Introductory Remarks to the "Edward Teller Lectures"

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1. Overview

Edward Teller was celebrated by the media together with Albert Einstein as one of the greatest and most influential scientist of the 20th century. He had to succeed not only by his many scientific achievements but also by having the strength of character and courage to take controversial positions on the role of science and technology in the cold war. Many believe that only Teller's unique strength allowed him to understand how science could serve as a way of saving mankind from totalitarianism and oppressive dictatorships [1].

The challenge of developing controlled fusion energy by lasers and other energy sources was only a part of Teller's wide range of interests and achievements. Indeed his personnel influence and encouragement in this field was far more wide-ranging than is usually recognized. Now after 40 years of enthusiastic work on laser fusion, we can see that laser-driven inertial fusion energy (IFE) has emerged as a serious energy option. This development was initiated out of the fact that Teller in 1960, immediately envisioned after the discovery of the laser, for its use to create fusion energy. Indeed this early insight was mirrored by his ingenious counterpart Andréi D. Sakharov.

However, Sakharov's work was in a somewhat of a different direction. The carefully underlined section in Sakharov's editorial remarks for his collected papers [2] is most significant: "In a seminar in 1960 (perhaps 1961, I do not recall), I discussed the possibility of realizing a controlled thermonuclear reaction by means of lasers". Sakharov's attention to the laser was developed in his paper 1948 where he also mentioned the possibly first observation of superradiance (laser) emission by Kopfermann and Ladenburg of 1931 and the work of Fabrikant of 1937, see page 43 of Ref. [2].

Teller's familiarity with the laser precedes the work of Charles Townes who, with James Gordon, produced the very first microwave laser in 1983. In Teller's memoirs, he cites a correspondence with John von Neumann [3,p. 408]: "I suggested using Einstein's very early ideas about stimulated emission. My idea, which turned up later in some way of our correspondence, describes a laser and anticipated that invention several years. But, of course, an idea is unimportant unless one develops it." This historical remark is very important in view of the extreme difficulties Townes had when promoting his experimental discovery of the laser [4]. During this project two Nobel laureates (Rabi and Kusch) - whose "research depended on the support from the same source" - tried to stop him by saying " 'Look, you should stop the work you are doing. It isn't going to work. You know it's not going to work, we know it's not going to work. You're wasting money. Just stop!' ", see page 65 of Ref. [4]. However, three months later, the laser worked. When Townes presented this to an APS meeting, the response was not overwhelming. Apart from remarks like that of a Columbia-theoretician who flatly said that this cannot be true since it is against all rules of physics, others simply ignored the results. "Niels Bohr in Copenhagen originally said 'but this is not possible' [4]. Bohr later modified this statement more as a courtesy" when Townes told him how it worked.

After all of this turmoil it is remarkable that Townes writes [4]. "John von Neumann said in Princeton 'that cannot be right!' but few moments later understood it and wrote a famous proposal to Edward Teller". Therefore it was most fortunate that Teller ingeniously had pre-developed the scheme of the laser before in the correspondence with von Neumann who responded then so positively to Townes' experiment. This was one of the "Sternstunden der Menschheit" [5].

It was then only logical that in 1960 Teller initiated a program to study laser fusion at the Lawrence Livermore National Laboraotory. Fortunately he got his associate, John Nuckolls, involved [3]. Nuckolls had specialized in studying the smallest possible nuclear explosions and could bring this experience to bear on laser target studies. Over all these years, Teller never said that laser fusion had achieved a solution for energy production, but he was optimistic. His lecture at the IEEE conference on Quantum Electronics in Montreal [6] 1972 was a most stimulating promotion for the study of laser fusion energy [7]. Another crucial moment in 1979, Teller's cardinal merit to keep laser fusion going occurred was his intense focus and willingness to fight for the concept [3 p. 523]. In early 1979, when Greg Canavan was chief administrator of IFE in the Department of Energy there was an effort to move the IFE budget into magnetic fusion. In Canavan's fight to keep IFE alive, he called on Teller to help to prevent the cancelling of the budget. Teller spent a long afternoon in a congressional hearing "strenuously arguing for the cause" of IFE. At 71 years of age, he was then "exceedingly exhausted". The following morning his medical advisor ordered absolute resting. Then came the news about Three Miles Island and Teller forgot about being tired. Unfortunately after three days of vigorous action, he was hospitalised with a heart attack.

Thus Edward Teller was not only involved with the creation of the laser and among very first experts to initiate laser fusion energy research, but he continued to lead the field, not only with his prestige but with his intense mental and physical strength.

It was then quite natural that the executive board of the conference series "Laser Interaction and Related Plasma Phenomena LIRPP" established the "Edward Teller Medal" with the blessing by Edward Teller in 1990*. This medal is to recognize outstanding research contributions in the development of laser fusion. It is now formally incorporated as an award of the American Nuclear Society thanks to the efforts by G. Miley and by the present Board of Directors, M.E. Campbell, A. Migus, K. Mima and E. Storm and the Managing Director, W. Hogan, for the "Inertial Fusion Science and Application IFSA" conferences (the continuation of the LIRPP-series since 1999).

This book provides a collection of the lectures by the recipients of the Edward Teller Medal presented including the IFSA-Conference 8-12 September 2003 in Monterey, CA. It also presents the speeches by Edward Teller, delivered at various LIRPP conferences, over thirty years prior to when it changed into IFSA. These speeches bring out a vigorous dynamic with a mixture of various views of these developments for the creation of a key energy source for the future: inertial fusion. There is the possibility that ***laser fusion energy may be generated at considerably lower costs*** than any other present energy source on earth. This is exactly what mankind expected from nuclear energy when it was first discovered. This may finally lead what mankind expected: the 'Golden Age', at least with respect to energy source [8].

Why has it taken so long - more than forty years - before the optimism to offer the option of laser driven inertial fusion energy (IFE) could be substantiated? The optimistic statements by the early promoters can be traced back to underestimating the physics difficulty of compressing and heating micro-targets. The measurement of the first fusion neutrons

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*The Advisory Board with inclusion of John Nuckolls resolved a constitution unanimously in a Board Meeting in Osaka, April 1991, to invite unrestricted nominations and by secret ballot of the Board Members – later including the awardees – through an awards committee, the awardees were all elected and in all cases approved by E. Teller.

produced by lasers was reported in 1968/69 and over the following thirty years the number of fusion neutrons per laser shot was increased by 100 billion times. Thus, the fusion gain is now close to break-even, but not yet at the level needed for a fusion power station. It is expected that the National Ignition Fusion (NIF) laser facility nearing completion at LLNL, will demonstrate fusion ignition and modest fusion gain.

A great step forward occurred during this time in laser technology. After sophisticated techniques permitted the generation of laser pulses in the femtosecond (fs) range [9,10], there was the essential discovery by Gerard Mourou of the chirped pulse amplification (CPA) of ultra short pulses [11] giving up to several Petawatt (PW) power [12] which development totally changed the field of laser applications enabling relativistic laser-plasma research [13] with numerous applications [14,15].

The Centurion-Halite experiments with underground nuclear explosions [16] clearly demonstrated experimentally that x-ray driven ICF works but at energies not available in the laboratory, needing at least some dozens MJ of driver energies [17]. Using the much more controllable energy of a laser pulse in the ns range with 10 MJ input energy a fusion yield of 1000 MJ can be expected [18]. This is an interesting definite option for laser fusion which could be studied with the newer facilities such as NIF being developed in the U.S. [19] and discussed in Section 2 and the LMJ [20]. Since the discovery [11,12] of the CPA by Mourou, the verification of PW-ps laser pulses [21-23] and the speculation, now possible, on reaching Exawatt and Zettawatt pulses, it pays to search for alternatives or modifications of the fast igniter concept [24] (Section 3). One route can be seen in the fact that laser pulses of about 10-100 kJ energy may produce a fusion energy output of 100 MJ or more if the laser pulse can be designed to ignite a fusion detonation wave. In this approach, the wave propagates in a controlled way into very large fuel mass of a low compression (solid state density or up to ten times higher) DT fuel. This process was previously considered for an electron beam ignition of targets [25] (Section 4) or for a DT ion beam block ignition [26,27] (Section 5). To emphasize this optimism the following sections detail at least some of these concepts.

2. Big Laser Solution

The present summary of the developments on laser fusion focuses on the last 10 years extending the abbreviated view given in “30 years Laser Interaction and Related Plasma Phenomena” added at the end of the here reproduced Edward Teller Lectures [28]. One key well-known earlier result [29] was the measurement of laser compression of a carbon polymer containing deuterium and tritium to 2000 times the solid-state density. The temperatures achieved, however, were disappointing low, in the range of 300 eV. As a consequence, Mike Campbell [30] explained in his contribution to a celebration of Chiyoe Yamanaka's laser research that he and colleagues, notably Max Tabak, had originally suggested additional heating should be done using short laser pulses. Campbell could develop a program to study this approach on the newly discovered CPA technique of Mourou [11,21]. This effort added new emphasis to the scheme of the fast igniter [31]. Details about this are discussed further in the following Sections. The initial aim [31] was to concentrate the ps additional laser energy into the center of the highly compressed plasma and to initiate a spark (or central core) ignition [32].

An alternative to the short pulse heating of the compressed plasma with spark ignition [32] was revealed by following up the numerical results of the volume ignition [33,34]. At this time, Atzeni [35] discussed laser fusion schemes using laser pulses of some MJ energy [19,20] in the ns range.

The most studied approach for added heating is "conventional" spark ignition where the laser compresses the plasma [7,18,32,36] in a prescribed way such that a central region core is generated at high temperatures and low density and an outer shell of high density and low temperature. The core ignites on "spark" fashion. A self-sustained fusion detonation wave is generated at the inner surface of the outer shell and that is directed into the high-density low temperature plasma.

In contrast to this spark ignition scheme and its' demanding density and temperature profiles, volume ignition [33] uses a natural adiabatic compression of the whole fuel at nearly uniform temperature and at nearly uniform density at each instant. Both parameters develop a linear velocity profile as prescribed by a self-similarity model. Unfortunately, volume compression results in a very inefficient DT burn if the target gain is less than 8. But at higher gains, alpha reheat in the fuel acts like an additional heating source. This resulting burn more than compensates radiation losses and fuel depletion, giving gains above 1000 per unit energy in the compressed plasma or above 100 overall [13,33,34]. Volume ignition compression and burn dynamics are rather "robust" (see Lackner, Colgate et al. [33]) and involve less chance for several instabilities and asymmetries than is the case for spark ignition.

Experiments using volume reaction with self-similarity dynamics led to the highest published fusion reaction gains from direct drive irradiation of spherical micro balloons [34,37,38] based on DT fusion neutron measurements. Gains of 1.5% per incident laser energy were reached, giving gains up to [34] 50% per energy in the compressed plasma core, with laser pulses in the 10-kJ range. With these small input energies, ignition was not reached but the measured data for compression density, temperature and gain fully followed the volume ignition plasma dynamic model.

These single-event [24,34,39] results should be mentioned as an alternative to the otherwise very extensively studied spark ignition [32] which details may not need to be repeated here. The difficulties are well known [34,39] and studied extensively [32]. We underline the aspects of volume ignition here only because there may be the possibility to find more simplified solutions [40].

Coming back to the result of low temperatures at high compression [29], volume ignition can provide a solution. If laser pulses of 5 MJ or more are available, volume ignition with compression to 3000 or 5000 times solid-state density results in optimum ignition temperatures as low as about 500 eV. These temperatures are, in fact, not much above the values already measured with laser pulses of about 100 times lower in energy. Detailed numerical evaluations confirm [34,39] that with few MJ laser pulses target conditions with natural self-similarity compression will arrive at a crossing point of parameters for high gain volume ignition. This approach avoids the need for additional short pulse laser input or sophisticated shaped density and temperature profiles as needed for spark ignition.

This consideration is based on the use of 5 MJ red laser input available next [19,20]. Beam smoothing would be used for the suppression of the 10-ps stochastic pulsation, avoiding the need for expensive large single crystals commonly used for conversion of the laser beam to higher frequencies [41-43]. Such beam smoothing [44] was originally introduced to reduce beam filamentation. However, this technique turned out to also reduce parametric instabilities by a factor of more than one hundred [43-45]. Instead of reducing beam filamentation, a clear disappearence of the 10-ps stochastic pulsation was observed by Labaune et al. [42,46]. Since hydrodynamic effects, absorption, parametric instabilities etc. were mostly the topic of research it may have been overlooked that smoothing techniques are much more crucial to overcome problems of instabilities [45] and of the stochastic pulsation [13,41]. Therefore, direct drive laser fusion with the fundamental red laser wavelength with appropriate smoothing may be a simplifying solution for the "big laser" option.

The spark ignition scheme [32] is recognized by the community as the basic approach for studying the fusion detonation physics. Thus, it provides a reasonable basis for near term MJ laser facilities experiments [19,20]. Although engineering type experiments and computer-assisted solutions have contributed to a growing insight into the basic processes involved, many physics issues remain unsolved. The physics is difficult since a hydrodynamic calculation cannot follow up the interpenetration of the energetic particles from the hot plasma into the cold plasma. Kinetic theory (Boltzmann equation) studies lack an adequate description of collisions, without an adequate treatment of the Boltzmann collision term. Single particle computations that typically already use one million particles are insufficient in view of the long-range Coulomb collisions. Extremely large computer capacities would be required for accurate fast multi particle simulations.

Nevertheless, for illustrative purpose, we use here the reasonable and very sophisticated evaluations to examine the computation of spark ignition a case with a laser pulse [18] of 10 MJ where instabilities and asymmetries were ignored. This is very useful for a comparison of spark and volume ignition in order to demonstrate some merits and differences between these schemes [34]. This method is also useful for comparing results obtained for the fusion detonation wave with other calculations [47].

Spark ignition [18] can result in a state of high compression as shown in Fig. 4 of [34]. This requires a precise compression process where a plasma core with average temperature of 10 keV and average density 250 n_s (n_s is the solid state DT density) is produced, surrounded from a cold and very dense outer shell with maximum density 2300 n_s. A fusion detonation wave is then ignited at the 0.158 mm radius of the compressed inner core (while the radius of the compressed outer shell is 0.323 mm). A detonation front is ignited by the inner core at the spherical interface between the core and the outer shell at about 400 n_s density. The reaction of the inner core then, in effect, corresponds to volume ignition for which the data of Fig. 5 of [34] can be used. The parameters used here have been reconstructed from the diagram of Fig. 4 of [34]. It is remarkable that they fit very well with the volume ignition of the core having $E_0 = 0.46$ MJ deposited in the core of 1.45×10^{-5} cm^3, density of 250 n_s and 10 keV temperature. Indeed these conditions fit well with optimum volume ignition requirements. The fusion gain G is then close to 10, i.e. 4.69 MJ [5] of fusion energy is produced which impinges on the core surface producing an energy per trigger area of

$$E_{spark} = 1.62 \times 10^9 \text{ J/cm}^2. \qquad (1)$$

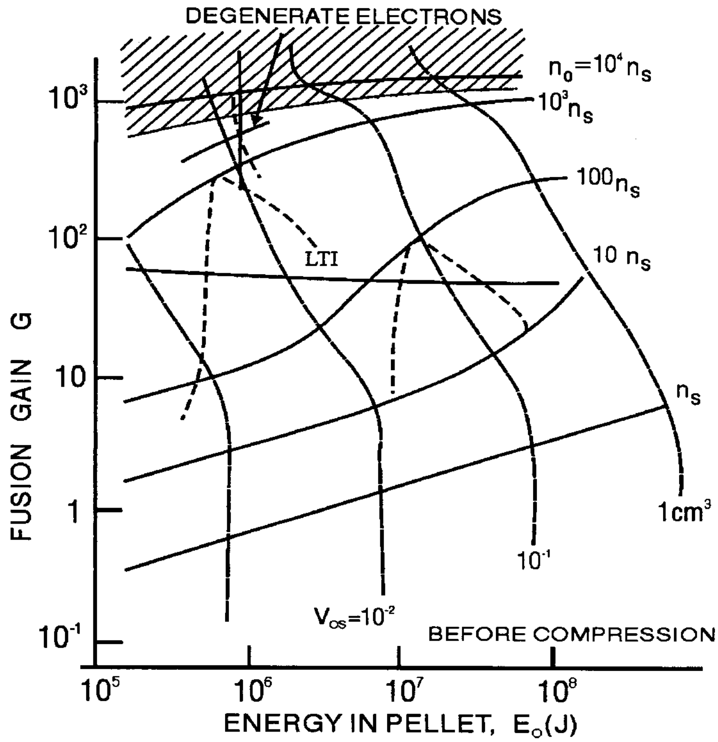

Fig. 1. Optimised core fusion gains G with the cross hatched area for Fermi degenerate electrons for evaluation of optimised volume ignition at temperatures in the 500 eV range [39].

This energy triggers the fusion detonation wave, which travels into the surrounding cold outer plasma shell.

While one may be very skeptical about the feasibility of spark ignition due to the Rayleigh-Taylor (R-T) instabilities, a more severe problem is the spherical symmetry. (In contrast, symmetry and R-T instabilities are not crucial for volume ignition.) However, if the strongly shaped radial density and temperature profiles at spark ignition have not been properly established (cf Fig. 4 of [34]) into different radial directions, the fusion detonation wave may not at all be possible within the very short trigger time available. Apart from this problem, one may assume that the conditions for the ignition Eq.(1) had been properly scaled with respect to particle interpenetration, stopping power, radiation etc.

It is very remarkable that the energy flux of Eq. (1) falls close to values cited by other references, (Chu, Bobin, Kidder, Bodner, Ahlborn, Babykin, and Shvartsburg [47]) where instead of (1) a value was found of

~ 10^8 J/cm^2. It was previously elaborated [47] that the inhibition of thermal conduction based on the double layer processes [13] and the collective effect of reduction of the stopping length [48,49] for the reaction products may reduce the limit (1) to about 10^7 J/cm^2. This estimate is based on possible interpenetration of the beam of energetic ions moving from the hot core plasma into the cold peripheral plasma to ignite the reaction wave. The following evaluation is based on this interpenetration model [47] but with modifications to include radiation mechanisms. As a pessimistic assumption, Brueckner and Jorna's ignition condition is used [36]. Then the ignition by irradiation of the cold plasma by fast ions requires a current density of

$$j = 10^{10} \text{ A/cm}^2. \tag{2}$$

Experts consider this early result as much too pessimistic on the hot spot spark ignition mechanism. This has to be realized when the ignition values from Eqs. (1) and (2) are employed in the following discussion of recent results from laser fusion schemes using ps laser pulses. The reference to the large laser experiments [19,20] for studying the spark ignition [32] has to be reserved for future research on the fusion detonation physics while the aspects of single-event [24] volume ignition may directly aim the application of energy production [39].

3. Physics of the Fast Igniter

Since the original paper by Max Tabak et al, on the fast igniter [31] was published, much attention and research has been focused on this unique concept. The enormous interest extended Mourou's CPA [11,12] to a new dimension involving laser fusion. Today, lasers with ps pulses of PW power are available [21,50]. The numerical evaluation of the fast igniter highlighted that estimated fusion gains, based on fusion energy per laser energy, reach values close to 300 for laser energies below MJ. Preceding schemes had typically predicted gains around 100 and required much higher energy and longer (ns) laser pulses. Nevertheless longer laser pulses, such as employed in other schemes will also be necessary for the fast igniter, perhaps with 10 times lower energy for the first step of the compression to densities above 2000 times solid state density.

In the second step of fast ignition short PW laser pulses are deposited into the precompressed plasma. These new ideas [31] require moving into a new field of relativistic effects during such laser plasma interactions.

The initial dream guiding the PW pulse to the center of the high-density fuel with the energy of the PW pulse deposited within a very small central spark volume was fascinating but very questionable. First experiments [51] with ps pulses of powers in the 10 TW range showed the enormous complexity of the relativistic interaction. An incomplete list of interaction phenomena includes stopping lengths, electron and ion acceleration, double layer effects (now called "Coulomb acceleration"), and generation or self-focusing for guiding of the PW beam to the center etc. These phenomena were considered, though with very simplified and incomplete models. Conditions were found such that most of the PW energy may be uniformly spread over the compressed fuel for volume ignition. If this can be achieved experimentally, fast ignition [52] may arrive at interesting fusion gains.

A funnel concept was implemented experimentally to study fast ignition. This technique uses a gold cone inserted in the target [23,50] to guide the beam into the center core with complicated interactions in the outer volume plasma. The output from such experiments has increased from 10^4 DT fusion neutrons to 10^7 fusion neutrons using a cone [50].

Other recent studies with ps laser pulses of more than 3 TW power indicate a number of very unexpected phenomena can occur with these ultra high power interactions. Gammas up to 50 MeV energy appeared and subsequent nuclear photoeffect interactions produced a variety of radioactive isotopes [53-56]. These gamma bursts had intensities far above the limits of radiation safety requiring new safeguards [56]. There are also speculations about Zettwatt pulses, (see Mourou and Tajima [21]), for producing pair production in vacuum or Hawking radiation similar to black holes [57,58]. For other experiments 30 TW pulses focused into ~ atmospheric pressure gas produced 10^8 electrons conical directed in beams of 30 MeV energy [59]. These beams could be explained theoretically (in competition to other theories [60]) in number, energy and conical angle by electron acceleration by lasers in vacuum [61,62]. That process is identical to the "free wave acceleration" derived by Hartemann, Woodward et al. [63]. Experiments by Malka et al. [64] measuring 200 MeV electrons at similar conditions as of Umstadter et al. [59] can quantitatively be explained by the free wave acceleration [60,63] in contrast to vaguely assumed wake field models. There appears to be some interesting application of these energetic electron beams for example, if an electron beam is used, lead target can generate positrons with an extremely high intensity by the Bhabha process [65].

4. Fast Igniter for Electron Beam Fusion

While the funnel scheme [50] is a straight forward advancement of the initial fast igniter concept [31], further generalizations evolved for the fast ignition. The nonlinear and relativistic properties of compressed plasma produced by irradiation with PW-ps laser pulses, especially the dominating conversion into extremely intense relativistic electron beams, is generally viewed as the main energy transfer process [25] involved in the fast igniter scheme [31]. In order to reach condition (1) for ignition of a detonation wave, the 10 to 100 kJ in a ps laser pulse must be focused to ~ 0.03-mm diameter. The basic issue then is if this energy can be deposited within a sufficiently short depth in the fusion fuel. When correctly fitting the observations of relativistic electrons of more than 5 MeV energy (30 TW pulses produced 30 MeV electrons in less than solid state densities [59]) the necessary short stopping length can only be reached at high plasma densities of > $1000n_s$. This result sets the goal for precompression of the plasma in the fast igniter scheme [31].

Under these conditions, a fusion detonation wave may be ignited. Nuckolls and Wood [25] consider propagation of this wave into low density DT fuel and explain the advantages of this technique, even for densities of ten times the solid state (3 g/cm^3). It is important to note that then 10-kJ laser pulses can produce 100 MJ or more output energy, depending only on the amount of low-density fuel into where the detonation wave is propagating.

These considerations are consistent with the preceding discussions. For example, spark ignition [18] can be evaluated with the reaction of the inner core of average density ~ $300n_s$ and radius ~0.158 mm where the incorporated 0.5 MJ laser energy produces 5 MJ in full agreement with the volume ignition calculation [34,39] and the more general analysis by Atzeni [35]. This energy corresponds to $3.3\text{x}10^{10}$ J/g in good agreement with the basic $4\text{x}10^{10}$ J/g in the Nuckolls-Wood model [25]. While this agreement is encouraging, this represents only a part of the physics of fast ignition. Various researches cited here have identified a large number of effects that still need to be explored before the numerous assumptions in this spark ignition concept can be fully verified.

One important problem is to understand how the 10^8 30-MeV electrons produced by 30 TW-0.4 ps laser pulses fits so well with the free wave acceleration mechanism [60,62,63]. Collective effects for ions slowing down in such plasma [48,49] may well occur reducing the alpha stopping length such that the estimation of Nuckolls and Wood [25] in Eq. (1) could be modified to predict even more favorable conditions.

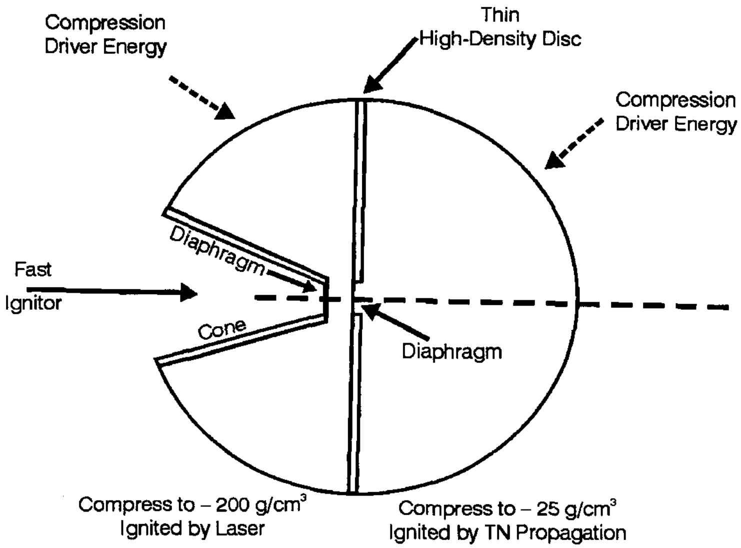

Fig. 2 Laser fusion ignition scheme of Nuckolls and Wood [25]. The PW-ps laser pulse in the pre-compressed DT plasma in the left hand half sphere produces an intense electron beam which ignites a fusion detonation wave in the right hand side half sphere with nearly uncompressed large amount of DT fuel.

5. Block Igniter for Producing Ion Beam Ignition

A further example should be mentioned here to show the richness of ICF research as a single-event [24] further generalization of the fast igniter. One aim is to provide conditions how the petawatt-picosecond laser-plasma interaction may provide a further access to study the physics of fusion reaction fronts similar to the Nuckolls-Wood scheme [25] discussed in the preceding paragraph. The following modification of the fast igniter scheme [31] using a "block" igniter is intended to avoid the high precompression of the plasma such that all the advantages of the low density, large mass targets envisioned in the Nuckolls-Wood scheme would result [25].

The experiments described next open the way to produce very intense DT ion-beam blocks for the ignition near conditions at or below the relativistic beam threshold. Such blocks avoid the various undesirable relativistic beam effects in the irradiated plasma. These blocks follow immediately from the PW-ps interaction of the irradiated solid DT fuel. It is expected that this technique will produce a reaction front in a long

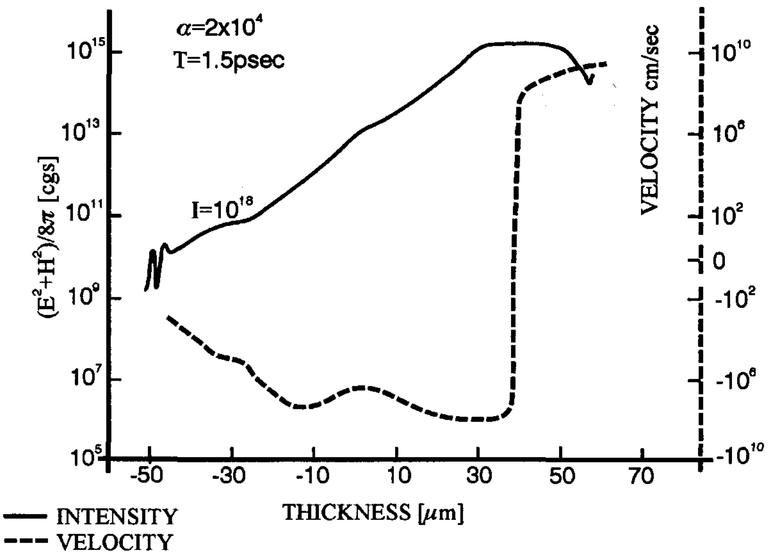

Fig. 3. Deuterium ion velocity at 1.5 ps showing the generation of blocks of deuterium plasma moving against the neodymium glass laser light (positive velocities v to the right) and moving into the plasma interior (negative velocities) at irradiation by a neodymium glass laser of 10^{18} W/cm^2 intensity onto an initially 100 eV hot and 100 μm thick bi-Rayleigh profile (Fig. 10.17 of [13]) with minimum internal reflection. The electromagnetic energy density $(E^2+H^2)/(8\pi)$ is shown at the same time of 1.5 ps after begin of the constant irradiation [13].

stretched target or in a half sphere [25] that fulfils the condition of a low density, large mass reaction volume. If so, 10 kJ laser pulses may well produce 0.1 to few GJ of fusion energy.

The block ignition scheme follows from the analysis of the anomalous ion emission from solid targets during ps-TW laser irradiation [15,66]. While laser pulses of about ns duration produce maximum MeV ion energies in agreement with relativistic self-focusing, ps pulses result in more than 50 times lower maximum energies. Furthermore, the numbers of emitted ions do not vary much with laser power. This experiment had a suppression of the prepulse by a factor of 10^8 (contrast ratio) until 100 ps before the main ps pulse. Thus, it was concluded [67] that relativistic self-focusing was avoided and that a pure skin-depth interaction occurs within a constant interaction volume. As theoretically expected, the measured ion energy is then proportional to the input power P. The experimentally determined quiver energy corresponded to the ion energy assuming a

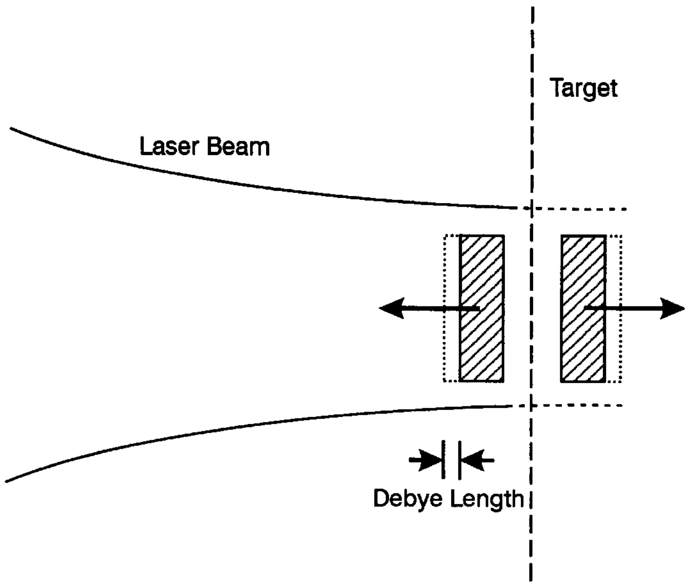

Fig. 4. Scheme of skin depth laser interaction where the non-linear force accelerates a plasma block against the laser light and another block towards the target interior. In front of the blocks are electron clouds of the thickness of the effective Debye lengths of less than 500 nm [26].

plasma-dielectric swelling of the nonlinear force by a factor of three due to the 100 ps prepulse. This conclusion is based on a contrast ratio of 10^4 during the last 100 ps before the main pulse arrives, in agreement with a numerical simulation using an extensive two-fluid calculation (Fig. 1 of Ref. [27]). This analysis of prepulse mechanisms and the contrast between skin depth vs. relativistic self-focusing interaction was evident [27] also in similar measurements with precisely controlled prepulses [68].

The generation of fast moving high density plasma blocks from direct electrodynamic forces at laser-plasma interaction is based on the complete derivation of the nonlinear force [13]. Detailed numerically studies of plane inhomogeneous plasma with perpendicular incidence of lasers [13] consider a neodymium glass laser pulse of 10^{18} W/cm^2 irradiating a 100 wave length thick deuterium plasma of up to the critical density (Fig. 3). After 1.5 ps a profile of energy density and as negative gradient produces forces that drive the plasma into blocks with velocities up to 10^9 cm/s. One block moves against the laser light while the other moves into the plasma interior. For the conditions leading to the skin layer interaction [67], this results in the block generation (Fig. 4). The nonlinear forces drive an electron cloud, such that the ions are dragged within a double layer given by the Debye length which value is sufficiently small for the conditions discussed here for laser fusion (Fig. 5).

The plasma block moving into the plasma interior can be interpreted in terms of prior studies of light-ion beam fusion. The conditions for ignition of a fusion reaction front moving into an uncompressed large volume of fusion fuel have been studied by a number of authors [47], and they find an energy flux of Eq. (1) necessary. These numbers are in fair agreement with the generation of the fusion detonation wave at spark ignition of laser fusion [18] and also with the electron-beam ignition requirement now introduced for the PW-ps laser pulses [25]. The rather pessimistic condition for initiating the fusion reaction wave of Eq. (2) following Brueckner and Jorna [36] can easily be achieved by the PW-ps laser pulses using the skin layer conditions with carefully selected prepulses to avoid relativistic self-focusing but allowing generation of some swelling.

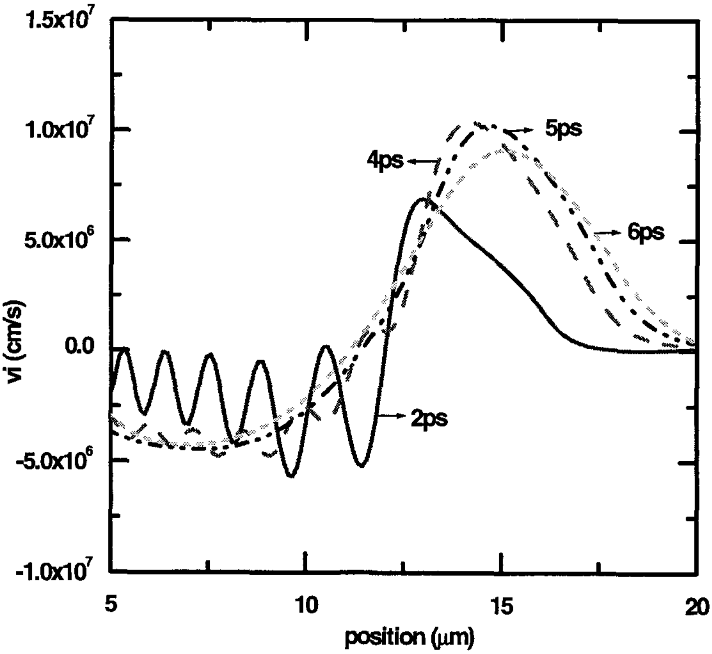

Fig. 5. Ion velocity profiles at the times 2, 4, 5 and 6 ps at irradiation of a 4 ps neodymium glass laser pulse on a deuterium plasma of initial density of a linearly increasing ramp of 30 eV temperature, confirming the generation of an ablating plasma block (negative velocity) and a compressing plasma block (positive velocity) [Y. Cang et al., J. Plasma Physics 2004, in print].

This requires the DT ion density of the compressing block is 10^{21} cm^{-3} for neodymium glass lasers. The laser intensity has to be selected in the range of 10^{18} W/cm^2 or less adjusted, such that swelling can produce ion energies of 80 keV. The resulting current density of 4×10^{10} A/cm^2 is then sufficient to fulfill even the pessimistic threshold of Eq. (2). The thickness of the igniting block can be adjusted by the swelling.

In summary, to simulate high gain laser fusion by PW-ps laser pulses is expected based on light-ion beam type ignition of the skin layer process [27,67] and associated effects measured by Badziak et al [15,66]. This is an extension of the fast ignition [31] scheme which is an alternative to Nuckolls-Wood electron-beam type fusion scheme [25]. The block ignition scheme provides a continuation of the laser fusion gain curve starting from the high gain values [69] achieved by irradiating 6 J-ps laser pulses focused on 10-μm diameter deuterium targets.

The prepulse controlled nonlinear-force driven skin layer block igniter may be extended later to use $p^{11}B$ fuel since ever present PW laser intensities can produce ion energies in the blocks up to MeV or more. Thus energies required of the block ions for $p^{11}B$ ignition, (e.g. to go to several 100 keV energy to match the resonance of the reaction) appears to be achievable. In this case, the plane wave skin layer interaction could even employ lower laser intensities (around or even less than the relativistic threshold) avoiding the numerous relativistic anomalies. If achieved $p^{11}B$ fusion plants could use direct conversion of the reaction particle energies into electricity [70] less radioactivity per gained electricity is produced than from coal plants [13]. Such plant would also involve a minimum of waste heat generation, reducing the huge cooling burden of today's power stations.

There are well a number of problems to be solved for the block igniter, but the basic mechanism of the skin-layer laser-plasma interaction at sub-relativistic conditions in plane geometry without relativistic self-focusing has been confirmed experimentally [15,27,66,67]. The earlier results from light-ion beam fusion [47] provide insight into the conditions needed for driving reaction waves into large volumes of solid-state density DT fuel. If successful, this would give extremely high gains avoiding the need for complicated precompression processes.

6. Concluding Remarks

Since this book collects the results of many very outstanding experts in the field of laser fusion, why were these remarks about possible ignition schemes given as an introduction? The most imperative reason was that this provided an opportunity to give references to lesser known documents about how the laser was created and how Edward Teller contributed to it's early development. Further his essential support for laser fusion had to be underlined. To illustrate how Teller's statement that laser fusion may be not too far away could be implemented, recent results with the large scale NIF-like laser for a technologically clarified solution for energy production and new aspects using PW-ps laser pulses have been developed in some detail. The numerous different points in the following Edward-Teller-Lectures underline further what a wide range of science must be considered in search for useful laser fusion. Still we are only at a beginning, but clearly aimed toward the most important goal envisioned by Teller of very low cost, safe, clean and in exhaustive energy generation. The way to this goal seems clear now that the main routes, either with the ns or with the ps pulses - or both, have identified.

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