Laser-Plasma Interaction of Petawatt-Picosecond Laser Pulses with Very High Contrast Ratio

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Abstract: A significant new effect was discovered with the measurement by Sauerbrey irradiating terawatt laser pulses of less than picoseconds duration producing ideally directed plane plasma acceleration where the Doppler effect resulted in accelerations of 10^{20} cm/s^2. This acceleration by the nonlinear (ponderomotive) force was predicted and numerically elaborated in exact theoretical agreement based on plasma-fluid models including the non-thermal radiation acceleration. The generated directed non-thermal plasma blocks with ion-current densities above 10^{11} Amps/cm^2 permitted a come-back of the Bobin-Chu side-on ignition of solid density DT and HB11. Further results for He3-He3 and pLi(7) are reported. The most significant result consists in the fact that BH11 fusion is less difficult by a factor ten only compared with DT. This may lead to low cost nuclear power, producing less radioactive radiation per generated energy than from burning coal.

Key words: inertial confinement; fast ignition; non-linear simulations; aneutronic fuel;

1. Introduction

Very general and detailed hydrodynamic computations of laser-plasma interaction in plane geometry including the nonlinear (ponderomotive) force 1978 from [1] (see [2] Figs. 10.18a&b) resulted in the generation of deuterium plasma blocks moving with velocities above 10^9 cm/s against the laser light or into the target after 1.5 ps irradiation with neodumium glass laser intensities of 10^{18} W/cm^2. The accelerations were in the range of 10^{20} cm/s^2. This was never measured before 1996, because the condition of plane geometry was violated by relativistic self-focusing [3] generated in the plasma plume made by the laser pre-pulses squeezing the laser beam to less than wave length diameter. The extremely high laser intensities in this filament generated ions with very high ionization Z and the nonlinear force accelerated them to energies of MeV up to GeV (see [4] Section 12.6).

It was not before 1996 that the accelerations to 10^{20}cm/s^2 were discovered experimentally from the Doppler measurement at the plane plasma fronts by Sauerbrey [5]. It was essential that relativistic self-focusing was avoided by using an extremely high contrast ratio (intensity of the main laser pulse above the intensity of pre-pulses) up to several ps before arrival of the main pulse at irradiation with TW power and duration in the ps range. Of the many experiments with such laser pulses, very rare cases with such high contrast resulted in the same effect of avoiding relativistic self-focusing with the clean laser pulses. Zhang et al [6] measured the x-ray emission from targets at TW-ps laser pulse irradiation which were drastically lower than what was measured anywhere since 1975. Only when relativistic self-focusing was intentionally permitted for plasma plume generation, did the very intense and short wave length x-rays appear. A similar effect was observed with clean pulses [7] from fast ions moving against the laser light. One expects more than 20 MeV ions from relativistic self-focusing, but only 0.5 MeV ion energies were measured. A further curiosity was that the number of the fast ions did not change with the laser intensity. This all was recognized [8] as the result of plane geometry nonlinear-force-acceleration (NOFA) of the plasma blocks in the skin layer. Its thickness could indeed be up to 20 [1][2] wave lengths due to the dielectric plasma properties of the nonlinear force action. The subsequent high directivity of the plasma blocks were measured in contrast to relativistic self-focusing [9] and thin film targets showed the other plasma block accelerated into the target. This was summarized by including the fact that Sauerbrey's measured 10^{20} cm/s^2 acceleration was reproduced by the nonlinear force within the measurement accuracy [10].

What was evident from the beginning [8] was that the plasma blocks represented space-charge-neutral directed ion current densities of 10^{11} Amps/cm^2. The ion energies could be 100 keV and even much more while the electrons in between had a rather low temperature as seen from the computations due to minor collision heating during the interaction. These properties of the block were ideal for the earlier studied side-on-ignition of uncompressed solid density fusion fuel [11][12] studied by Chu [13] and Bobin [14]. We present results following the preceding IAEA Fusion Energy conference [15] summarized before [16].

2. Side-on ignition of solid density fusion fuel following Chu and Bobin

These extraordinary high ion current densities produced by the laser pulses of TW or PW power and ps duration offered a comeback of the side-on laser ignition of fusion fuel at solid state density as calculated by Chu [13], however ps long energy flux densities above 10^8 J/cm^2 were needed for a deuterium tritium (DT) reaction. Because of these exorbitant numbers, side-on ignition was given up and the spherical compression of DT to 2000 times the solid state for laser fusion was followed up, presently ready for demonstrating the historical first controlled ignition of DT with the NIF-laser [17]. The discovery of the plasma nonlinear force driven plasma blocks, however, permitted a comeback.

The question of whether a laser pulse can ignite solid state DT fuel without compression side-on was studied using hydrodynamics by generating a shock-like fusion flame, by Chu [13] and Bobin [14]. The result was very disappointing, because laser pulses of ps duration needed an energy flux density E^* with the threshold E_t^*

$$E^* > E_t^* = 4.7\times10^8\ J/cm^2 \qquad \text{for DT} \qquad (1)$$

This was far beyond the then available capacity and this side-on scheme was dropped in favor of spherical laser compression. The situation changed after 1 PW (500 J ind 500 fs best case) laser pulses of half ps duration were available [18], and now potentially increased to 10 PW (RAL Vulcan 10 PW project planned to start in 2012 [19]) but where the numerous complex relativistic effects might prevent many applications especially in ICF. However, only after the drastic anomaly of the interaction was discovered by Sauerbrey [5] and subsequently clarified [8] that block/skin-layer acceleration worked only by suppression of pre-pulses by contrast ratio better than 10^8, all other effects from relativistic self-focusing could be excluded and a plane-geometry interaction was possible as confirmed experimentally in much detail [10]. It should be underlined that the conditions of plane-geometry acceleration of plasma blocks were fulfilled in further experiments [20] where the measurement of directed blocks of fast deuterons are fully in accordance with nonlinear-force action including dielectric swelling.

The highly directed plasma front moving perpendicular to the irradiated target and another moving into the target were confirmed [7][10]. Their origin was from dielectrically strongly increased skin layers [8][16]. The generated plasma blocks of modest temperature consisted in space-charge quasi-neutral direct ion beams of up to

$$j > j^* = 10^{11}\ Amps/cm^2 \tag{2}$$

or even higher current densities *j*. This permitted a come-back of the side-on ignition of the fusion flame in solid density DT from the Chu-Bobin theory which had to be modified with respect to later discovered effects of thermal inhibition and collective (Gabor) stopping power [21]. The application of the ultra-intense ion beam blocks for nuclear fusion was formulated before [16] using ps laser pulses in the range of 10 PW. Similar to the electron driven laser ignition by Nuckolls and Wood [22], gains up to 10,000 may be possible in which case a pre-compression to 12 times the solid density by chemical explosives was included. A basic difference between the electron and the ion driving is due to the fact that the electron beam ignition needs a three dimensional energy deposition [22] determined by a ρR-criterion (see Eqs. 13.7 and 13.8 of Ref. [4]), while the fusion flame [13][14] is a two-dimensional detonation wave.

3. Results for ignition of a fusion flame at solid state density

a) Ignition of Deuterium Tritium DT

The side-on fusion ignition can be followed up by the reaction-characteristic curves as shown by Chu (Fig. 2 of [13], see also Fig. 2 of Ref. [15]). The hydrodynamic computation for an input of an energy density E* per square centimeter during a time in the range of ps on solid state density DT produces a combustion wave moving into the DT of a temperature T depending on the time t. When the curves decay, no ignition happens in contrast to ignition when the curves are continuing to increase. In between is the curve for the threshold for ignition defining the threshold

$$E_t^* = 4.7\times10^8\ J/cm^2 \tag{3}$$

at an ignition temperature

$$T_{ign} = 7.2\ keV \tag{4}$$

When repeating these computations at the same conditions of Chu [13], the same values resulted. Later discovered phenomena had to be included as the reduction of the thermal conduction in inhomogeneous plasmas by an inhibition factor and the change of the stopping power at very high plasma densities due to collective effects according to Denis Gabor lowering the threshold values of (3) and (4) by a factor up to 20 [21] and the ignition temperature dropped to 4.9 keV. The computation of Chu has completely included the energy losses by Bremsstrahlung. The ignition is estimated to be reached with ps laser pulses with a contrast ratio better than 10^8 and pulse energy between 10 and 20 PW.

b) Ignition of proton-^{11}boron (HB11): Nuclear Energy with negligible Radioactivity

A most surprising result appeared, when the side-on ignition was calculated by exchanging the DT reaction cross section with that of the reaction of protons with boron isotope 11. This reaction

$$H + {}^{11}B = 3\,{}^{4}He + 8.664\ MeV \qquad (5)$$

does not produce neutrons and was considered as an ideal reaction for fusion energy. Secondary reactions lead to some radioactivity, which however, was calculated to be less than from burning coal per unit of produced energy because of the 2 ppm contents of uranium and thorium in coal [23]. When calculating the conditions for laser driven fusion energy with spherical compression, it turned out that the compression had to be 100,000 times solid state and when going into detail for volume ignition [24], it turned out to be 100,000 times more difficult than igniting DT. The factor 100,000 compared with DT is due to about 100 times higher compression, 100 times higher input laser energy and 10 times lower fusion gain.

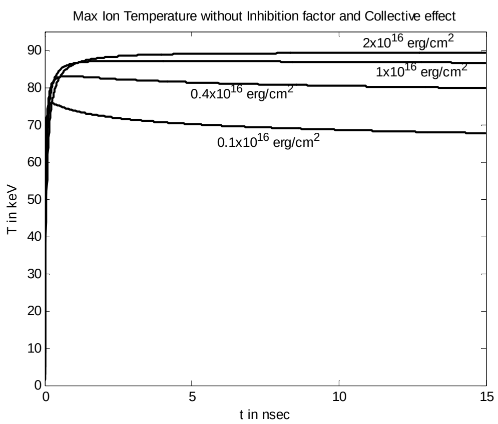

Fig. 1, Characteristics of the kind of Fig. 4 for p-^{11}B under the assumptions most similar to Chu [13] for comparison with DT fusion.

Extending the hydrodynamic computations of laser driven side-on ignition from DT to HB11, a surprising result was achieved, namely, that this is only less than about ten times more difficult than the fusion of DT. Extending the hydrodynamic computations of laser driven side-on ignition from DT to HB11, a surprising results was achieved namely, that this is only less than about ten times more difficult than the fusion of DT. Fig. 1 shows the reaction-characteristic curves for the HB reaction [25][26]. This is in strong contrast to the fusion ignition by spherical compression. It seems then that the very simplified laser fusion of solid density HB11 by using ps laser pulses of few dozens of PW power may lead to remarkably lower cost generation of nuclear energy without all the difficulties of radioactive radiation in the fuel, the reactor and the waste, known from all other nuclear power stations where details have been published. The result is with an error of ±33%

$$E_t^* = 1.5\times10^9\ J/cm^2 \qquad (6)$$

with an ignition temperature T of the plasma of

$$T_{ign} = 87\,keV \quad \text{HB11} \tag{7}$$

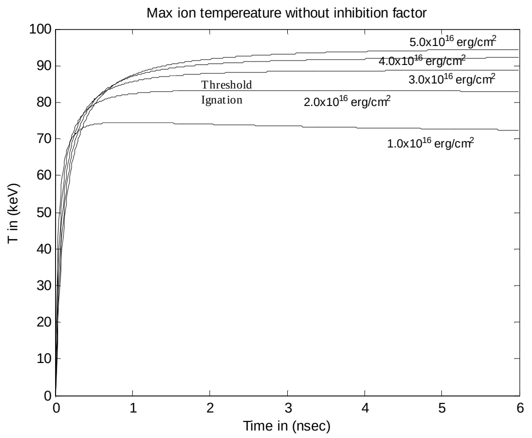

Fig. 2. Side-on ignition characteristics for the fusion by ps side-on laser driven reaction of solid state density ^3He.

The inclusion of the inhibiton factor and of the collective stopping power reduses the ignition temperature in the range of few keV. But in views of the much higher ignition temperature than for DT, the threshold for the energy flux density E* changes relatively little.

c) Ignition of helium isotope 3 at condensed density

It is then interesting to consider another case of fusion energy with no primary neutron production. Such a case is to burn helium-3 following the reaction

$$^3He + {}^3He = {}^4He(1.429MeV) + {}^1H(5.716MeV) + {}^1H(5.716MeV) \tag{8}$$

The fuel He-3 can be harvested from the surface of the moon as known from the scheme to produce fusion of deuterium with He-3 [27] where the load of one Space Shuttle with He-3 could produce all energy in the USA for half of a year.

Reaction (8) is primarily without any neutrons as the HB11 reaction. Only secondary reactions of the 5.716 MeV protons with the helium will lead to radioactive nuclei. Whether these consist of much more or less radioactivity than burning coal per generated unit of energy needs to be evaluated but should not differ by orders of magnitudes from the case of HB11. Performing the hydrodynamic computations at the same conditions as before by Chu [13], results in the characteristic plots shown in Fig. 2. To find the threshold driver energy flux density one notes that 2×10^9 J/cm^2 does not lead to ignition while 3×10^9 J/cm^2 does ignite. By interpolation, the threshold of laser side-on ignition of solid state density ^{3}He has a threshold energy flux density and threshold temperature

$$E_t^* = 2.7\times10^9\,J/cm^2 \tag{9}$$

$$T_t^* = 88\,keV, \quad \text{He3-He3} \tag{10}$$

where, as before, the emission of Bremsstrahlung is just compensated by the generated fusion energy.

d) Ignition of proton-^7Li (H7Li)

Another case of a fusion reaction without neutron production is

$$^{1}H + {}^{7}Li \;=\; 2\;{}^{4}He \;+ 17.348\; MeV \tag{11}$$

The side on ignition characteristics for the conditions of Chu [13] are shown in Fig. 3 resulting in the values

$$E_t{*} \;=\; 2.5\times10^{9}\; J/cm^{2} \tag{12}$$

$$T_{ign} = 69\; keV \quad \text{p-}^{7}\text{Li} \tag{13}$$

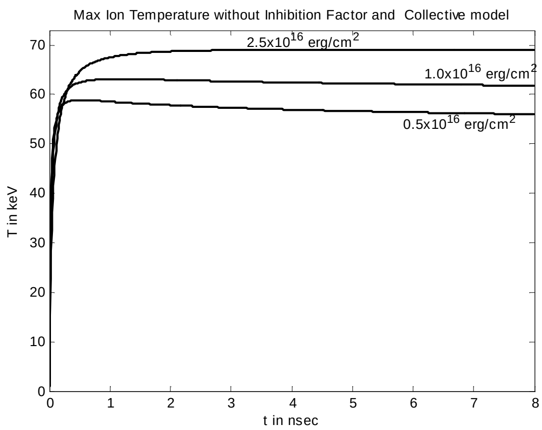

Fig. 3. Side-on ignition characteristics for the fusion by ps side-on laser driven reaction of solid state density p-^{7}Li.

It is remarkable that the ignition temperature is comparably low. This may be due to the high energy in the alpha particles as the reaction product. The significant preference was repeatedly underlined by Sir Mark Oliphant. The energies of the alphas in (11) and in (5) are each as long as the energy of the proton before the reaction is not higher than 200 keV as in all the cases considered here.

4. Ignition of DT at modest compression and discussion

Following the case of modest pre-compression of the fusion fuel by chemical explosion as explained for side-on fast ignition with electron beams [22], we calculated the ion-driven block ignition for ten times solid state density, Fig. 4. Using – for comparison – the presumptions of Chu [13], the threshold energy flux density E_t* in this case is $7\text{x}10^{7}$ J/cm^2 with the threshold temperature of 14 keV. Approximately, a decrease of E* was assumed to be linearly on increasing the density but the detailed hydrodynamic computations showed a decrease only by a factor 7 and not 10. The reason is that the maximum temperature of the fusion flame is increased by about 35% due to the shorter stopping length of the alpha particles at the increased density.

The general discussion of the side-on ignition by the directed ultrahigh ion current density in the space charge neutralized nonlinear force driven plasma blocks is based on two phenomena. The first is the generation of the plasma blocks. This process is based on the direct conversion of laser energy into hydrodynamic motion of the blocks [1][2] finally confirmed from the Doppler measurement for plane geometry by Sauerbrey [5] and the subsequent clarification [10]. The acceleration [5] in the range of 10^{20} cm/s^2 is typical for the nonlinear force process in contrast to the thermokinetic acceleration in the range of 10^{15} cm/s^2 available from the NIF laser interaction for application to laboratory astrophysics uses [28].

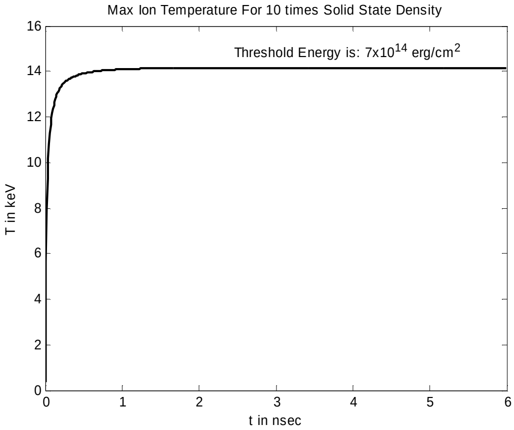

Fig.4. Side-on ignition threshold characteristic for deuterium tritium at ten times solid state density.

The second phenomenon for consideration is the hydrodynamic basis for treating of the generation of the fusion flame. The stopping lengths of the 100 keV ions in the blocks and of the alpha particles are in the range of dozens of micrometers and justify the Dirac-delta-function-like assumption, it nevertheless has to elaborated how the details of particle interpentration and non-equilibrium electron distributions etc. are of influence. PIC computations for electric field phenomena are a solution against hydrodynamic limitations where Debye-lengths are very high. But where electron collisions with collective effects are important [29] and the fusion produced creation and thermal stopping of alpha particles are involved, limitations for the PIC techniques are evident. The best may be to study the block produced fusion flames experimentally for which first steps with the Trident laser are on the way.

The studies reported here show that laser ignition of solid state or modestly pre-compressed fusion fuel with no primary neutron generation may be possible. This development was in principle favorably acknowledged in an IAEA Review by Tanaka [30].

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