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# Ideal Energy Source by Mark Oliphant's Beam Fusion

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**Abstract:** The 70-year anniversary of the first nuclear fusion reaction of hydrogen isotopes by Oliphant, Harteck and Rutherford is an opportunity to realize how beam fusion is the path for clean, safe, unlimited and low-cost energy production, including magnetic confinement fusion and inertial fusion energy (IFE). The measurement of unpredicted low energy fusion reactions compared with the usual nuclear reactions was a significant discovery. It is intriguing that Oliphant's basic concept from 1937 for igniting controlled fusion reactions for generating energy by beams has a comeback even for magnetic confinement plasma, after this beam fusion concept was revealed by basically non-linear processes of the well-known alternative of inertial confinement fusion using laser or particle beams. After reviewing both directions some results are reported as to how experiments with skin layer interaction and avoiding relativistic self-focussing of clean PW-ps laser pulses for IFE may possibly lead to a simplified fusion reactor scheme without the need of special compression of solid deuterium-tritium fuel. It may be that energy can be produced at a five times lower cost than from any present energy source.

**Keywords:** nuclear fusion, energy, plasma, laser, particle beam, Oliphant

## INTRODUCTION

The very first nuclear fusion reaction (Oliphant et al. 1934) was achieved using a 100 keV gas discharge. Heavy water for the deuterium was produced by Paul Harteck and analysis of the cloud chamber pictures by Lord Rutherford was especially difficult (even for the grandmaster Rutherford, the founder of nuclear physics), since the unknown super-heavy hydrogen isotope tritium T = $^3$H appeared as well as the light helium isotope $^3$He, protons p = $^1$H, neutrons n and the usual helium isotope $^4$He.

$$\begin{aligned} \mathrm{D} + \mathrm{D} &= \mathrm{T} + {}^1\mathrm{H} + 4.03\ \mathrm{MeV}\ (50\%) && \text{(1a)}\\ & \quad {}^3\mathrm{He} + \mathrm{n} + 3.27\ \mathrm{MeV}\ (50\%) && \text{(1b)}\\ \mathrm{D} + {}^3\mathrm{He} &= {}^4\mathrm{He} + {}^1\mathrm{H} + 18.3\ \mathrm{MeV} && \text{(2a)}\\ \mathrm{T} + \mathrm{D} &= {}^4\mathrm{He} + \mathrm{n} + 17.6\ \mathrm{MeV} && \text{(2b)} \end{aligned}$$

The tritium reaction (2b) has an extraordinary large reaction cross section and is the main subject of the discussion below, although the neutron-lean reaction (2b) is now of special interest in view of the possibility of harvesting $^3$He as fusion fuel from the surface of the Moon.

Reactions of the very light elements at beam energies around 10 keV was a significant discovery since the usual beam energy has to be considerably above 1 million volts in order to move the nuclei against electrical Coulombic repulsion to distances of their diameters (of the order of femtometers, 1 fm = $10^{-13}$cm). The tools for these experiments were the multi-million-volt accelerators. Cockroft was sufficiently adventurous (with little knowledge of systems using many millions of volts) to look to see what happens when only 100 to 200 keV were used; light nuclei such as boron did react with protons (Cockroft et al. 1933). It was then that Oliphant's gas discharge technique was used to produce the necessary high currents to get more precise results, such as the correct value of the proton-boron reaction (Oliphant and Rutherford, 1933), and this was the prelude to the discovery (Oliphant et al. 1934) of the famous fusion reactions (1) to (2b). It has to be realized that these 'hot fusion' reactions at 10 keV impact energy (corresponding to temperatures of $10^8$ °C) happen at distances about hundred times larger than the femtometer distances of the usual nuclear reactions. This cannot be explained by a Gamov factor. Measurements of the fusion reaction cross sections involved are now highly accurate, but there was no theory for explaining them, apart from numerical fitting (Clark et al. 1979). It was not before Li et al. (2000) that a reasonable theory was developed using a Schrödinger potential. The cross sections could be reproduced using the two obvious parameters, the resonance energy and the resonance width (Li et al. 2004).

The following reflects on some initial experiments of Oliphant (1972) in 1937, especially in the direction of fusion reactions using beams, and how these may be considered some seventy years after the first fusion reaction (Oliphant et al. 1934). Developments went first against the initial concept of beam fusion in favour of avoiding any beams; these moved in the direction of magnetic confinement fusion. The subsequent text is an analysis how this aspect has changed back towards the initial view of Oliphant for beam fusion. This is not only a question of inertial fusion energy (IFE) without magnetic fields, as known from laser- or particle beam-driven fusion reactions. Even the initial magnetic fusion concept has developed into a beam fusion scheme during recent years.

## DISCUSSION

### The Spitzer Criterion and the Impossibility of Beam Fusion

First attempts to develop the reaction into an energy source were made by Oliphant (1937) and a continuation of a controlled reaction for power production was considered about 1950. Studies of fusion reactions for energy production were a continuation of the work of 1937 carried out under the leadership of Nobel Laureate E.O. Lawrence, together with Oliphant and other important pioneers. The aim was just to produce extremely intense deuterium or D-T beams from gas discharges or otherwise with about 100 keV energy to irradiate targets containing D or D-T. These attempts were emphatically rejected by Spitzer (1957), who argued that such beam experiments do result in fusion reactions as measured (Oliphant et al. 1934), but that it was absolutely impossible to produce more energy by fusion than that used to generate the beams. Lawrence and the others simply argued that one just had to apply higher and higher beam powers, but this was made ridiculous by Spitzer's suggestion that the fusion cross section is more than 300 times smaller for the incident 100 MeV nuclei than their interaction with the electrons in the bombarded target. The ion energy is used mostly to heat the electrons in the target, but never permits an exothermal fusion reaction.

Spitzer's argument was mathematically simple, and physically and logically fully clear. It led to the decision that, instead of bombarding a cold target, one had to heat the all reacting particles — as in the sun — up to the plasma state at a temperature of dozens of million degrees, so that ions do not lose their energy by collision with electrons, and the desired fusion reactions can take place. The problem was then how to confine the plasma by magnetic fields and to find conditions where the loss of radiation energy and confinement mechanisms for the hot plasma are more than compensated for by the generation of fusion energy.

Following Spitzer's argument, the handling of the fusion plasma with magnetic confinement is at a stage that a test reactor (ITER) is to be built by 2015 and may lead to a power station with 4 GW fusion energy output by 2040 (Hoang et al. 2004). This all is based on expensive research during the last 50 years, with the highest fusion gain of 16 MW being reached in the Joint European Torus (JET) experiment at Culham, England. However, this was mainly a *beam fusion experiment* (Hora et al. 1998; Hora 1987), supporting Spitzer's argument that the irradiated target had no problems with low temperature electrons. In a wider sense, this is a sophisticated *verification of Oliphant's beam fusion* idea by way of a 'Spitzer option' for fusion energy. It should be emphasised that the concept of neutral beam irradiation was introduced by Harold Furth, based on his 'idea of exploiting fusion reactions that arise from injected energetic ions' (Fisch et al. 2004). It is noted in passing that Furth was the nephew of Paul Harteck the co-discoverer of the first fusion reactions (Oliphant et al. 1934).

There is another reason why Spitzer's arguments are invalid and this concerns linear versus non-linear physics. In non-linear physics, results from linear physics can be completely different, as experienced in other physics examples (Hora 2000). Non-linear physics does indeed permit beam fusion, in contrast to the Spitzer argument, as initiated by Oliphant (1937), especially since the invention of the laser opened the door to the application of non-linear physics for fusion energy (Tanka et al. 2001). This perhaps may be considered as a further confirmation of the comeback of beam fusion envisaged by Oliphant and is discussed below as the 'Non-Spitzer' option.

## The Spitzer Option for Fusion Energy

Magnetic confinement of a plasma is mostly focussed on toroidal geometries. Spitzer's initial magnetic stellarator configuration, built at comparably high costs, was simplified into a toroidal configuration and the early problems of generating a very low current stellarator plasma were overcome by Grieger et al. (1981), who produced fusion neutrons with an 800 eV deuterium plasma. The diffusion of the plasma against the confining magnetic field due to collisions was about 20 times faster than classical collisions predicted. This could be explained directly as a quantum correction to the collisions for anomalous resistivity, since the factor of 20 did immediately fit the change at a temperature above 37 eV by a linear temperature factor (Hora 1981). The experiment had the advantage of transparent measurements as can be seen from the abovementioned factor of 20. There is a modification of the classical electron ion collision frequency, $\nu_{\rm class}$, which is valid only below the temperature $T^* = z^2(4/3)mc^2\alpha^2 = 36.8\ Z^2$ eV (using the ion charge z), as shown by Marshak (1941) and generalized later (Hora 1981; see Hora 1991, Chap. 2.6). Above the temperature T* the quantum mechanical value has to be taken, as in (3).

$$\nu_{\rm ei} = \nu_{\rm class}\ T/T^* \tag{3}$$

This is the modification of the diffusion of the plasma across the magnetic field and was confirmed by Grieger et al. (1981), who arrived at the factor 20 by the relation 800 eV/T* (= 21.7).

In contrast to this zero-current toroidal magnetic confinement stellarator, a toroidal confinement with a very high axial electric current for heating the plasma was developed as a tokamak (Hoang et al. 2004). This most advanced scheme is used in the International Toroidal Experimental Reactor (ITER) at a cost of $US10 billion, and planned to be operational in 2015. Confidence for this decision is based on recent achievements with tokamaks (Hoang et al. 2004). It is envisaged that a subsequent test power station may be finished in 2040 if no unforeseen difficulties, such as wall erosion, blistering from the walls or anomalous ion implantation, arise (Hoang et al. 2004). These time scales agree with what the Director for the very large European budget for magnetic confinement fusion research formulated in 1993 in that this development 'will need at least 50 years ... and it is not sure whether the produced energy will be of sufficiently low cost' (Maisonier 1994).

The high achievements of tokamak developments are seen (Hoang et al. 2004) from the fact that its performance doubled every 1.8 years, compared with that of transistor and chip technology every 2 years, and that of the particle accelerator every 3 years. Operating the tokamak completely as a magnetic confinement device by inductive heating has not succeeded yet for more than about one second. The operation of advanced tokamaks with superconducting coils, with external heating by neutral beams and RF electromagnetic irradiation, is possible over 1000 seconds in the Tore Supra at Cadarache, France, or with a smaller Japanese device with 100 times lower input power over three hours. The maximum neutral beam density for driving the tokamak is limited by the Langmuir-Child space charge law for ion beam generation to less than 10 mA cm$^{-2}$, in contrast to the measured many orders of magnitude higher ion current densities emitted from targets by laser irradiation (Laska et al. 2003; Wolowski et al. 2003).

The highest nuclear fusion gain measured by the Joint European Torus (Hoang et al. 2004; Hora et al. 1998) was 16 MW, produced by 21 MW neutral deuterium beams of 60 keV energy and by irradiation with MW RF power. The tokamak was filled with D:T = 40:60 (Hoang et al. 2004). This 66% gain, close to break-even, does not take into account the power needed to operate the tokamak. In this connection, instead of the very high power consumption of the tokamak coils, superconducting magnets could have been used at considerably lower power but with losses for cooling of magnets and limiter etc. It is important to note that operation of JET without beam injection as a purely magnetic confinement device results in very much lower fusion reaction gains.

Returning to the initial question about Oliphant's view on beam fusion, we see that the highest fusion gain of the JET is in a clear (neutral) beam fusion experiment, irradiating a target which fulfills the linear physics conditions of the Spitzer option, but using a sophisticated high temperature tokamak plasma instead of a solid state target. In this case, as postulated by Spitzer, collisions between the irradiated ion beam and the target electrons do not consume much of the main ion beam energy (Hora et al. 1998).

A higher gain (above break-even) could have been expected if the number of ion beam injectors had been multiplied. Further improvements may be expected if the detection of the inward particle flux as observed at the Tore Supra could be analysed as being caused by E×B-net plasma rotation (Goldsworthy et al. 1987; Hora 1991, p. 171) or reduced thermal conduction due to anomalous resistivity (Hora 1981; Hora 1991, p. 50). In view of the problems of wall erosion in tokamaks, mainly due to disruption instability, one may consider a neutral beam fusion device where instead of the tokamak target, a stellarator is used and disruptions are excluded (Wobig 2002).

## Non-Spitzer Option for Fusion Energy

We refer now to beam fusion where non-linearities overcome the Spitzer criteria. The idea was obvious in 1960 after the discovery of the fact that lasers can be used for producing extremely high energy densities within very short times in very small volumes, as needed for controlled ignition of nuclear fusion reactions. The pioneers of large-scale fusion reactions (Teller 2001; Nuckolls 1992; Sakharov 1982) immediately devoted attention to this concept. Particle beam fusion — fully excluded under aspects of the Spitzer criteria — was also revoked in view of non-linearity. Spitzer's argument keeps its full validity as long as the beam-irradiated target remains solid. However, if the beam intensity creates plasma with very complex hydrodynamic developments, dynamics of pressure profiles and radiation effects, exothermic energy production can be expected by laser driven fusion or from igniting self-sustained fusion reaction fronts by an intense electron beam (Yonas 1978), or by light or heavy ion beams working through solid fusion fuel. The laser fusion concept has been well-developed since, but new developments with picosecond laser pulses may allow us to return to several earlier arguments for ion beam fusion.

When estimating the necessary conditions for igniting a self-sustained fusion detonation front in uncompressed solid DT by impact of a DT ion beam, a minimum ion beam density of

$$\mathrm{j}_{min} = 10^{10}\ \mathrm{A\,cm^{-2}} \tag{4}$$

was given (Brueckner et al. 1974); this may be too pessimistic and a lower value may be possible. A further condition is that the energy density of the hot detonation front should be at least that given in (5) (Bobin 1972).

$$\mathrm{ED} = 4 \times 10^{8}\ \mathrm{J\,cm^{-2}} \tag{5}$$

This value may be decreased by a factor of 20 or more when interpenetration processes are included (Hora 1983). These conditions are far beyond available electron or ion beam technologies for igniting solid state DT. With the laser, however, these conditions have been achieved experimentally, as will be explained in the following section.

A further improvement for igniting beam-irradiated DT fuel is its compression above the solid density. This can be achieved with the irradiating laser or particle beam itself, by producing an ablation of fuel from the irradiated surface, which results in a compression of the interior by recoil. With spherical geometry the compressed core of maximum density $n_o$ and volume $V_{Os}$ (s denotes that this is the volume of the uncompressed solid fuel with a density $n_s$) receives an energy $E_o$ which may be assumed to be uniformly spread over the core volume. The adiabatic compression and expansion of the core, confined only by its inertia (inertial confinement fusion, ICF), following the self-similarity model (Hora 1991, Sect. 5), results in a DT fusion core gain G at an optimum temperature $T_{opt} = 17\,\text{keV}$ at maximum compression

$$G = (E_O/E_{BE})^{1/3}(n_O/n_s)^{2/3} \tag{6}$$

(Hora 1991; Hora et al. 1998; identical to the $\rho$R value), where $E_{EB}$ is the break-even energy (6.3 MJ for DT). This result, based on numerical values of the fusion cross sections, shows immediately how a compression to 1000 times the solid density requires a million times less core energy for reaching the same gain.

Formula (6) does not include fuel depletion, partial reabsorption of lost bremsstrahlung and the gain of temperature by the fusion products before leaving the reacting plasma (self heat). When including this (Hora et al. 1998), the result in Figure 1 is very close to the value of (6), where for constant core volume a standard isochor touches the optimised fusion gain plots at $T_{opt}$ if the gain is less than 8.

For higher gains, the isochors are deformed, showing volume ignition (Hora et al. 1978) with increased gains and lower optimum temperatures (bending of the vertical dashed lines to the left). It is remarkable that the measured highest gains at direct drive laser fusion spheres fully agree with these isentropic self-similarity computations (Fig. 1), indeed below ignition as simple volume fusion burn or quenching.

In contrast to this volume burn with rather low gains, the scheme of spark ignition was introduced at end of the 1960s (Nuckolls 1992) to produce very much higher gains than by simple burn, before volume ignition was discovered (Hora et al. 1978; Hora et al. 1998). This could reach nearly the same high gains in a much more natural way of adiabatic compression. The spark ignition is rather complicated. It tries to schedule the compression in a very sophisticated way, especially when, instead of direct laser drive, indirect drive by hohlraum X-radiation is used. The laser irradiates the inner walls of a capsule to convert the radiation into X-rays, which then produce a very symmetric compression of the fuel pellet within the capsule. The aim is that the compressed pellet has a low density, high temperature central spark plasma surrounded isobarically by a very high density, low temperature outer part. At the interface, the hot plasma ignites a spherical fusion detonation wave in the cold outer plasma with similar conditions as given by (4) and (5), but with higher densities.

In summary, the highest laser fusion gains by spherical irradiation were $2\times10^{14}$ DT neutrons from a 35 kJ neodymium glass laser pulse, unexpectedly following the exact adiabatic volume compression (Hora et al. 1998; Fig. 1), while the best gains from hohlraums were about 1000 times lower. If one assumes that only 5% of the 35 kJ energy went into compressed cores (95% to ablation because of bad hydrodynamic efficiency), the fusion gain is then 31%.

For better studying these mechanisms with both the fusion energy source and large scale fusion reactions in mind, glass laser facilities for producing pulses of a few MJ energy with about nanosecond duration are being built, the NIF in Livermore, California and the LMJ in Bordeaux, France (Tarter 2002; Pellat 2002). The aim is to demonstrate ignition with a modest total fusion gain not much above 10, by about 2010.

One of the problems experienced by the experiments was too low heating of the laser-compressed plasma. Azechi et al. (1991) succeeded to laser-compress polyethylene to 2000 times the solid density thanks to Kato's laser beam smoothing with random phase plates where, however, the maximum temperature of about 300 eV was unexpectedly low. For very large scale laser fusion using few MJ laser pulses including smoothing for working with long wave lengths, this should not be too problematic if volume ignition is used for direct drive and not spark ignition. It has been calculated by Hora et al. (2003) that by doubling the compression density, volume ignition will reach the range where the bremsstrahlung re-absorption results in ignition temperatures of only a few hundred eV. This would be sufficient for a one step laser fusion reactor based on robust adiabatic volume compression as was successful with the hitherto highest laser fusion gains, but avoiding the problems of spark ignition. This would at least be a conservative solution for laser fusion based on well-established technology (Hora et al. 2003). Broad research is aimed at spark ignition (Lindl 1994) where the fusion efficiency may be two times higher than with the volume ignition concept (Hora et al. 1998), but where the problems with compression symmetry and instabilities are much more difficult.

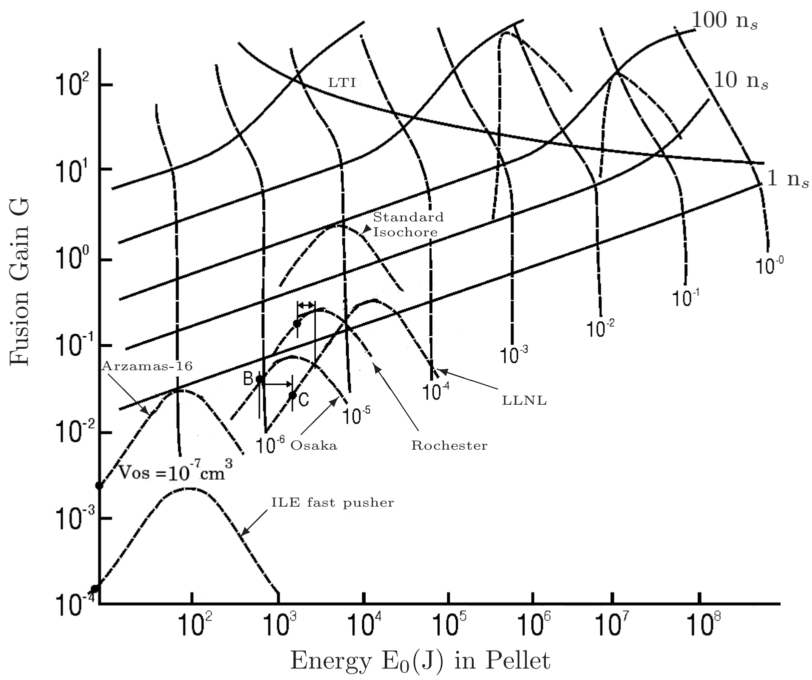


Figure 1. Optimised core fusion gains G (full lines) for the three-dimensional self-similarity hydrodynamic volume compression of simple burn (G < 8) (sometimes called quenching) and volume ignition for G > 8 with low temperature ignition above the LTI line. The measurements points A-D agree with the isentropic volume burn model, while the earlier fast pusher, point E, with strong entropy-producing shocks does not fit.

## Non-linear Laser Force Driven Beam Ignition for Inertial Fusion Energy

The scenario for laser fusion changed dramatically with Chirped Pulse Amplification, CPA, discovered by Mourou et al. (2002). This led to the generation of pulses with neodymium glass or Ti:sapphire (or iodine) lasers of pulses in the range of picoseconds or less duration and powers exceeding 2 PW. Irradiation of targets with these pulses results in numerous, not yet fully explored, relativistic effects. Very intense gammas in the 10 MeV range cause nuclear transmutations (Ledingham et al. 2002) with elimination of long lived nuclear waste (Magill et al. 2003), producing ions of more than 0.5 GeV energy (Clark et al. 2001) or intense 5 MeV proton beams (Roth et al. 2000, 2001), with the possibility of easy generation of laser spark ignition in indirectly driven fusion pellets, or electron acceleration to more than 100 MeV energy (Hora et al. 2000).

For laser fusion, after Azechi et al. (1991) had measured 2000 times solid compression but at the low temperature of 300 eV by nanosecond laser pulses, Campbell et al. (2000) proposed that an additional ps-PW pulse may heat the centre of compressed DT for spark ignition. This fast ignitor (Tabak et al. 1994) preliminarily led to the generation of nearly $10^8$ fusion neutrons (Kodama et al. 2002). The study of this fast ignition (FI) scheme is now one of the broader streams in laser fusion research. There were numerous new phenomena observed that deserve much more detailed studies and may lead each to one or other modifications of the laser fusion application. More as a possible alternative example, one of these phenomena will be considered here in some details.

One of the numerous unexpected observations was that the ions emitted with very clean TW-ps laser pulses, having a suppression of any pre-pulse by a factor $10^8$ (contrast ratio), resulted in drastically low energies. The emitted ions in this special case (Badziak et al. 1999) had maximum energies of 450 keV, while 22 MeV energy was expected under the usual conditions after relativistic self-focussing. A similar observation concerned low X-ray emission from targets following irradiation with comparable intense sub-ps laser pulses of similar high contrast ratio (Zhang et al. 1998). Only when a pre-pulse was introduced at least 70 ps before the main pulse was X-ray emission usual. The explanation was very straight forward; with clean pulses there was no relativistic self-focussing possible. When an earlier (70 ps) pre-pulse was used, the necessary plasma in front of the target was produced for relativistic self-focussing (Hora et al. 2001; Fig. 2), leading to very high laser intensities in the filament for high X-ray emission. The same happens for ion emission (Hora et al. 2002) when the high contrast ratio prevents relativistic self-focussing (Hora et al. 2004), resulting then in the conditions of plane wave interaction geometry within the skin depth of the plasma. Details of this evaluation led to splendid agreement between ion energies, quiver motion for X-ray emission and dielectric swelling by a factor of 3.5 (Hora et al. 2004). Some authors now call this long-known dielectric phenomenon (Hora 1991) 'amplification', in error.

The plane geometry laser field interaction with plasma for a few picoseconds duration (Fig. 3) was studied numerically with more comfortable initial plasma distributions (Hora 1991, Sect. 10.5) than in the experiment where at least the basic mechanisms could be followed up. The laser energy goes nearly collision-less by the non-linear (ponderomotive) force (Hora 1991) into the kinetic energy of a block of plasma moving against the laser light and another block moving into the plasma interior. For this plane geometry, the general non-linear force (Hora 1991, 2000) can be expressed by the electrical and magnetic amplitudes of the laser field $\mathrm{E_L}$ and $\mathrm{H_L}$ by the ponderomotive force with the plasma refractive index $\mathbf{n}$,

$$\begin{aligned} f_{\mathrm{NL}} &= (\mathbf{n}^2 - 1)(\partial/\partial x)(\mathrm{E}_\mathrm{L}^2/16\pi) \\ &= -(\partial/\partial x)[(\mathrm{E}_\mathrm{L}^2 + \mathrm{H}_\mathrm{L}^2)/8\pi] \end{aligned} \tag{7}$$

where the second expression denotes the force density as the negative gradient of the electromagnetic energy density.

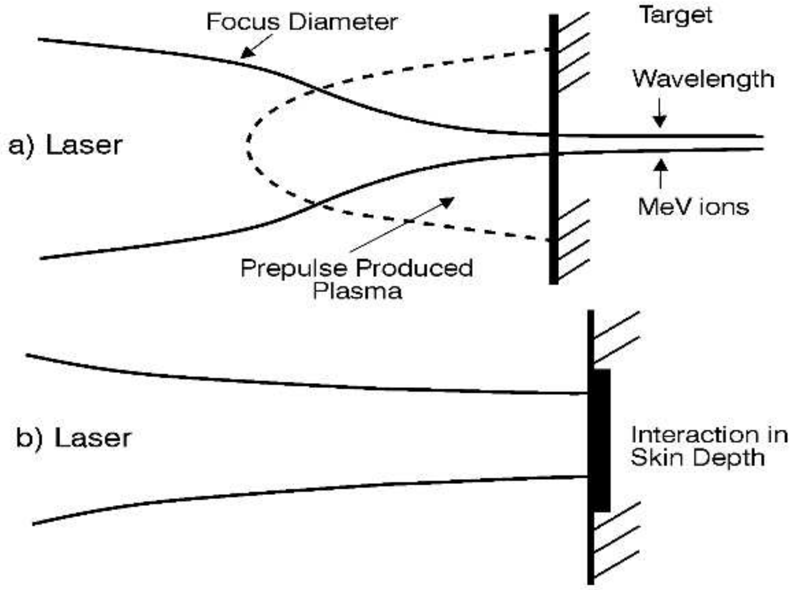


Figure 2. Scheme for demonstration of the essential different geometry of the laser-plasma interaction volumes for subsequent volume-force non-linear electron acceleration with separation by the ion charge, z. In case *a*, the pre-generated plasma before the target causes instantaneous relativistic self focussing of the laser beam to shrink to less than a wavelength in diameter with very high non-linear force acceleration due to the strong gradient of the laser field density. In case *b*, the thin plasma in front of the target permits only interaction in the skin depth with much lower ion energies but nearly ideal plasma geometry conditions.

The deuterium plasma (Fig. 3) reaches velocities up to $10^9$ cm s$^{-1}$ and more ($10^{18}$ W cm$^{-2}$ neodymium glass laser intensity), within a block of more than 15 wavelengths thickness. An advanced computation (Fig. 4) closer to the experimental conditions (Badziak et al. 1999; Hora et al. 2002) reproduced this block motion in detail, with numbers as expected from global calculations and experiments.

The DT ions in such non-linear-force driven plasma blocks have ion current densities of or above $10^{10}$ A cm$^{-2}$ (Hora 2003; Badziak et al. 2003). These fast ions are emitted within very narrow angles against and with the laser light in total contrast to the wide angles for fast ions emitted after relativistic self-focussing (Badziak et al. 2003). The property of the accelerated space charge neutral high density blocks with no strong surrounding magnetic fields underlines the basic difference to the high current density 5 MeV ions (Roth et al. 2001) from PW laser irradiation of plasmas. Here, relativistic self-focussing led to a decrease of the ion density in the focus (Hora 1975; Jones et al. 1982, Häuser et al. 1992). Magnetic fields were generated (Pukhov et al. 1996) such that the ion beams are not space charge neutralized. In this case the ions follow a free electron acceleration process with a conical emission (Hora et al. 2000) in agreement with the measurements of Umstadter et al. (1996). Since space charge neutral, highly collimated, sub-relativistic ion current densities of more than $10^{10}$ W cm$^{-2}$ (Badziak et al. 2003) can be expected for 80 keV deuterium and or tritium ion energies, the condition of (4) is fulfilled and these ions may ignite a self-sustained fusion reaction front in uncompressed solid DT if condition (5) could be fulfilled simultaneously.

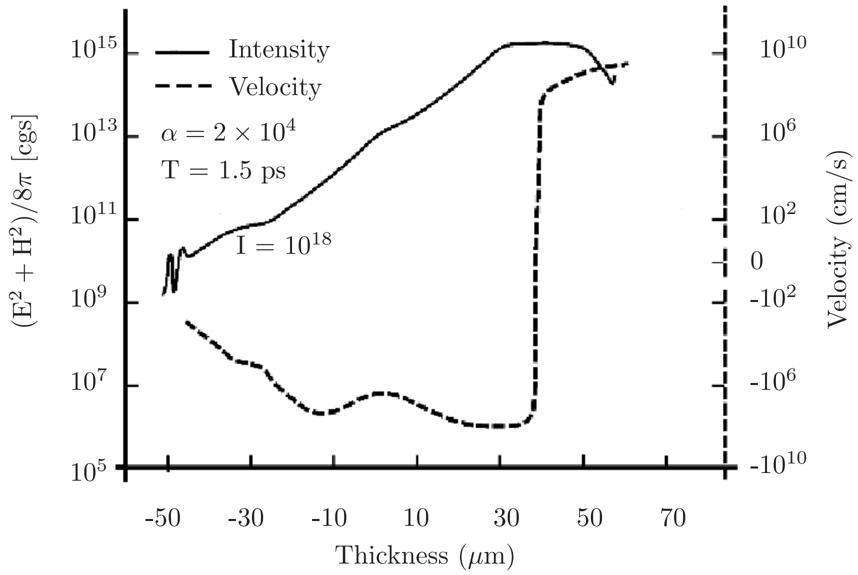


Figure 3. Generation of blocks of deuterium plasma moving against the neodymium glass laser light (positive velocities, $v$, to the right) and moving into the plasma interior (negative velocities) at irradiation by a $10^{18}$ W cm$^{-2}$ intensity neodymium glass laser onto an initially 100 eV hot and 100 $\mu$m thick bi-Rayleigh profile with minimum internal reflection. The electromagnetic energy density $(E^2 + H^2)/8\pi$ corresponding to the intensity is shown at the same time of 1.5 ps after the beginning of constant irradiation.

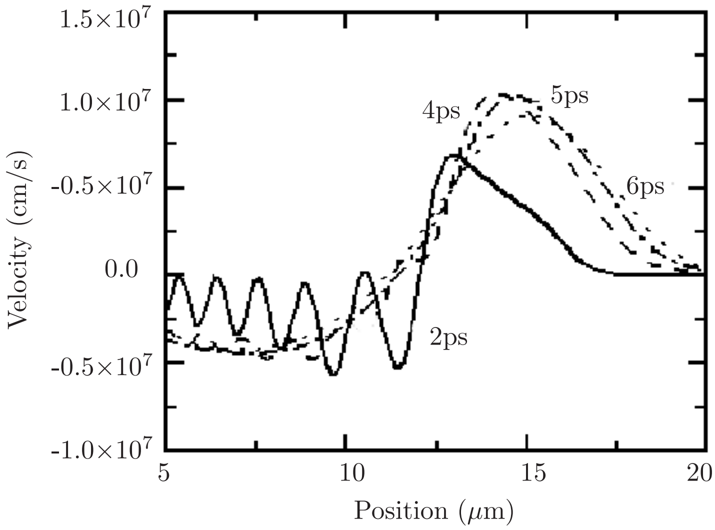


Figure 4. Ion velocity profiles at times 2, 4, 5 and 6 ps taken from genuine two fluids computations for a 3x10$^{15}$ W cm$^{-2}$ 4 ps rectangular laser pulse irradiating a deuterium plasma ramp of 20 $\mu$m thickness with critical density at 12 $\mu$m, confirming the generation of an ablating plasma block (negative velocity) and a compressing plasma block (positive velocity).

It is important to emphasise the fact that generation of laser accelerated blocks was measured even before the results of Badziak et al. (1999) led to the detailed conclusion of the skin layer interaction (Hora et al. 2002, 2002a; Hora 2003; Badziak et al. 2003). This was detected and analyzed from the backscattered spectra and the red or blue shift at laser irradiation of targets with 100 fs TW laser pulses (Sauerbrey 1996). Though the considerations begin with the obsolete argument of ion acoustic wave velocity, Sauerbrey (1996) acknowledges the action of the non-linear (ponderomotive) force as found in related experiments (Kalashnikov et al. 1994) and considered elsewhere (Schmutzer et al. 1977).

It is especially encouraging that the non-linear force acceleration of plasma layers to blocks moving against and with the laser light was well-recognized (Sauerbrey 1996). Experiments confirmed an acceleration in deuterium blocks of $10^{17}$ g, as seen also in the computations of Figure 3, where 10 $\mu$m thick deuterium blocks of $10^{21}$ ions cm$^{-3}$ received an acceleration of $10^{18}$ g (see then discussion of how laser acceleration may reach that of the surfaces of black holes with $10^{29}$ g; Hora et al. 2002c). Since energy transfer to the blocks in a kind of collision-less, non-linear absorption is well known and even emerge as one of the rare analytical solutions of an integral equation (Batchelor et al. 1985), this method was proposed by Shank (1985) for measuring the pulse lengths and energy transfer of sub-picosecond laser pulses.

The remaining question concerns how the energy flux density for generating a reaction front (flame propagation) into uncompressed solid DT can be fulfilled as derived theoretically (Bobin 1971; Chu 1972) to be above the threshold of (5). Even more pessimistic higher thresholds, E*, were considered, but these may be upper bounds as long as the very extensive details for the derivation of the threshold (5) are not found to be incorrect.

It may be possible that the value from (5) is too pessimistic, as there are indications from theory as to how interpenetration of the igniting energetic ions into the cold uncompressed DT fuel may reduce E* to that in (8) (Hora 1983).

$$E_1^* = 2 \times 10^7 \,\mathrm{J\,cm^{-2}} \tag{8}$$

How unexplored these beam fusion conditions are may be seen from experiments (Kerns et al. 1972; Guenther 1972) where 2 MeV electrons of an estimated current density of 3 $\times$ $10^6$ A cm$^{-2}$ interacting with a $CD_2$ target showed a penetration of only 0.3 cm. The single electron penetration would have been more than 40 times longer. The disagreement with the Bethe-Bloch-Bohr binary collision theory for the stopping length could be clarified by applying the collective interaction process, which fully reproduces the measured 0.3 cm. The collective interaction was initially studied by Gabor (1953) and based on the independently derived theory (Ray et al. 1976) for the successful explanation (Bagge et al. 1974) of the experiments (Kerns et al. 1972, Guenther 1972). Such reduction of the collective stopping length, combined with the not yet applied anomalous plasma resistivity (Hora 1991, Sect. 2.6) and electric double layer effects with reduced thermal conductivity (Eliezer et al. 1989), points to the further decrease of the threshold (8).

Thanks to the recent results on interaction of clean TW-ps laser pulses, it was possible to show experimentally (Badziak et al. 2003) that the rather extremely high threshold j* (4), for ion beam fusion has been fulfilled (Hora et al. 2004). The skin layer interaction mechanism accelerates a plasma layer or block initially of 30 wavelength width and several vacuum wavelengths thickness with a critical density of $10^{21}$ electrons cm$^{-3}$ against the laser light, whose velocity from 20 keV nucleon at 8 $\times$ $10^{16}$ W cm$^{-2}$ intensity could be understood in the case of a DT plasma to be 1.23 $\times$ $10^8$ cm s$^{-1}$. This results in a block motion with an ion current density at the target of 1.9 $\times$ $10^{10}$ A cm$^{-2}$. Together with this block moving against the laser light, measurements with thin foils confirmed the generation of a similar block moving into the target with similar energy and ion current density. This result can be related to earlier plane geometry detailed hydrodynamic computations (Fig. 2).

From this result it was concluded that the compressing block may be used as requested for light ion beam fusion for a power station. A 10 kJ laser pulse could then produce 100 MJ of fusion energy where the exclusivity for use for the controlled reaction was confirmed (Hora 2002).

For the physics — within many more problems to be clarified — it has to be shown that at least condition (5) has to be fulfilled. For the compressing block, the whole maximum quiver energy of the electron is converted into translation energy of the ions. The oscillation energy of 80 keV of the resonance maximum of the DT reaction may not necessarily be the best choice. Since this is close to the relativistic threshold intensity $I_{rel}$ (Hora 1991), we have to use the general case,

$$\epsilon_{\mathrm{osc}} = \mathrm{m_o c^2}[(1 + 3\mathrm{SI_{vac}}/\mathrm{I_{rel}})^{1/2} - 1] \qquad (9)$$

where the maximum intensity $\mathrm{I_{max}} = \mathrm{SI_{vac}}$ due to dielectric swelling near the critical density is expressed by the factor S with the laser intensity $\mathrm{I_{vac}}$ in vacuum at the target surface.

For the general analysis we have to be flexible about the chosen values of the applied maximum (dielectrically swelled) oscillation energy, $\epsilon_{\mathrm{osc}}$, into the translation DT ion energy, $\epsilon_{\mathrm{trans}}$, in adjustment to fusion cross sections. We further leave open the value of the energy flux density $\mathrm{E^*} = \mathrm{I_{vac} t_L}$ for reaction conditions (5) or (8), or possibly even a lower value depending on future research, to find the correct value $\mathrm{E^*}$, where the laser pulse duration, $\mathrm{t}_L$, will have to be in the range of ps. According to extensive numerical studies (Cang et al. 2004) in agreement with summarizing estimations, this value could well be a few ps. From relations (5) or (8) and (10), we arrive at the function for the laser wavelength (11, see bottom of page).

$$\mathrm{I_{vac}} = \mathrm{E^*/t_L} \qquad (10)$$

Using as a special case $\mathrm{t_L} = 3\,\mathrm{ps}$, $E^* = 2 \times 10^7 J\,cm^{-2}$, $\epsilon_{trans} = 80\,keV$, we find (12).

$$\lambda = 0.516/\mathrm{S}^{1/2}\mu\mathrm{m} \qquad (12)$$

The non-linear force driven two-block skin layer interaction model works for swelling considerably large than 1, as is the case automatically from detailed analysis of measurements (Hora et al. 2002a; Hora 2003; Cang et al. 2004) with S = 3. The lowest possible case, with S = 1, is that without any dielectric swelling where the whole laser pulse energy is transferred as in the simple case of radiation pressure (Hora 1991) to the absorbing plasma. We conclude that the conditions of the kind in (5) or (8) could well be fulfilled for the ignition of uncompressed solid DT fuel when applying shorter laser wavelengths than that of the neodymium glass laser, and which are well within the reach of present technology, as seen with excimer lasers (Teubner et al. 1993). For the pessimistic case of Bobin (1971) and Chu (1972), the numerical factor in (12) is 0.105, such that with S = 1 just the borderline of higher harmonics CPA excimer lasers (Teubner et al. 1996) would be covered. Further research on lower values of $\mathrm{E^*}$ and numerical studies for a little longer laser pulses may further relax the conditions, and longer laser wavelengths would be possible. No discrepancy was found in the detailed analysis (Bobin 1971; Chu 1972) when followed up recently (Kishony et al. 2001). Figure 5 shows the dependence of the necessary laser wavelength for a pulse length of 3 ps and swelling S = 1, which one needs for a desired ion translative energy in multiples of $\mathrm{m_o c^2}$ ($\mathrm{m}_o$ is the rest mass of the electron), if the threshold $\mathrm{E^*}$ is given.

$$\lambda(\epsilon_{trans}, E^*, t_L, S) = [t_L I^*_{rel}/(3SE^*)]^{1/2}\ \{[(\epsilon_{trans}/m_o c^2) + 1]^2 - 1\}^{1/2} \qquad (11)$$

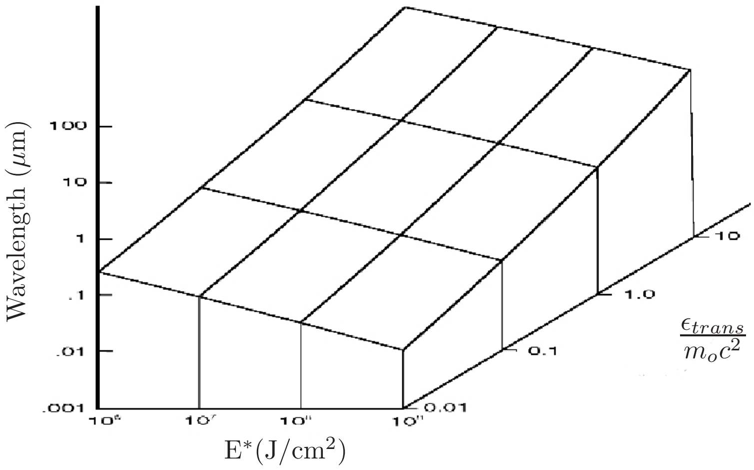


Figure 5. Relation between the laser wavelength, the aimed ion energy, $\epsilon_{\mathrm{trans}}$, in multiples of $\mathrm{m_o c^2}$, and the necessary energy flux density E* for ignition of uncompressed solid DT fuel for S = 1 and a laser pulse length of 3 ps.

The gain for a controlled reaction has been estimated to be of a high value. A 10 kJ ps laser pulse may result in 100 MJ fusion energy (Hora et al. 2004). From the block ignition of solid DT without compression there may perhaps be the possibility for neutron lean reaction leading to direct conversion of the nuclear energy of the charged reaction products into electricity (Hora 2002; Hora et al. 2003a).

These developments may be considered in view of the project of the ITER tokamak to be built with $ 15 billion during the next 10 years in Cadarache/France and which may produce electricity with high gain (Tran 2004). For energy production by controlled inertial confinement fusion, it was demonstrated by the Centurion-Halite project (Broad 1988) that a 50 MJ x-radiation pulse on a fusion pellet produces a very high gain of fusion energy (Phipps 1989) where the computation with the use of a much more sophisticated laser irradiation of 10 MJ instead of the x-rays may produce 1000 J fusion energy (Strom et al. 1988, Hora, Azechi et al. 1998). Since the ignition of large amounts of solid state DT or of some higher density for energy production (Nuckolls and Wood 2002) may be possible by electron beams, the just described block ignition will come closer to the radiation ignition of these very high gain reactions as underlined by Nuckolls (1992). After the necessary conditions of very high energy flux density E* and the $10^{11}$ Amp/cm$^2$ are available now by the just described block ignition it may be indicated that the then interacting $10^{17}$ W/cm$^2$ laser intensity is in the range of the 20 million K radiation temperature involved in the ignition processes explained by Nuckolls (1992).

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