Single-Shot Laser Driven Inertial Confinement Fusion Based on Nanosecond and Picosecond Laser Pulses

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Abstract. Nuclear fusion gains of deuterium-tritium (DT) at volume ignition are discussed for the forthcoming conditions of the NIF or LMJ laser pulses in the range of nanosecond duration at direct drive. This turns out to be similar to the expected values known form spark ignition. These conditions should be reached also by single pulse interaction of picosecond pulses using the unique anomaly of nonlinear force driven plasma block acceleration with ps pulses for volume ignition. Total gains of 200 for MJ laser pulses are expected.

1. Volume Ignition
Numerical studies of the adiabatic compressions and expansion of spherical DT pellets led to the discovery of volume ignition due to self heating of the plasma by the fusion reaction products and by partial re-absorption of bremsstrahlung [1,2]. Ignition happened as soon as the gain $G$ (fusion energy per input energy $E_o$ into the compressed plasma of maximum density $n_o$ in multiples of the solid state density $n_s$) was exceeding the value 8. Below this gain there was only the slightly corrected volume burn following the relation

$$G = \left(\frac{E_o}{E_{BE}}\right)^{1/3} \left(\frac{n_o}{n_s}\right)^{2/3}$$

(1)

where $E_{BE}$ is the break-even energy of 6 MJ for DT at the optimum temperature of 17 keV [1; Eq. (13.7) of Ref. 3]. Self-heat and re-absorption led to a change of the cubic root in (1) to linear increase above $G=8$ until about $G=800$ when the fuel depletion caused a saturation of $G$ [4]. A refinement of all this by inclusion of the heating by the fusion neutrons led to even higher gains due to higher ion heating [5] while the electron temperature was much lower due to insufficient time for equipartition and even lower background Planck radiation [6: Fig. 4] as Martinez-Val et al discovered [5].
Further evaluations of volume ignition [6-9] led to the result that volume ignition arrive at nearly the same very high fusion gains as the rather complicated spark ignition [10] and that the natural adiabatic compression results in “robust” conditions to avoid instabilities and asymmetry problems known from spark ignition [7]. The highest ever measured fusion gains were reproduced by the theory of volume burn before ignition in agreement with Eq. (1) for $G<8$ [7: Fig.8]. When measurements of laser compression of polyethylene arrived at 2000 times the solid state [11] with the then highest fusion gains, the disappointingly low maximum plasma temperature of 3 Million degrees was tried to be overcome by introduction a two-step laser irradiation (fast igniter FI [12]). But it was discovered that a very low ignition temperature of few hundred eV is automatically possible [8] by a single-step irradiation of ns laser pulses if the input laser energy $E_L$ is in the range of many MJ and the compression is several thousand times the solid density $n_s$, though these MJ pulses for $E_L$ even may simplify the conditions compared to the measurements [11] with $E_L$ of less than 20 kJ.

2. Laser beams smoothing for direct drive
The very high plasma compression by laser ablation and the record high fusion gains [11] were possible only by using Kato’s et al random phase plates [13] for smoothing the laser beams. This led to the suppression of the stuttering (randomly pulsating around 10 ps) interaction of the laser light with the plasma [3: Sect. 10.8] and a highly efficient incorporation of laser energy into the plasma corona for the heating and compression by thermal ablation. The stuttering was detected before by several groups and the smoothing e.g. by broad band lasers beams [14] was clarified numerically in all details [15].

![Fig. 1 Volume ignition fusion diagram [8] with ranges ❶ for high gain single-pulse MJ-ns laser fusion, ❷ for direct drive NIF conditions, and ❸ for single pulse ps plasma block spherical shell ignition.](image)
The action of the smoothing was first aimed to reduce filamentation as it was demonstrated visibly by Labaune et al [16] but there were also the stuttering structures and their suppression by the sufficiently fine random phase plates [17]. As expected [15] long before, the parametric instabilities as measured from the 3/2 harmonics emission were reduced by much more than a factor 100 (!) [18]. This was a visible way how stuttering and parametrics were eliminated by smoothing [15-19]. The advanced smoothing [19] will be the main ingredient for future success of direct drive laser fusion. The volume ignition [1-9] has been clearly recognized for the developments of laser fusion under NIF conditions [20] with optimised smoothing [21].

3. Single-shot with nanosecond laser pulses
We now discuss the conditions for volume ignition fusion gains using direct drive NIF-like nanosecond single-shot laser pulses following the volume gain diagram [6] in Fig. 1. In the preceding paper [8], it was discussed, how ns-10MJ laser pulses with plasma compression up to 10,000n, by single shots may lead to the parameters for a fusion power station. This is located near the range ❶ in Fig. 1. Using a laser pulse of 10 MJ and compression 5000n, and assuming optimistic 10% hydrodynamic efficiency (90% of the laser pulse needed for the gas dynamic ablation of the plasma corona for the pellet compression) results in a total gain (fusion energy per energy of the applied laser pulse $E_L$), $G_L$ is then 80. If the compression would be 10,000n, the total gain is 120.

For NIF conditions we assume an energy $E_L$ of the laser pulse of 3 MJ. We let the question open whether green or blue laser light is being used, or even the fundamental red neodymium glass laser frequency what was considered possible at appropriate smoothing by avoiding losses with the harmonic generation. Realistically taking a hydro-efficiency of 5% and a DT fuel compression to 2000n, as shown before [11], the total gain is 11 after the gain $G$ is 170, see ❷ of Fig. 1, which is well within the ignition range. The total gain of 11 is expected also when using spark ignition [10].

4. Picosecond driven plasma blocks
The fast ignition option [12] for overcoming the too low temperature of the 2000 times solids compressed plasma [11] led to the development of lasers with ps duration and 2 PW (petawatt) power [22]. For next developments, powers of several 10 PW up to EW (exawatt) are considered [23]. An exceptional anomaly was observed since TW laser pulses of ps duration were available where measurements by Sauerbrey, by Zhang et al. and Badziak et al. [24] were extremely different from all the numerous usual observations of extremely relativistic effects. Since highly general numerical one-dimensional computations by Hora et al in 1978 [3: Sect.10.5] had resulted in the observations [24] of the anomalies, it was evident, that the anomalies are due to the fact that relativistic self focusing was avoided. This was confirmed in the experimental details [24] following the first realization of the effect [25] due to the fact that a very high contrast ratio was preventing relativistic self focusing.

One consequence is that space charge neutral plasma blocks produced in the surface area (skin layer) of the plasma by nonlinear force acceleration of cold, highly directed plasmas, generate ion current densities exceeding $10^{11}$ Amp/cm². This result was numerically well known [24: Fig. 1] and the conical concentration of these plasmas may lead to ignite fusion flames in modestly compressed DT fuel. Alternatively it was proposed before that these low temperatures and highly directed plasma shells [26] could be used for highly efficient fusion
of spherically compressed DT plasmas, see Fig. 5 of Ref. [26]. The advantage is that the nonlinear force of direct and non-thermal laser-plasma interaction is providing an ablation with 50% efficiency in contrast to the efficiency of about 5% for the thermal ablation for plasma compression. More details are in a separate paper [27].

This will result again in a single-shot laser fusion process for which case the range $\Theta$ in Fig. 1 shows the interaction of a neodymium glass laser pulse of one MJ energy and 3 ps duration (333 PW power) producing an initially compressing DT layer with modest swelling with a factor 5 after irradiating a sphere of 3.27 cm radius. This shell collapses to a plasma core of density $2000n_s$. With the optimum temperature of 1.4 keV for volume ignition this results in a total fusion gain of 200. It should be mentioned that this efficient nonlinear-force driven fusion with ps laser pulses is basically different from a thermokinetic driven impact ignition scheme using ns laser pulses [28] though the exceptional compression by a factor 15 at plane wave interaction [29] is anomalously new.

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