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Hydrodynamic Studies of Laser Fusion using Plasma Block Ignition Driven by Nonlinear Ponderomotive Forces

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Abstract: In contrast to laser fusion with spherical plasma compression to very high densities, the alternative was studied with side-on ignition of solid state (or modestly higher) deuterium-tritium, based on hydrodynamic theory. The extremely difficult conditions may be overcome using petawatt-picosecond (PW-ps) laser pulses, however, only by applying the advantages of a discovered anomaly of plane geometry interaction without relativistic self-focusing using very high contrast ratios of the laser. The conditions of this side-on ignition could be further relaxed by inclusion of interaction effects. Ignition of solid state density or modestly compressed deuterium-tritium (DT) and of proton-boron11 (HB11) seems to be possible with laser pulses of several PW power and ps duration.

1. Introduction

Laser driven fusion aims for a clean, inexhaustible, safe and everywhere available energy source. For this aim, the largest laser on earth is now available [1] producing pulses of 1.1 MJ energy of few nanosecond duration leading for the first time on earth, to a controlled fusion reaction generating more energy than the laser pulse needed for the ignition. The fusion fuel consists of isotopes of heavy hydrogen (deuterium D) with the super-heavy hydrogen isotope tritium T, where a *spherical laser irradiation compresses the fuel to more than 1000 times the solid density* with heating to ignition temperatures of several ten million degrees centigrade. Following this scheme, a prototype of a power station [2] is scheduled for 2020 based on very compact and high-efficient diode pumped lasers which are now available.

Parallel to these developments are schemes for generating fusion energy by using the new type laser pulses [3] with more than PW (petawatt) power [4] and of ps (picoseconds) or shorter duration. Following the modified scheme of Nuckolls and Wood [5] it should be possible for working with power reactors using DT fuel after chemical compression to about 10 times solid state density, ignited with very intense electron beams of 5 MeV energy arriving at fusion gains of 10,000.

This paper reports on another scheme using PW-ps laser pulses following a side-on ignition of solid state density fusion fuel developed 1972 [6][7] which was not possible then because energy flux densities E^* with pulses of about ps duration above a threshold E_t^* for DT

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

were necessary. These conditions were very far away from reality and the scheme of laser fusion with spherical compression of the fuel to very high densities was followed up [1]. This situation changed after 2 PW-ps laser pulses were available [3]. Highly relativistic effects appeared as pair production and nuclear transmutation, but in contrast to these usual measurements, an anomaly was discovered with drastically different observations. 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 (see section 10 of [8])[9] and confirmed by experiments in many details [10]. Only laser beams with the high contrast ratio avoided the generation of a plasma plume in front of the target leading to relativistic self focusing [11]. The plane geometry interaction was verified for the first time in experiments by Sauerbrey [12] with the clean pulses, where the measured Doppler shift of the accelerated plasma agreed then exactly as predicted before from nonlinear (ponderomotive) force acceleration [10]. Based on these results, a come-back of the ignition of solid density or modestly compressed fusion fuel with irradiation of the laser driven ion current densities above 10^{10} Amp/cm² became interesting again.

2. Side-on Ignition by nonlinear force driven clean PW-ps laser pulses

The limit of Eq. (1) of the energy flux density E^* for ignition of solid state density DT by pulses of about ps duration was derived hydrodynamically [6][7]. The condition (1) 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 ([6] see there Fig. 2) shows where the characteristics increase (ignition) down to E_i^* where a stationary temperature is reached. For lower E^* the characteristics decay with time after a maximum with no ignition.

Other effects are also very important in this new side-on driving scheme. The threshold E_i^* decreases considerably [13] 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 [6]. A highly increased skin-layer thicknesses is created using – as an example - Rayleigh density profiles for initial conditions [8][14]. This approach also resolved the problem of internal reflection of light in inhomogeneous optical media ([8] section 7) at least during the initial stages of interaction.

For clarification it has to be underlined that this is basically no new theoretical work. It is a continuation what Chu [6] and Bobin [7] had achieved at about 1972. New are only the now available PW-ps laser pulses, however with the exception that the usually measured wild relativistic effects are carefully excluded. Instead the very rare measurements of plasma block generation with extremely clean laser pulses for avoiding relativistic self-focusing is the new result [9,10] as it was predicted by computations with the nonlinear force ([8] section 10).

3. Ignition of proton-boron(11)

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 if the incident protons have an energy of less than 150 keV [15] for direct conversion into electricity. Initially no neutrons are produced and [16] less radioactivity per generated energy appears than by burning coal due to its content of 2ppm uranium. For *spherical laser ignition*, however, it was calculated from the beginning [17] that compression to 100,000 times the solid state is needed for burning $p\text{-}^{11}\text{B}$.

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 [10][13] to the case of $p\text{-}^{11}\text{B}$, the very surprising fact was experienced [18] that the ignition conditions are *only about 10 times more difficult* than for DT. The factor 100,000 for more difficulties for $p\text{-}^{11}\text{B}$ at spherical compression compared with DT is given from 100 times higher density, 100 times higher laser pulse energy, and 10 times lower gain [17]. For the side-on block ignition of $p\text{-}^{11}\text{B}$ first only the very conservative assumptions

of Chu [6] are taken arriving at the characteristics (Fig. 1) similar to those for DT Chu (see his Fig. 2 [6]). In difference to the earlier reported results [18], we present here new computations for much longer times t of the temperature T of the reaction wave front at incident energy flux densities E^* as parameter. If E^* is too low, the curves decay on time t and no ignition happens. Only if T is not decreasing as for $E^* = 2 \times 10^9 \text{ J/cm}^2$ or a little lower, but above $1 \times 10^9 \text{ J/cm}^2$, then ignition happens. From Fig. 1 the resulting threshold E^* for ignition of $p\text{-}^{11}\text{B}$ is then within a error bar of 35% is

$$E_t^* = 1.5 \times 10^9 \text{ J/cm}^2 ; \text{ ignition temperature } 87 \text{ keV} \quad (2)$$

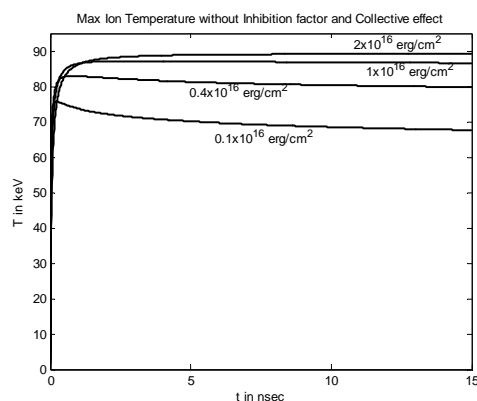


Fig. 1. Dependence of the temperature T on time t for side-on ignition of solid density $p\text{-}^{11}\text{B}$ working with conditions used for DT by Chu [6] (parameter E^* in units used by Chu).

Further new results were with inclusion of the inhibition factor and including Gabor's collective effect for reaction products similar to the case of DT [13] arriving at a minor decrease of the temperature in absolute values of the temperature similar to the results for DT. Bremsstrahlung losses were automatic included in the computation but again as new result confirmed by new computer outputs.

The essential result presented here – without more precise evaluations – is, that the side-on ignition of solid $p\text{-}^{11}\text{B}$ is less than about a factor 10 more difficult than igniting DT *only*, while the spherical laser compression was about 100,000 times more difficult. Laser fusion of uncompressed $p\text{-}^{11}\text{B}$ may then work with dozen PW laser pulses of ps duration

with sufficient suppression of prepulses [10][14].

4. Discussion and Conclusions

The results are based on the highly detailed and modified [13] hydrodynamic computations of Chu [6]. This model works basically on the generation of a hydrodynamic two-dimensional shock front and is in principle different from the three dimensional volumetric processes considered by Nuckolls and Wood [5] who needed the ρR criterion for the ignition with electron beams. It should be mentioned that the volume ignition results [19] – confirmed by the evaluation of the Wheeler modes [20] – are basically different to the two-dimensional shock-like interactions of the Chu analysis [6]. This has been clarified in details following the equivalence of Eqs. (13.7) and (13.8) of Ref. [8] about ρR .

More serious problems with our purely hydrodynamic results may need to be studied with other methods, e.g. with ingeniously modified single particle models, discovered by Wilks, et al [21] as Particle In Cells (PIC) techniques. The problem of the interpenetration of plasma particles between very hot and cold plasma [22] may lead to an improvement of the conditions at least for our situation at sub-relativistic temperatures and sufficiently small Debye lengths for the block description with electric double layers [8].

Another problem is that the here reported hydrodynamic analysis is based on plane geometry presumptions. In reality there is a lateral spread of the interacting laser beam though this is of a radius in the range of thousand laser wave lengths. Several of these geometries were evaluated by Bobin [7] indicating that the better conditions for the nonlinear force driven block ignition of HB11 by several orders of magnitudes in contrast to the spherical laser compression scheme may sustain a further analysis. Experiments about the side-on ignition should guide and clarify short-cuts of the theoretical research.

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-¹¹B 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 in a power station or for space propulsion. Modest precompression by chemical driving [5] will improve the conditions especially for HB11. The x-radiation in the reactor is around or below 100 keV and can be screened off. No secondary nuclear reactions in the power station will occur. 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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