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Inertial Confinement Fusion Propulsion for Deep Space Missions Revisited

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Laser-driven Inertial Confinement Fusion (ICF) is extremely attractive for deep space propulsion and has been the subject of several conceptual design studies. However, these studies were based on older ICF technology using either "direct "or "in-direct x-ray driven" type target irradiation. This leads to rather low energy gains. Plus, traditional DT fusion was selected, requiring tritium breeding and delivering 80% of the fusion energy in neutrons that cannot be directed thorough an exhaust nozzle. However, important new directions have developed for laser ICF in recent years following the development of "chirped" lasers capable of ultra-short pulses with powers of TW up to a few PW. This has led to the exciting concept of "fast ignition (FI)" where the peta-watt laser beam strikes a pre-compressed target, creating a hot spot in the interior of the target burn that propagates outward into the surrounding fuel. This then gives a much higher energy gain, since part of the input energy required is replaced by the propagating burn.

In the present study, we employ a new type of FI, termed "block ignition". In this approach, a non-laser interaction causes a plasma block to be accelerated into the target to ignite the hot spot. This is very efficient in giving very high gains while maintaining a low electron temperature, allowing ignition of more demanding fusion fuels like p-^{11}B. The p-^{11}B reaction is employed here and releases energy by energetic alphas particles that can be very effectively guided through a magnetic nozzle to produce thrust while avoiding tritium involvement or neutron induced radioactivity. These advances are considered here and are shown to meet and exceed the requirements anticipated (but not then available) for optimum ICF fusion propulsion ship design.

Nomenclature

A_{exp}	= experimental acceleration
AU	= astronautical units
D	= deuterium
D^{3}He	= deuterium-helium-3 fusion
DD	= deuterium-deuterium fusion
DT	= deuterium-tritium fusion
E	= electric field, V/cm
E*	= energy flux density
eV	= electron-volt
fs	= femtosecond
GeV	= giga electron-volt
H_z	= cycles per second

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ICF = inertial confinement fusion
j = ion current density
keV = kilo electron-volt
KrF = krypton-fluoride
MeV = mega electron-volt
MJ = mega joule
n_i = ions/cm3
NIF = National Ignition Facility
Ns = nanosecond
ps = picosecond
PW = petawatt
p-B^{11} = proton-boron-11 fusion
rpm = revolutions per minute
SLANF = skin layer acceleration by nonlinear forces
T = tritium; or plasma temperature.
t_p = pre-irradiation time
TW = tetrawatt
V = ion velocity, cm/sec
VISTA = Vehicle for Interplanetary Space Transport Applications
Σ = cross section
Z = ion charge
Ω = plasma frequency, sec -1
Θ = angle of measurement, deg

I. Introduction

Fusion propulsion is generally considered to be one of the most promising approaches for future deep space travel. A number of prior studies have examined this approach through design studies intended to indentify performance capabilities and advantages, e.g. see Ref. 1. Both magnetic and inertial confinement fusion have been explored, including various alternate confinement approaches, such as inertial electrostatic confinement (IEC), studied by the authors and colleagues.[2] More recently, the authors and colleagues explored the use of the exciting new block ignition approach for ICF power and propulsion.[3] In that case, it was pointed out that the improved performance with block ignition could enable bypassing D-T fusion and going directly to tritium-lean D fusion. Thus, avoiding problems of tritium breeding. More recently, improvements in block ignition techniques have opened the very exciting possibility of using hydrogen-boron II (p-^{11}B) fuel, removing issues of tritium and neutron induced radioactivity.[3-4] Here, we first briefly review ICF propulsion design studies, block ignition and its use for p-^{11}B fusion.

II. Prior ICF -Powered Spacecraft Concepts

The early history of ICF driven propulsion was well summarized in a 2003 Lawrence Livermore National Laboratory (LLNL) report by Charles Orth et al.[5] Application of the ICF to rocket propulsion began in the early 1970's. Balcomb, et al.[6] at the Los Alamos National Laboratory (LANL) proposed a laser-fusion concept that retained the idea of acquiring acceleration through particles striking a pusher-plate. This idea was originally suggested in Project Orion.[7] In Orion, nuclear explosions were to be detonated behind a massive plate attached to the spacecraft through a pneumatic spring system. Later Hyde, Wood, and Nuckolls[8] at LLNL proposed the use of laser fusion with a magnetic nozzle to redirect the charged-particle debris from the fusion microexplosions to provide thrust. In their concept, the debris never touched any vehicle structure, and was hence never forced to thermalize with other materials. This offered specific impulses in the range from 10^5 to 10^6 seconds, which were much larger than the 10^4 obtainable with the LANL concept. At about the same time, Winterberg[9] proposed the use of relativistic electron beams to initiate the fusion microexplosions with a concave mirror reflector open on one side to redirect the debris.

These studies motivated systems study by the British Interplanetary Society, called Daedalus.[10] The Daedalus 2-stage propulsion system employed relativistic electron beams plus a magnetic reaction chamber. The objective was to design a vehicle that would be able to go to Barnard's Star 6, light years away, at about 12% of the speed of light with a one-way trip time (without deceleration at the destination) of 50 years.

Later, Rod Hyde[11] developed a concept for a laser-fusion powered pencil-shaped vehicle for interplanetary transport that used DD fuel and assumed an ICF capsule energy gain of 1000 at a driver energy of 2 MJ. The thrust chamber incorporated a 16-Tesla superconducting magnet to redirect the capsule debris, and operated at 100 Hz with an assumed jet efficiency of 42%. His so-called VIP missions, with low payload mass, allowed roundtrip times to Mars in less than 3 weeks. With the effects of solar and planetary gravitation, his companion cargo missions to Mars would take only 45 days.

In 1986, LLNL scientists began with Hyde's concept and conducted a detailed systems study of an ICF propulsion unit and space craft design,[7] which is used as the starting point for the present study. They chose a piloted- Mars mission trip as the baseline mission. The resulting concept is called VISTA (<u>V</u>ehicle for <u>I</u>nterplanetary <u>S</u>pace <u>T</u>ransport <u>A</u>pplications). They assumed the use of technology presumed to be available by AD 2050 or before, assessed as a reasonable and viable extrapolation of existing technology. Nevertheless, they sated that this technology base could be developed by AD 2020 if there was sufficient national commitment. Such technology was labeled as "early 21st Century technology."

The VISTA spacecraft concept (Fig. 1) can be described as follows: A 13-m-radius superconducting magnet generates a magnetic field (12 Tesla peak) that defines the boundaries of a thrust chamber. Preassembled fuel capsules are filled enroute with cryogenic deuterium (D) and tritium (T). The fuel capsules surrounded by ~ 50 g of added hydrogen mass are injected and positioned at the center of the fusion chamber at a repetition rate of up to 30 Hz, depending on the desired throttling (i.e., acceleration). Beams from a laser delivering about 5 MJ with 6% efficiency are focused on the capsule, causing it to implode and release up to 7,500 MJ in neutron, x-ray, and plasma-debris energy. The conical spacecraft design permits most all of the neutron and x-ray energy to escape to space since the spacecraft structure lies in the shadow of the thermal shield for the superconducting magnet coil. Only 4% of the emitted capsule energy strikes the shield protecting the superconducting coil, and must be radiated as waste heat or used in a Rankine power cycle. The crew quarters reside inside the propellant tanks at the outer lip of the conical structure, to provide shielding from cosmic radiations. Crew access is thereby slowly restricted as the mission proceeds because the consumption of propellant reduces the shielding. The entire structure is rotated about its axis to provide artificial gravity (e.g., 3 rpm provides 1 gee at R = 100 m).

In the VISTA concept, the capsule debris, being conductive, expands spherically until the plasma pressure drops below the magnetic pressure. The debris is then deflected by the magnet, which stores an energy that is five times the debris kinetic energy. The debris, which is recombining and decreasing in conductivity, exits the thrust chamber in a limited solid angle, producing thrust and propelling the spacecraft with its blunt end forward. The ICF engine achieves variable thrust capability, changing the repetition rate. Changing the amount of expellant mass surrounding each capsule (or by changing the capsule design), the ICF engine has variable specific-impulse capability. We here assume that the target gain (the ratio of the energy produced by the fusion to the driver energy supplied to the target) can be as large as 1500 for very advanced DT technology. Such gains allow the ICF engine to have a power/mass ratio of about 20 W/g at a repetition rate of 30 Hz. The avoidance of debris thermalization with surrounding structures allows effective specific impulses (i.e., specific impulses multiplied by the square root of the jet efficiency) near 20,000 seconds.

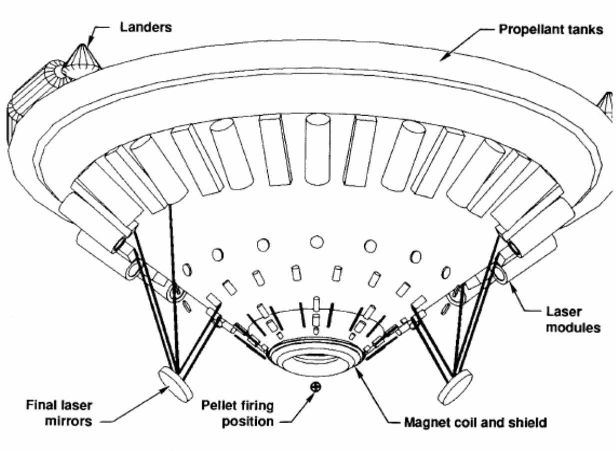

Figure 1. Schematic of the VISTA space ship.

Steerage of the entire spacecraft is accomplished by injection of the ICF capsules slightly off the axis of the magnetic thrust chamber. For power conversion, VISTA used both a Rankine thermal cycle and Hyde's inductor pickup coil system. Radiators based on heat-pipe technology remove the waste heat from the driver and power systems. One notable aspect of the conical design is that the radiators are incorporated into the conical surface. LLNL scientists considered some advanced fusion fuels (DD and D^3He), but selected DT "until extremely advanced ICF technological levels are attained." However, they noted that there *are* advantages to using the advanced fuels, namely reduced tritium acquisition costs, reduced tritium hazards, and reduced hazards to personnel in other (nearby) spacecraft because of reduced neutron emissions. Therefore, the 2003 LLNL development plan was to begin with DT as the best choice for near-term missions, but switch to DD or perhaps D^3He in the far term (provided an economical source of ^3He can be developed). With the assumed high gain DT technology, piloted-Mars missions can be conducted with a total duration of about 145 days, including a stay on the planet of about 10 days. Roundtrip missions to Pluto would require a little more than 7 years, and roundtrip missions 2.5 times further to 100 AU (1 AU = sun-Earth distance = 1.496×10^{11} m) require nearly 19 years. In essence, for roundtrips, VISTA reaches trip speeds of 50 to 60 km/s for destinations within the interplanetary system.

VISTA was not designed to go to more distant objects, but if it did, peak speeds would still not exceed about 100 km/s. A roundtrip to 17,225 AU (the Oort Cloud) would therefore take over 1,630 years! A roundtrip to the nearest star, Alpha Centauri (4 light years away, or about 250,000 AU), would take over 12,000 years! Although this performance is considerably better than that possible with either chemical, nuclear-electric (fission), or even antimatter propulsion systems, it is rather clear that VISTA cannot be used to visit the stars and return within a human lifetime. It would be possible, however, to go one-way to 10^4 AU in 20 years.

Orth et al. left to "further studies on advanced fuels". Time has since passed and the National Ignition Facility (NIF) is expected to achieve a burn in a year or so. Plus, the physics understanding has advanced, especially with the concept of using fast ignition (FI) to achieve high gains by effectively heating a central hot spot which ignites and burn propagates into the surrounding fuel. Now, the block-ignition approach to IFC discussed here offers an opportunity to achieve the ultra high target gain (1500 or higher) assumed in VISTA and to achieve the higher temperature needed for advanced fuel fusion. An immediate consequence of this improved target performance is the ability to go directly to p-^{11}B targets, bypassing early DT propulsion and thus greatly eliminating tritium and 14 MeV neutron complications. With these advances, discussed in more detail later, the VISTA goal of a 145 day piloted-mission to mars comes closer to reality.

III. Review of Block Ignition

The concept of block ignition comes from detailed analysis of unexpected effects discovered in recent PW laser interaction experiments (see Refs. 3-4), and references therein). The improved performance indicated could have a profound influence on both terrestrial fusion power and fusion space propulsion. Earlier observations from experiments with TW-PW laser pulses of ps duration in interaction with plasmas were very confusing. Laser intensities above 10^{19} W/cm^2 resulted in various relativistic effects producing beams of intense accelerated electron jets with energies up to several 100 MeV, highly charged ions with energies in the GeV range, and gamma bursts with subsequent nuclear reactions. In some cases, intense electron jets occurred at oblique incidence on targets. Later, it was found that the suppression of laser pre-pulses avoids excessive beam focusing such that these effects disappear. Instead, plasma block formation and acceleration away from the target was observed. These experimental observations have now been explained theoretically and form the basis for the block ignition concept that is applied here to space propulsion power units.

Block ignition relies on generation of space-charged neutral plasma blocks (plasma "bunches") by preventing self-focusing of the laser beam such that it remains uniformly distributed over a broad area of the target surface. Physically, this requires very strong suppression of laser pre-pulses, i.e. a very high "contrast ratio" (ratio of the main pulse intensity to pre-pulse intensity). The resulting plasma blocks have high momentum and are directed towards the incoming laser beam. Momentum conservation causes an imploding block of plasma which can cause ignition of the center portion of the target fuel.

The mechanism for creating these high velocity plasma blocks is attributed to skin-layer nonlinear force acceleration (see Refs. 3 and 4 and the references therein for a complete history of the development of block ignition). While long expected theoretically, the required threshold conditions were not well understood and were obscured by the enormously complex phenomena occurring during "normal" PW laser interactions associated with a low modest contrast ratio. Fortunately, some anomalous ion emission data suggested effects which led theoreticians to the realization that block formation could be achieved. Since the acceleration of the ions is by the nonlinear force, the observed blocks (pistons) are highly directed and have a comparably low temperature.

These results are very important for future fusion power reactors, not only for terrestrial use, but also for space. With our current understanding, fusion propulsion systems are expected to provide the fastest transport to Mars in the 21st century.[3] Systems based on nuclear fission (e.g., nuclear-electric propulsion), although closer to reality than fusion systems, can provide this performance. Thus, if man continues to emphasize speed to minimize physical and radiation effects to the crew, the development of fusion propulsion systems appears to be a necessity. The objective of the present study is to achieve a piloted-main mission with total time, including a stay of a few weeks on the planet, of less than a year.

Radical new approaches to laser-driven fusion energy were opened when laser pulses in the order of a picosecond duration and powers of TW up to few PW became available. The initial aim was the fast ignition (FI) of near term DT fuelled targets. Initially only the interaction of laser beams was considered for FI but modifications followed for using laser produced intense proton beams for fast ignition (PFI)[12] the proton beams irradiating targets pre-compressed to about 1000 times solid state density. Using 10 TW-ps laser pulses for producing very high intensity 5-MeV electron beams, ignition of nearly uncompressed solid DT of larger volume controlled fusion reactions with gains above 10^4 were also predicted to be possible. This is applicable also when using the here considered *ion beam* ignition similar to the *electron beam ignition* scheme of Nuckolls et al.[13] and the somewhat similar scheme of Tabak, et al.,[14] but based on space-charge neutral plasma blocks[3,4,15] (termed "plasma bunches or pistons") with ultrahigh ion current densities.

The crucial new aspect with the space charge neutral ion beams of ultrahigh ion current densities come from an experimentally unexpected effect of skin-layer nonlinear-force acceleration of plasma blocks. These drastically anomalous observations were long expected theoretically, but the conditions were buried under the enormously complex usual phenomena observed. In contrast, the rather unique few anomalous experiments permitted a transparent simplification of the facts. Since the acceleration of the ions is by the nonlinear force, the observed blocks (pistons) are highly directed and have a comparably low temperature. This may be of interest for fusion reactions in plasmas at comparably low densities similar to the fast ignition scheme for electron beams.

Attention should be given first to the very rich but nevertheless confusing results from TW-PW laser pulses of ps duration at interaction with plasmas. Laser intensities above 10^{19} W/cm^2 resulted in all kinds of relativistic effects producing beams of intense accelerated electron jets with energies up to several 100 MeV highly charged ions with energies in the GeV range gamma bursts with subsequent nuclear reactions – even for elimination of long-lived nuclear waste, electron-positron pair production, and other unexpected relativistic phenomena. A special observation is the generation of intense electron jets at oblique incidence on targets, even with lower intensities with and without suppression of laser pre-pulses (one crucial point to be considered in the following) also in view of the Nuckolls-Wood scheme noted earlier, the measured relativistic effects of intense laser produced electron beams were due to very high electric fields in the Debye layer as a double layer effect and where the 10-MeV electrons were essential in PIC simulations.

On the other hand, there are very transparent and uncomplicated observations at very wide focus interactions at lower laser intensities as needed for direct drive laser interaction for conditions in the experiments of NIF. However, in contrast to this, at such low laser intensities below 10^{15} W/cm^2 at very wide focus interaction with rather smooth iodine laser beams, the generation of plasma jets could not be avoided. Even then, the global observation of the ion-mass independent axial velocities indicated a nonlinear (ponderomotive) force acceleration while the radial acceleration definitely was thermally as seen from the strong mass dependence.

In contrast to this pluralism of observations, a few anomalous experiments appeared to be very different, however with clear and transparent properties. In this paper, the essential properties of this anomalous mechanism with its comparably uncomplicated results are clarified first. These can be transparently understood as the plasma block (piston) generation in contrast to the mentioned highly diffuse pluralism of the usual phenomena of PW-ps laser plasma interaction. Furthermore, for the application to fusion energy it is of interest how these highly directed low temperature plasma blocks (pistons) may be transformed into blocks with a large thickness. This is evaluated for the first time by using the geometric convergence of laser driven spherical plasma shells. Indeed, this work about the skin layer acceleration by nonlinear forces (SLANF) is performed for the application to laser fusion. This nonlinear force acceleration follows mainly the scheme of plasma shells for fusion where nearly all laser energy is converted into kinetic energy of directed motion of plasma to distinguish from classical thermally determined ablation of plasma shells. We focus then on the question how these blocks can be transformed to such thicknesses that ion beam ignition for fusion and a strong improvement of the proton fast ignition PFI may be achieved.

V. Physics of Plasma Block Generation

The new effect consists in the generation of plane geometry laser-plasma interaction in contrast to all the usual measurements where TW-ps laser pulses produced extreme relativistic effects in the irradiated plasmas. Together with an interpretation of these differences, new theoretical and experimental facts are reported in preparation for further studies. Various experiments that have led to the block ignition concept are discussed next.

A. Experiments with 300fs-TW Excimer Laser Pulses

This experiment by Sauerbrey[16] was designed to measure the acceleration of plasma emitted against the laser light at irradiation of a solid target by the Doppler shift and was rather unique. It was anomalous because nowhere before had such a Doppler shift been detected. The fact that such Doppler measurement was not observed before is simply due to the fact that in earlier experiments involving highly intense laser pulse on a target, the laser prepulse normally included to aid the interaction produces a plasma plume before the target. The relativistic dielectric interaction of the plasma with the laser front causes a bending of the laser light front such that the beam is squeezed to a diameter of about one wave length. The laser beam reaches an extraordinarily strong focusing, beyond that possible with a normal optics system. The extreme intensity in the squeezed beam then causes a nonlinear force driven acceleration of the highly charged MeV ions up to nearly a GeV, with motion into all directions as explained in detail in Ref 17. The main difference in the experiment of Sauerbrey[16] was that the laser pulses he used were exceptionally clean, i.e. with a suppression of prepulses to achieve a contrast ratio of 10^8. He employed 300 fs dye laser pulses amplified in a laser pumped KrF medium to gain the TW pulse power. This was the first case where the prepulses at target interaction where relativistic self-focusing was suppressed, giving a plane wave interaction of the laser beam of about 30 wave length diameter. This technique gave a 350 fs TW KrF laser pulse at $3.5\text{x}10^{17}$ W/cm^2. Under these conditions Sauerbrey measured by Doppler effect an acceleration A_{exp} in a carbon plasma front moving against the laser:

$$A_{exp} \;=\; 10^{20}\ \text{cm/s}^2 \tag{1}$$

The laser intensity corresponded to an electric field

$$\mathbf{E}^2 = 2.9\text{x}10^{15}\ \text{erg/cm}^3 \tag{2}$$

and a density $n_i m_i$ of the accelerated plasma layer of $5.4\text{x}10^{-3}$ g/cm^3 at the critical density such that

$$n_i = 1.6\text{x}10^{21}\text{cm}^{-3} \tag{3}$$

for C^{+6} ions at the krypton fluoride (KrF) laser frequency.

We show next, for the first time, how these measurements compare in the theoretically expected acceleration by the nonlinear (ponderomotive) force for the simplified plane geometry which allows a more transparent formulation of force densities as gradients of energy density, identical to the simplified case with a ponderomotive force density of:

$$f_{NL} = -(\partial/\partial x)\,(\mathbf{E}^2 + \mathbf{H}^2)/(8\pi) \;=\; n_i m_i A \;=\; -(1/16\pi)(\omega_p/\omega)^2\,(d/dx)\,\mathbf{E}^2 \tag{4}$$

Assuming for simplification $dx = \Delta x = 10$ μm and a swelling S = 2 (consistent with later experiments at similar conditions by Badziak et al.[18,19] with ps pulses resulted in S = 3.5), we obtain a theoretical value for A_{NL} in good agreement with Sauerbrey's measured in eqn. 1; that is:

$$A_{NL} \;=\; 1.06\text{x}10^{20}\ \text{cm/s}^2 \tag{5}$$

Applying this result to the accelerated plasma blocks of DT with a critical density at for $n_e = 10^{21}$ cm^{-3} and ion velocity above 10^8 cm/s, shows that the accelerated plasma block moving against the laser lights can achieve an ion current density above

$$j \;=\; 10^{10}\ \text{Amp/cm}^2 \tag{6}$$

The plasma block is space charge neutral since the effective Debye length is sufficiently smaller than the block thickness. The basics of this process can be envisioned from Figures 2, 3, and 4.

As illustrated in Fig. 2, conventional laser pulse irradiations have a precursor "foot" beam that arrives to the target slightly before the main pulse. As a result, the main pulse must pass through a pre-formed plasma plume to reach the target surface. This plasma serves like a converging lens and focuses the laser beam into a small, high intensity beam which dominates the light-target interaction resulting in the emission of high energy ions. The ratio of the intensity of the "foot" laser light that precedes the main light pulse to the beam intensity is called the contrast ratio. If this is reduced drastically to $\leq 10^{-6}$,self focusing is avoided and, as illustrated in Fig. 3, the ions created in the interaction have lower energies. This then gives emission of a "block" of ions and electrons, i.e. a block of plasma. As illustrated in Fig. 4, this outward moving block causes an in moving block of target plasma in the target which provides the desired compression and temperature needed for ignition and burn.

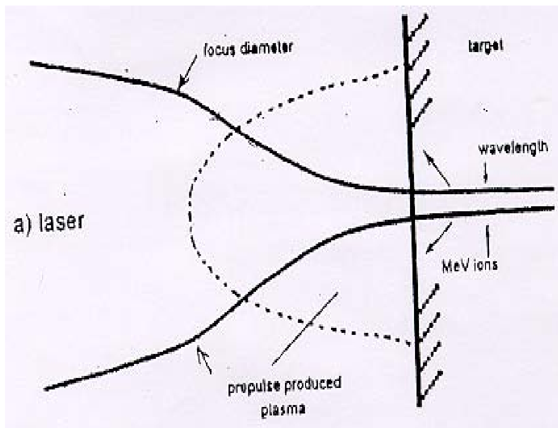

Figure 2. Pre-generated Plasma Causes Self-focusing. Geometry for subsequent volume-forced nonlinear electron acceleration with separation by the ion charge Z. The pre-generated plasma before the target causes relativistic self focusing of the laser beam to less than a wave length dia. and very high acceleration due to the strong gradient of laser field density.

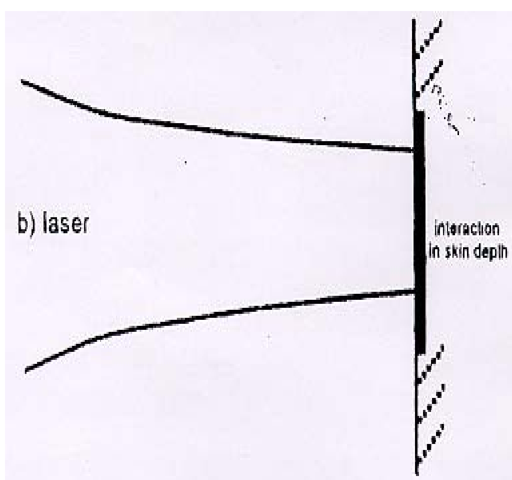

Figure 3. Elimination of Plasma Prevents Self-focusing. The very thin plasma does not produce self-focusing, hence lower ion energies.

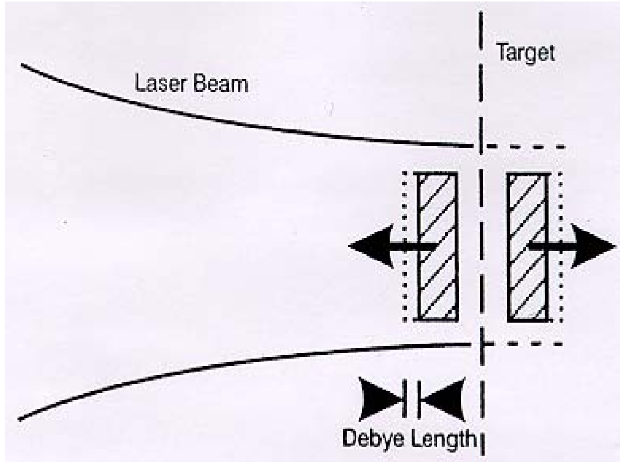

Figure 4. Plasma Block Acceleration By Non-Linear Force. Skin depth laser interaction: nonlinear force accelerates a plasma block against the laser light and another block towards the target interior. Election clouds form with a thickness of the effective Debye length.

Computations of this type of a plane, one-dimensional plasma block motion at the laser intensities used by Sauerbrey for laser pulses in the range of ps, was numerically calculated long before the experiment (see a combination from Figures 10.18a and 10.18b of Ref. 19 for a neodymium glass laser intensity of 10^{18} W/cm^2 in deuterium plasma Fig. 5). Only a comparison with experiments was never possible before the experiments of Sauerbrey since all the other numerous experiments had no suppression of the prepulse to avoid relativistic self-focusing and therefore no plane interaction fronts. The comparison of the measurement with theory, however, was possible only after the knowledge about the anomalous conditions realized after the results described in Fig. 5.

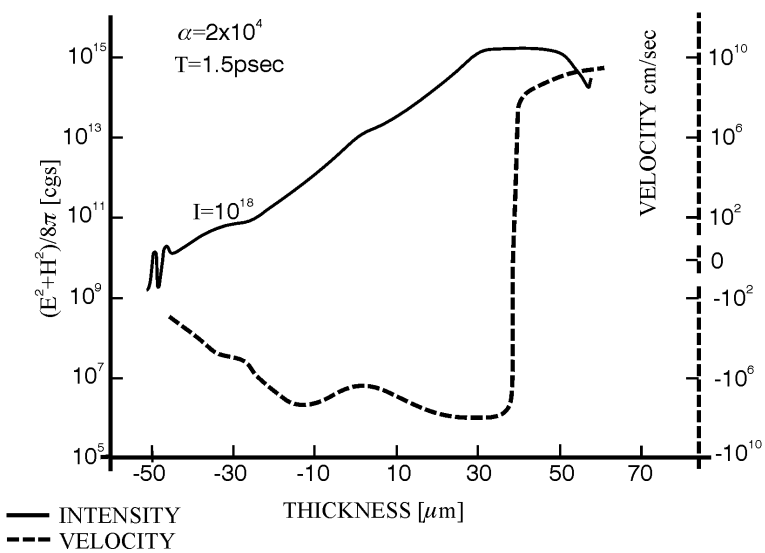

Figure 5. Generation of blocks of deuterium plasma moving against the neodymium glass laser light (positive velocities v to the right) and moving into the plasma interior (negative velocities) at irradiation by a neodymium glass laser of 10^{18} W/cm^2 intensity onto an initially 100eV hot and 100m thick bi-Rayleigh profile.

In the electron beam scheme of Nuckolls et al.,[13] the side-on block ignition proposed cannot work without an initial plasma pre-compression. However, the present scheme is based on the generation of extremely intense ion beams. The new scheme is therefore a single step interaction PW–ps laser irradiation process that works with uncompressed DT fuel or with modest compression similar to the electron beam scheme. These results show the promise of side on ignition of uncompressed fuel compared to the well known scheme of spherical laser compression and ignition. Before extending side-on block ignition to ignition of p–^{11}B fusion, we need to acknowledge some key difficulties with burning this fuel:

From the beginning of fusion energy research, a long term goal has been to use the unique p–^{11}B reaction:

$$p + {}^{11}B = 3\ {}^{4}He + 8.66\ \mathrm{MeV}\ . \tag{7}$$

This reaction can be achieved by bombarding boron targets with protons of energies up to 150 keV. It results in the production of MeV alpha particles and no neutrons.[4] The energetic alpha particle products are ideal for highly efficient direct conversion into directed momentum and a reduction in waste heat. The alpha particles can be collimated with magnetic fields for space propulsion.[2,3] Secondary reactions lead to some p-^{11}B radioactivity but this is less per unit of energy produced than is produced in burning coal,[4] which naturally contains 2 ppm uranium. However, it has been evident from the beginning that the p-^{11}B fusion reaction is much more difficult to achieve than using deuterium–tritium (DT) fusion fuel, as seen from the relative reaction cross sections. Also early calculations assuming spherical laser compression of p-^{11}B required extreme densities of 100,000 times the solid state[20] and input laser pulses of some 10 MJ energy to produce modest energy gains per laser energy of less than ~25.[21] These conditions are exorbitant and seemed to exclude any hope for laser driven p–^{11}B fusion. Now, the new developments involving block and side-on ignition described here overcome these difficulties. This can lead to the first "clean" nuclear energy production without the prior environmental disadvantages of nuclear energy. Such power plants would be extremely attract active for terrestrial use as well as for deep space propulsion as discussed here.

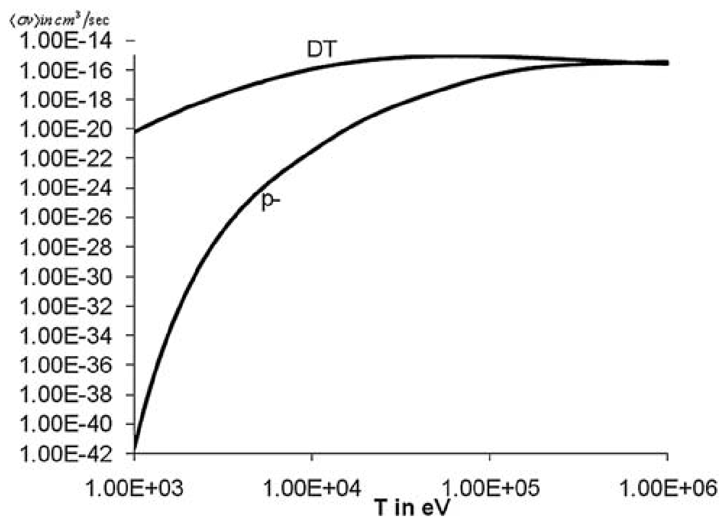

Figure 6. Fusion reaction rates for DT and for p-11B dependence in the ion temperature T. At high temperatures, the two are the same order of magnitude. However, in traditional low temperature fusion DT is selected due to its high reaction rate.

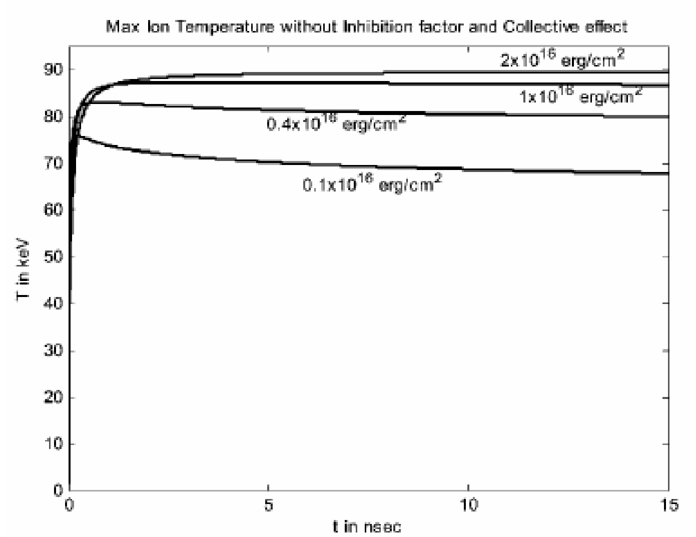

Figure 7. Characteristics of the kind of Fig. 2 for p-^{11}B under the assumptions most similar to Chu for comparison with DT fusion.

VII. Side-on Block Ignition Threshold for Hydrogen Boron

The reaction cross section Σ was averaged for a temperature T over a Maxwellian distribution of the velocity v of the particles. Fig. 6 shows the rates for the DT reaction together with that of the p–^{11}B reaction used in the hydrodynamic calculation. This results in the time dependence of the plasma temperature shown in Fig. 7 for DT. The parameter of the curves is the energy flux density E*. What is important is to find the value of E_t* (ignition threshold) where the plasma temperature T merges into a constant value after longer times, t. In order to define the threshold E_t* for p–^{11}B, the computation of the temperature T in Fig. 7 was run for a comparatively long time (15 ns) in order to determine converged values. From these results, it can be estimated that the final value is approximately

$$E_0^* = (1.0 \text{ to } 2.0) \times 10^9 \text{ J/cm}^2; \quad \text{and} \quad T_{ign} = 87 \text{ keV} \ (\text{p–}^{11}\text{B}) \tag{8}$$

These results appear to be very modest compared with the values of DT obtained by Chu.[23] In view of the exorbitant difference between DT and p-^{11}B for volume ignition based on spherical pellet compression, it is truly surprising how much easier the ignition of p-^{11}B works for a side-on generated thermonuclear reaction wave. Part of the explanation can be shows that the <Σv> values for DT and for p–^{11}B are reasonably close for their respective ignition temperatures. The correctness of the hydrodynamic results shown is supported by the consistency observed in the resulting temperatures. In the case of DT, the energy averaged value ignition without reheat and without partial X-ray re-absorption falls from about 12 keV for spherical compression to 7.2 keV even under the simplified conditions of Chu.[23] There is a clear similarity for the case of p–^{11}B. There, the temperature for the spherical compression without reheat and without partial self-absorption is in the range of 150 keV while the present side-on ignition of solid fusion fuel is ~87 keV for the assumptions of Chu.

In summary, these computations confirm that side-on ignition of uncompressed p–^{11}B fuel is not very much more ‘‘difficult’’ than DT fusion. Further, it is estimated to be possible with laser pulses in the range of ps duration and several dozens of PW power Some slight pre-compression should give an even further reduction of these requirements. Among the numerous additional details to be evaluated, we report here about one important modification of Chu's :namely, the reduced thermal conduction in the extremely inhomogeneous plasmas. This effect has traditionally been handled using an inhibition factor F*. This factor was evaluated before for DT. The theoretical background was based on the creation of an electric double layer, which reduced electron flow. An inhibition factor $F^* = 10^6$ was introduced here for p–^{11}B and the hydrodynamic computation of Chu was repeated. The results for p–^{11}B are shown in Fig. 8. The factor F* is based on the theory of electron depletion in the electric double layers, reducing the thermal conductivity by the square root of the electron mass to the ion mass which was expressed by the average ion mass. Due to the lower thermal conduction, the threshold energy flux density E_t^* is reduced to 7.7 x 10^8 J/cm^2. Further details of these theoretical studies were given previously.[3] These computations also showed that Bremsstrahlung radiation losses were reasonably low for both DT and p–^{11}B cases. Bremsstrahlung is not nuclear radiation, but is caused by electron slowing during deflection by charged ions. It typically falls in the 100s of keV range vs. MeV gammas. Since Bremsstrahlung radiation falls into the X-ray range of energies it can easily be stopped from escaping the reaction chamber by a modest shield. It's main effect then, is to serve as a power loss from the plasma which, if severe, would prevent ignition.

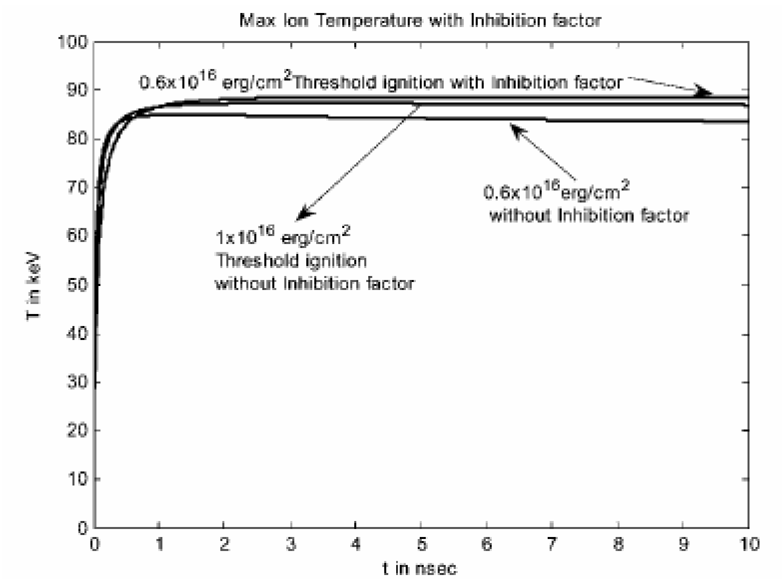

Figure 8. As Fig. 7, with inclusion of reduced thermal conduction due to the inhibition factor F*.

Side-on ignition for fusion energy using nonlinear force acceleration of plasma blocks by PW–ps laser pulses is clearly a new frontier. In comparison with the matured scheme of spherical laser compression, there are still a number of issues/questions to be answered. These concerns will be addressed in due course, as an extensive experimental program for clean PW–ps laser interactions with solid targets is combined with an appropriately diversified theoretical-numerical project.

VIII. Conclusion

The computations here are crucial to evaluation of the exciting new block ignition of p-^{11}B in ICF targets. In order to be as close as possible to the work of Chu the hydrodynamics for the model DT case uses a one fluid description. This was sufficient for verifying Chu's side-on ignition processes. For the block case, however, a genuine two-fluid hydrodynamic plasma model was used and generally applied for plane interaction geometry. This allowed the skin-layer acceleration to come into plasma block generation. Also, Rayleigh density profiles were specifically applied to the optimal irradiation conditions.

A much more detailed analysis is needed, but at least the basic characteristics for side-on ignition of p-^{11}B fusion are clearly visible. Most significant are the very surprising results that uncompressed p–^{11}B can be ignited. This fusion energy generation with laser pulses in the range of a few dozen of PW power and ps duration can achieve p-^{11}B power production. This remarkable fusion fuel uses naturally abundant elements and avoids tritium involvement and neutron generation. That then results in a power plant with negligible radioactivity, and allows direct energy conversion, either to directed thrust or to electricity. Such a power plant is ideal for stationary electrical generation in a power station or for space propulsion.[3] Modest pre-compression or using high density cluster methods[24] could improve performance even further especially for p-^{11}B. 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. However, the studies reported here show that such a system is rather close at hand—something not realized before, since p-^{11}B ignition had always been viewed as virtually impossible. The recognition that block ignition can lead to practical ICF operation with p-^{11}B opens an exciting new direction for fusion space propulsion. Replacement of the DT target in the VISTA study with this approach would maintain the forefront performance of such a space ship, while greatly reducing technological problems such as tritium breading and neutron- induced radioactivity inherent in the original design.

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