Cluster Induced Ignition - A New Approach to Inertial Fusion Energy

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Abstract: An ultra intense laser interaction with clusters produce energetic ions and electrons in MeV range due to cluster explosion. Here we discuss the possibility of harnessing these particle energies to heat a part of the pre compressed DT fuel to ignition condition. In this article we are striving to present the principle concept and the preliminary results are discussed.

Introduction

The concept of Inertial Fusion Energy (IFE) has under gone several modifications since its inception. Direct drive, indirect drive (hohlraum target), light and heavy ion driven fusion, fast ignition concept have been pursued with certain amount of success in this direction. However, no final scheme has been accepted for attaining the required fusion energy gain. The fast ignition concept [1], rather a latest addition in the series, separates the formation of a hot spot for fuel ignition from the main DT fuel assembly. Encouraged by the recent study on the generation of energetic ions and electrons due to ultra short laser interaction with clusters, here we propose a new approach referred as ‘Cluster Induced Ignition’ (CII) which is relevant to Inertial Fusion Energy. The proposed scheme draws the advantages from direct drive and fast ignition. Recent progress in experimental and simulation work on the generation of energetic particles in the range of a few MeV due to cluster explosion is the basis for the proposal.

A simple sketch of CII proposal is shown in fig. 1. This is also a two phase process. In the first phase DT fuel is compressed due to ablative implosion induced by a set of high power laser beams (called as ablation laser beams) irradiated symmetrically on the DT filled spherical target which is attached with a cone as shown in fig. 1a. Such cone arrangement is being discussed recently in context with fast ignition studies and can be used in the present scheme. At present it is not clear how the presence of the cone will affect the implosion. Success of direct drive in attaining a fuel compression of 600 times the solid density has been already established [2] by the Osaka group using 0.53 μm laser radiation with 9 KJ energy on the CDT shell targets. In the second phase when DT fuel is nearing an optimum compression, clusters are generated (for instance using a gas jet) in the vicinity of the edge of the compressing fuel. An ultra intense laser beam (now called as ignition beam) with intensity $I \sim 10^{20}$ W/cm^2 interacts with the clusters such that when DT fuel attains its maximum compression, the energetic ions and electrons are generated due to cluster explosion. All these operations need to be synchronized in sub-ps time scale.

The necessary condition for fuel ignition is that the areal mass density ρR should be of the order of ~ 0.3- 0.4 g/cm^2 at 5 KeV temperature. This corresponds to an α-particle range which is necessary for self heating of the DT fuel. The imploded core attains a nearly uniform density structure due to mixing of the fuel in the final compression zone [3]. Therefore a separate ignition spark concept has the credit of overcoming the problems associated with the pusher fuel mixing in direct drive scheme. According to Tabak et al. the fast ignition scheme does not rely on central hot spot ignition, hence mixing the main fuel with the hot spot can not quench ignition [1]. By simulations it has been shown that in fast ignition, ignition conditions are rather insensitive to the position of the spark in the compressed core [4]. Simulations related to ignition of a spherical DT core are reported for various compressed fuel densities in the range of 200-600 g/cm^3 [3]. According to these simulations, the minimum ignition energy required is 1.5 kJ for a compressed core density of 600 g/cm^3 and heating time is less than a picosecond; and the energy requirement increases with increased heating time. In an another report by Atzeni, a higher ignition energy of the order of 10 kJ has been estimated [1] and we assume such value to be conservative but effectively it may be lower. In CII scheme, we have the advantage of energetic charged particles to heat the DT fuel in sub-picosecond time scale as cluster explosion due to high intensity laser interaction takes place on a few femtosecond time scale. However, with the current technology, the development of laser systems which can deliver 10 kJ at $I \sim 10^{20}$ W/cm^2 seems to imply a laser pulse duration of at least a few ps. In this case this will be the minimum duration of ion source. This is not a real drawback since it corresponds to what is already predicted for fast ignition.

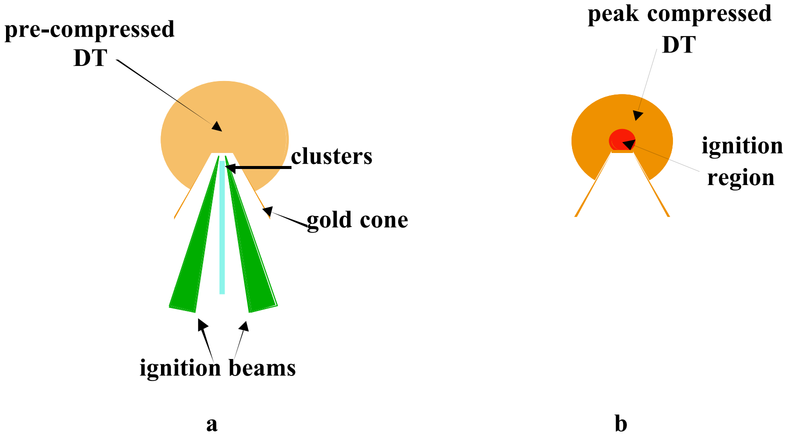

Fig. 1: Cluster Induced Ignition: a) ignition laser beam interaction with clusters for the generation of energetic electrons and ions; b) creation of an ignition region.

Generation of energetic particles

Recently, generation of energetic particles with energies exceeding few MeV has been reported by several authors [10,11,12] due to laser interaction with clusters (≥1000 atoms). Clusters undergo Coulomb explosion giving rise to energetic ions. 1 MeV Ar ions have been experimentally produced at $I \sim 10^{18}$ W/cm^2. By using a 3D fully relativistic particle in cell code, it has been shown that at $I = 10^{20}$ W/ cm^2, Ar^{+9} ion can attain ~ 13 MeV and 30 MeV at ~ 100 and ~180 fs after the laser cluster interaction [10]. When an argon cluster explodes corresponding to a laser intensity (~10$^{19-20}$ W/cm^2), ions of energy ~ 12-13 MeV and electrons of ≈ 1 MeV energy can be extracted. For simplicity we assume a minimum of ~15 MeV (~10^{-12} J) energy is released per atom due to the explosion of an Ar cluster. Since in cluster explosion energetic ions and electrons are simultaneously produced, both will contribute to heat the fuel at the same time.

A suitable way of producing clusters could be the use of gas jets. When a high pressure gas expands into vacuum through a nozzle, expansion is isotropic. Solid density clusters are formed due to cooling associated with the adiabatic expansion of the gas in to vacuum. This cooling causes the gas to supersaturate and nucleate. Effect of gas pressure, temperature, nozzle size on the cluster formation has been discussed in ref. [5]. Onset of the clustering and size of the cluster can be estimated using the Hagena formula [6,7], $T^*=k(d/\tan\alpha)^{0.85}\ P_o/T_o^{2.29}$ where d is the jet throat diameter in μm, α is jet expansion half angle = 45^0 for sonic expansion, P_o = backing pressure in mbar, T_o is initial gas temperature and k is condensation parameter which depends on atomic species; k [8] for Xe = 5500, Kr = 2850, Ar = 1650, Ne = 185, He = 3.85, D_2 = 181, H_2 = 184 etc. A density of 10^{24} molecules / m^3 for a collimated hydrogen cluster beam traveling through a vacuum with $5x10^{16}$ molecules /m^3 has been reported [6]. Absorption of laser light by clusters is very high; ~ 100% in Ar and Xe gas clusters at high backing pressures [9]. At present, ultra intense laser cluster interaction physics is reasonably understood.

Ignition conditions in pre-compressed DT fuel

Initial temperature of the compressed DT fuel in the direct drive scheme depends on various factors like the uniformity of compression, growth of instabilities, mixing of hot and cold DT fuel etc. for optimized laser parameters. In the present calculations we assume ~100 eV as the initial temperature of the compressed DT and the temperature increases with the subsequent absorption of ions and electrons. The range of ions (E = 10 MeV) is shown in fig. 2 and the range of electrons (E = 1 MeV) for a compressed DT fuel density of the order of 200-600 gm/cm^3 is presented in fig.3. As seen from fig.2, the average range of 10 MeV Ar^{+9} ion in a DT fuel of~ 600 ρ_s is ~ 3 μm at 5 keV, and that of 1 MeV electron is ~2 μm. Thus an ignition spark with an average range of ~ 3 μm around the exploding clusters can be created in the pre-compressed DT fuel, the alpha particles generated in the ignition spark will traverse the fuel with a range determined by the density of the surrounding DT fuel and the burn wave propagates. As the generation of energetic electrons and ions is simultaneous, absorption of these particles inside the DT fuel also starts at the same time. For 1 MeV electrons at ρ = 600 ρ_s and 5 KeV temperature, the stopping time has been estimated as 85 fs by Deutsch et al [13] defining the stopping time as the time required for a particle to loose 90 % of its initial energy. We assume that the absorption range of these charged particles forms a hot plasma volume with the main fuel as in fig. 1b and this will create an ignition spark in the pre-compressed DT fuel on a sub-picosecond time scale as discussed below.

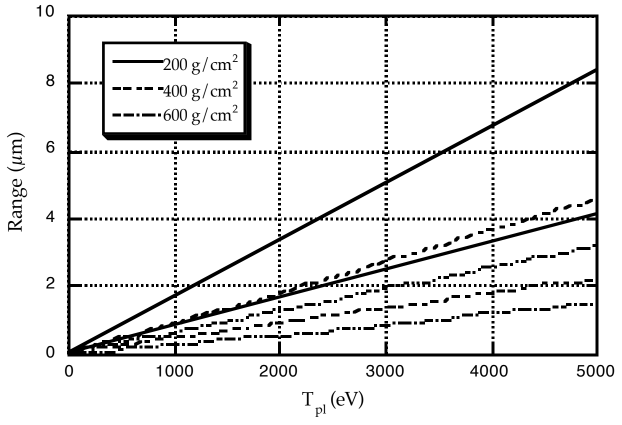

Fig.2: Minimum and maximum range of a 10 MeV Ar^{+9} ion at different DT densities as a function of pre-compressed DT temperature.

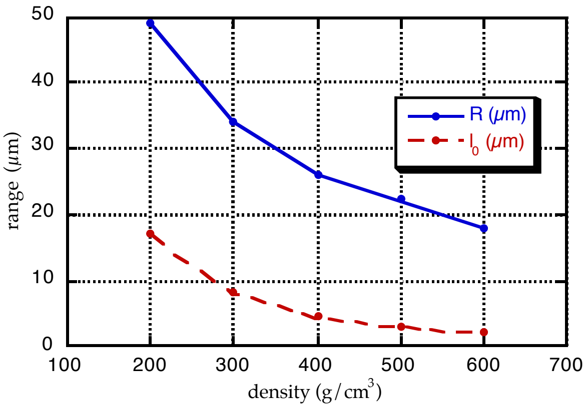

Fig. 3: Range of 1 MeV electron at different pre-compressed DT densities.
Solid line = total stopping range, dashed line = maximum penetration inside the target.

In the first approximation, we assume a complete conversion of the kinetic energy of the energetic particles into thermal energy of the compressed DT fuel. We can estimate the number of cluster explosions required to obtain the required ignition energy. If the fuel has to be heated to 10 KeV in the ignition region, the required energy to be supplied is $\approx$ 10 KJ. The required number of energetic ions (~15 MeV) to obtain $\approx$ 10 KJ ignition energy are ~10^{16}. We define the efficiency of a cluster as the ratio of the number of atoms which undergo Coulomb explosion to the total no. of atoms in the cluster and we assume ~ 80-90 % as Coulomb explosion efficiency [8]. If we can generate clusters with an average of ~10^{4} atoms per cluster then the required number of cluster explosions are ~10^{12}. Therefore a suitable irradiation of the required number of clusters in a given volume by ultra intense laser beams is necessary to deliver the energetic particles simultaneously to a part of the pre-compressed DT fuel. This will heat the DT fuel to ignition conditions as per our preliminary calculations. It could be advantageous to use few symmetrically and closely placed laser beams and irradiate the clusters simultaneously. This will also reduce the load on the high energy requirement in a single laser beam.

Merits of the Cluster Induced Ignition - CII scheme

The main merit of the proposal is that some of the prerequisites have been already achieved viz.1. High compression of DT fuel ~ 600 times the solid density in direct drive. 2. Generation of clusters is a well established technique and can be further improved on the need basis. 3. Although physics of ultra intense laser interaction with clusters is reasonably understood, new physical phenomenon could appear at 10^{20} W/cm^{2} in particular in connection with the presence of strong ponderomotive forces. 4. At present peta watt lasers are available or under development in various laboratories. Therefore we can clearly discuss the advantages of CII scheme. 1. Energetic ions and electrons of MeV range are simultaneously available to heat the compressed fuel to create ignition zone. 2. Energetic particles release the energy to the ignition zone in a sub-picoseconds after laser cluster interaction. Therefore heating of the ignition zone is rapid. 3. X-rays are generated after the cluster undergoes Coulomb explosion i.e. after the emission of energetic particles. Therefore, further preheating of compressed DT fuel by X-rays can be completely avoided. 4. Laser absorption by the cluster is ~ 100 % and Coulomb explosion efficiency is ~ 80-90 % implies, nearly 80-90% of the laser energy goes into the kinetic energy of the energetic particles. Thus, coupling efficiency of laser to energetic particles is quite high.

Our preliminary calculations show that the required ignition energy ~ 10 KJ could be obtained from energetic ions generated by the explosion of a suitable number of $\sim 10^{12}$ clusters each containing ~ 10^4 atoms. These numbers do not appear to be out of reach with the achievable technology developments. A major issue of this scheme, however, is the possibility of depositing ion and electron energy in a small region of the compressed DT fuel which becomes the ignition spark. This depends on the range of the energetic and electrons/ions and α-particles in the compressed fuel which appear to be adequate from our preliminary calculations. We are currently working on the issues which are crucial to judge the feasibility of the proposed CII scheme.

Conclusions

In conclusion, 'Cluster Induced Ignition-CII' could be a new approach to the Inertial Fusion Energy scheme. This concept is drawn on the practical merits of direct drive, fast ignition and cluster explosion. Further study is necessary to harness the benefits of this concept. Finally, in this article we are striving for the principle concept rather than the quantitative accuracy. Details of the work will be published elsewhere.

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