusion of hydrogen–boron by nonlinear force driven plasma blocks

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ABSTRACT

Anomalous interaction of terawatt–picosecond laser pulses allows side-on ignition of solid state density fusion fuel with the unexpected possibility of igniting uncompressed hydrogen–boron $p\text{-}^{11}\text{B}$. Suppression of relativistic self-focusing by using very clean laser pulses with an extremely high contrast ratio is essential to achieve ignition thresholds only ten times more difficult than fusion of deuterium–tritium (DT). This opens the possibility for laser driven fusion energy without neutrons and less radioactivity than from burning coal. The complex nonlinear optical properties involved are elaborated.

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1. Introduction

The discovery of the chirped pulse amplification for lasers [1,2] has led to an extreme anomaly during fusion target interactions of terawatt (TW) laser pulses of picoseconds (ps) duration. If the pulses are very clean with a contrast ratio of 10^8 the X-ray emission is found to be very low instead of the usually high intensity energetic bursts, and the emission of fast ions shows much lower energies than usual but with high directionality and in numbers independent of intensity. These effects were explained with skin-layer interaction predicted earlier from plane geometry analysis [3] and confirmed by experiments in many details [4]. The creation of the fast ions was attributed to nonlinear (ponderomotive) force generated plasma blocks of modest temperature and space charge neutrality containing highly directed ions with 100 keV and higher energies and current densities exceeding 10^{10} A/cm² as measured, theoretical expected, and numerical confirmed [3–5].

The key problem is then how to suppress the relativistic self-focusing of laser beams in the target interaction plasma [6]. The quiver motion of electrons in a laser fields at relativistic intensities leads to a change of the electron mass resulting in optical constants to bend a laser beam to less than a wave length diameter. At these very high intensities as measured since 1975, highly ionized ions with energies very far above 10 MeV are emitted due to nonlinear (ponderomotive) forces in the opto-mechanical interaction with inclusion of dielectric properties [7]. The high energy of the ions

created within the beam focus is even directly seen in X-ray line shifts [8] and analyzed with inclusion of soliton processes [9] ([10], Section 10.6). Analysis using plane geometry laser interactions with plasmas along with very general properties, including nonlinear absorption constants allowing demonstration of the predominance of the non-thermalizing direct conversion of optical energy into mechanical motion by the nonlinear forces at very high laser intensities ([10], Section 10). However this effect could not be observed experimentally with existing laser facilities because the laser prepulses produced a plasma cloud where beam self-focusing creates non-plane geometries. Finally, using the Szatmary–Schäfer method [11] for producing TW-ps laser pulses and plasma mirrors [12] generating “clean pulses” by suppressing prepulses with a contrast ratio of 10^8 it was possible to suppress relativistic self-focusing and realize plane interaction geometry [13]. Then as shown by Doppler shifts, the plasma acceleration exactly follows the nonlinear force interaction [4]. This is a rare anomaly for laser–target interactions because usual experiments with TW to PW laser pulses in the ps and shorter range include relativistic self-focusing producing many new relativistic properties [14] such as: pair-production; generation of 100-MeV electron acceleration by the nonlinear interaction [15]; GeV ions; and nuclear transmutations by the gamma bursts causing a nuclear photoeffect etc.

Recognition of the anomaly of these observations of the clean pulse interactions [3] led to a come-back [4,5] of interest in generating laser driven fusion energy using *side-on ignition* of *uncompressed* solid deuterium–tritium (DT). The fusion target ignition threshold was originally derived hydrodynamically by Chu [16] and confirmed by Bobin [17]. However they arrived at the need to provide the exorbitant energy flux densities E^* above the threshold E_t^*

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¹ Mark Oliphant, who was involved in very first measurements with $p\text{-}^{11}\text{B}$, showed a cloud chamber picture of a $p\text{-}^{11}\text{B}$ reaction looking like a Mercedes star (private communication in 1974 when Sir Mark was Governor of South Australia).

$$E^* > E_t^* = 4 \times 10^8 \text{ J/cm}^2; \text{ ignition temperature } 7.2 \text{ keV} \quad (1)$$

This condition can be seen from the computation of the characteristic plots of the plasma temperature in the interaction area vs. time for a given parameter E^* . The results of Chu ([16], see there Fig. 2) shows where the characteristics increase (explosion) down to E_t^* where a stationary temperature is reached. Then the emitted Bremsstrahlung is equal to the generated fusion energy. For lower E^* the characteristics decay with time after a maximum.

The consequence of requiring exorbitant values of E^* (1) is that side-on ignition is not possible so laser fusion must follow the classical way of spherical compression of the fusion fuel by lasers to very high fuel densities [18] with the expectation of 2009/10 for the historically very first controlled ignition of an exothermic DT fusion reaction. This result is expected at the national ignition facility at the Lawrence Livermore National Laboratory, USA. However, in sharp contrast to this spherical laser driven fusion, side-on driven laser fusion for clean petawatt (PW)-ps laser pulses based on the anomaly cited here [3,4] should lead to ignition of solid state density DT with nonlinear force driven plasma blocks [4,5]. This is then a kind of “fast ignition” [19] with the anomalously high ion beam currents. It is similar to the earlier Nuckolls-Wood scheme for laser ignition with electron beams [20]. With that approach, they arrived at gains of 10,000 in low compression DT.

Other effects are also very important in the new side-on driven scheme. The threshold E_t^* decreases considerably [21] when the reduction of thermal conduction by the inhibition factor and the reduction of the stopping length by collective effects is included into the analysis of Chu [16]. With inclusion of these effects, it appears that both side-on ignition schemes, that with electron beams [20] and that with the ion blocks [4,5] may lead to fusion power generation from uncompressed or modestly compressed DT using laser pulses in the range of 10 PW and ps duration. The optics problem to generate the desired contrast ratio of laser beam for creating ion beam blocks of sufficient thickness follows a conical geometry guidance [4]. In addition a highly increased skin-layer thicknesses is created using Rayleigh density profiles for initial conditions [22]. This approach also resolved of the problem of internal reflection of light in inhomogeneous optical media ([10], Section 7).

A very interesting fusion fuel is the reaction of light hydrogen with the boron isotope 11 ($p\text{-}^{11}\text{B}$) because it produces mono-energetic* 2.888 MeV alpha particles for direct conversion into electricity [23] initially no neutrons and less radioactivity per generated energy than by burning coal due to its content of 2 ppm uranium [24]. For spherical laser ignition, however, it was calculated [23] that the compression to 100,000 times the solid state is needed for burning $p\text{-}^{11}\text{B}$. This density limit has been confirmed by detailed evaluation of volume ignition [25] where the necessary laser pulse energies are considerably above 10 MJ in order to arrive at modest energy gains of 20. This is possible due to alpha particle re-heat of the target and partial re-absorption of Bremsstrahlung which reduce the $p\text{-}^{11}\text{B}$ ignition temperature to ~ 23 keV. The “normal” is 150 keV.

These results excluded any hope of laser fusion for $p\text{-}^{11}\text{B}$ by high compression with *spherical* ignition. However, extending the *side-on ignition* from DT [5,21] to the case of $p\text{-}^{11}\text{B}$, the very surprising fact was experienced [26] that the ignition conditions are *only about 10 times more difficult* than for DT. This is in sharp contrast to the exorbitant conditions at ignition by spherical compression for $p\text{-}^{11}\text{B}$.

This result can be understood as follows. Taking first only the very conservative assumptions of Chu [16] the characteristics (Fig. 1) required for a threshold for ignition of $p\text{-}^{11}\text{B}$ are

$$E_t^* = 1 \times 10^9 \text{ J/cm}^2; \text{ ignition temperature } 87 \text{ keV} \quad (2)$$

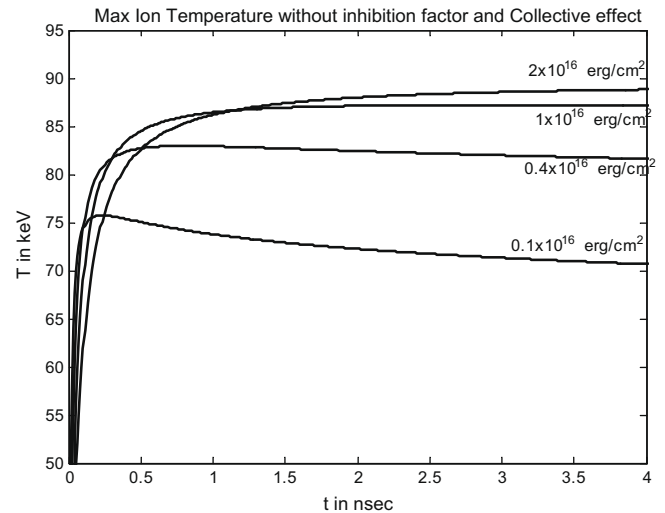


Fig. 1. Dependence of the temperature T on time t for side-on ignition of solid density $p\text{-}^{11}\text{B}$ working with conditions used for DT by Chu [16] (parameter E^* in units used by Chu).

Continuing these studies for $p\text{-}^{11}\text{B}$ by inclusion of the inhibition factor and including a collective effect for reaction products similar to the case of DT [21] arrives at a decrease of the temperature in absolute values similar to the results for DT. Fig. 1 shows clearly that at $E^* = 4 \times 10^8 \text{ J/cm}^2$ there is no ignition. Indeed the conclusions drawn from all the plots of the characteristics beginning with Chu [16] are not very accurate. A very more detailed analysis is needed but at least the basic properties for the side-on ignition are clearly visible. Most significant are the very surprising results for the fusion of uncompressed $p\text{-}^{11}\text{B}$ fusion energy generation with laser pulses in the range of few dozens of PW power and ps duration avoiding neutron generation, nearly no radioactivity, and with a minimum of heat pollution. The X-radiation in the reactor is around or below 90 keV and can be screened out without any secondary nuclear reactions in the power station structure. This provides an exciting vision of a very attractive sustainable future power plant for worldwide use. Its achievement will depend on continued advances in laser optics, target physics and power conversion technology.

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