Nuclear probes of an out-of-equilibrium plasma at the highest compression

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\textbf{Abstract}

We report the highest compression reached in laboratory plasmas using eight laser beams, \(E_{\text{laser}}\approx 12\) kJ, \(\tau_{\text{laser}}=2\) ns in third harmonic on a CD\(_2\) target at the ShenGuang-II Upgrade (SGII-Up) facility in Shanghai, China. We estimate the deuterium density \(\rho_D = 2.0 \pm 0.9\) kg/cm\(^2\), and the average kinetic energy of the plasma ions less than 1 keV. The highest reached areal density \(\Delta \rho_D = 4.8 \pm 1.5\) g/cm\(^2\) was obtained from the measured ratio of the sequential ternary fusion reactions (\(\text{d}+\text{t+p}\) and \(\text{t+d}+\text{n}\)) and the two body reaction fusions (\(\text{dd} \rightarrow \text{He+n}\)). At such high densities, sequential ternary and also quaternary nuclear reactions become important as well (i.e. \(\text{n}(14.1\) MeV) + \(^{12}\text{C} \rightarrow \text{n}+^{12}\text{C}\) etc.) resulting in a shift of the neutron (and proton) kinetic energies from their birth values. The Down Scatter Ratio (DSR-quaternary nuclear reactions) method, i.e. the ratio of the 10-12MeV neutrons divided by the total number of 14.1MeV neutrons produced, confirms the high densities reported above. The estimated lifetime of the highly compressed plasma is 52 ± 9 ps, much smaller than the lasers pulse duration.

The understanding of the fascinating supernovae explosions\textsuperscript{[1] [2] [3] [4]} as well as the social requirement of clean, cheap and easily available energy\textsuperscript{[5]} obtainable from nuclear fusion power plants requires the microscopic understanding of the nuclear reactions in plasmas. Especially for hot and very dense plasmas, such as in the interior of a star, or in a highly compressed nuclear fuel, it is crucial to know the probability of fusion and the range of the ions at the density and temperature of the system. Fusion reactions are usually measured in beam-target experiments and are reliable for relatively large beam energies. At low beam energies, the probabilities are extrapolated from higher energies through direct\textsuperscript{[5] [6] [7] [8] [10] [11]} and indirect methods\textsuperscript{[10] [11] [12] [13] [14]}, such as the Trojan Horse method (THM), the asymptotic normalization coefficient (ANC) and the Coulomb dissociation method (CD), but all these methods do not guarantee that in the hot and dense plasma the fusion reaction process is not influenced by the motion of the electrons and the other ions. Furthermore, the range of the ions in the plasma is quite different from the range in a cold target. We can express the probability of fusion as:

\[
\Pi = 1 - e^{-\Lambda/\lambda} = 1 - e^{-\Delta \rho \sigma} \approx \Delta \rho \sigma
\]

which contains all the ingredients needed for understanding the dynamics of fusion in the plasma. \(\Lambda\) is the range of the ion in the plasma, i.e. the distance travelled by the ion before loosing its kinetic energy; it is relatively well known and understood in cold targets as the slowing down of the ions due to electromagnetic interactions (plus nuclear processes at high energy)\textsuperscript{[15]}. \(\sigma\) is the fusion reaction cross-section and depends on the center of mass (C.M.) energy of the colliding ions and it is usually measured in beam-(cold) targets experiments\textsuperscript{[10] [11]}. New methods to measure these quantities directly in the plasma have been recently investigated using a petawatt laser impinging on a cluster target. Fusion cross sections for \(\text{d}+^{3}\text{He}\)\textsuperscript{[16]}, \(\text{d}+\text{C}\)\textsuperscript{[17]} and the range\textsuperscript{[18]} have been measured also in the cases where the system is prepared near the critical point for a liquid gas phase transition\textsuperscript{[19]}. While the fusion cross sections have been found in reasonable agreement with accelerator experiments, the range showed some dependence on the cluster distribution, which in turn depends on the
The typical density in these experiments is of the order of $10^{18} \text{ cm}^{-3}$, the target size around 0.5 cm and the temperature of the plasma tens of keV. Strong non-equilibrium effects did not prevent a good understanding of the plasma dynamics and a precise measurement of the ingredients entering eq. (1). Careful methods might be devised to keep the system as close as possible to equilibrium for instance using several laser beams to compress and heat a target to infinity. Nevertheless, important out of equilibrium effects might still be present and prevent the optimization of nuclear fusion reactions towards a prototype of a nuclear reactor. Stimulated by these considerations we decided not to fight non-equilibrium effects but rather enhance them, i.e. study plasmas highly compressed and completely out of equilibrium. A scheme for a colliding beam fusion reactor has been proposed as well. Recent experiments have also shown a substantial increase in the number of fusions using the Target Normal Sheath Acceleration (TNSA) mechanism, which utilizes short pulse lasers to accelerate light ions on a cold target or on a plasma. In previous experiments at the ABC laser facility these features have been explored using two laser beams strongly focalized on a flat and thin target from opposite directions. Microscopic simulations for out of equilibrium systems suggest that opportunistically choosing the target size and material, it is possible to reach high densities where catastrophic nuclear process might occur. A problem might occur if the system is also not locally neutral (a large number of electrons are extracted from the target at the beginning of the laser-target interaction) which might influence the fusion probability and in particular decrease it as compared to beam-cold target experiments. These non-equilibrium effects might not be properly included in hydrodynamical simulations thus reducing their predictive power. Strong (anti) screening effects might be at play and hinder the nuclear reaction rates as well.

At the SGII-Up laser facility, 8 beam lasers can be used to obtain exactly what we discussed above. A schematic view of the target chamber with the 8 laser mirror guides is given in fig. 1b. Using 4 beams impinging on a flat target from the top (t), and 4 laser beams impinging from the bottom (b), we can obtain a beam of ions moving from t to b, and another beam of ions moving in the opposite direction (b to t). In fig. 1c, we display a schematic view of the target geometry where the laser beams hit the target surface of radius R. The laser is focalized at the center of the CD2 target with a radius r. For very thin targets $R \approx r \approx 150 \mu \text{m}$, presently the highest possible focalization at SGII-Up. The thickness h (as well as r and R) was varied to optimize the number of fusions and to prove that effectively beam-beam collisions are occurring. For h→∞, we expect the laser beams to act independently, i.e. produce ion beams, which are reflected back. To find the optimal thickness for which the ion beams ‘follow’ the laser direction, we broke the cylindrical symmetry by using 3 laser beams on t and 4 beams on b for some shots. The target thickness was varied from 1mm to 3.6 µm and the focalization varied from 150 µm to 400 µm. The number and energy of the produced ions were measured using faraday cups (FC) located in the t and b directions at 2.9m distance, see figure 1. Other FCs were located at different angles in the same plane of the target, which we indicate as north-south (NS) plane. Thomson parabolas (TP) with image plates (IP) at the focal plane. Bubble detectors (BD) were used to measure the number of fusions close to the target. Liquid and plastic neutron detectors (ND) were located outside the scattering chamber at different distances to measure neutrons and they were calibrated on the BD. A schematic view of the chamber with the location of the detectors is given in figure 1.

The ‘trick’ of using 4 and 3 laser beams respectively demonstrated that even for the thickest target, 1mm, the ion beams follow the laser direction. In fact the FC located in the opposite direction of the 4 laser beams showed higher ion signals. For these ‘asymmetric’ shots, the total laser energy was about 12 kJ and the pulse duration 2 ns. The FC located in the NS plane gave essentially no signal, demonstrating the high directionality and out of equilibrium nature of the plasma. The TP gave no signal as well, thus suggesting that no ions of kinetic energy above roughly 100 keV (the minimum energy for which the image plate are sensitive) were produced in the NS plane. SGII-Up facility offers also the possibility to vary the lasers energy and the pulse duration by keeping the power constant. Thus we varied the laser energy from about 19 kJ in 3 ns to 2 kJ in 250 ps. Highest compressions were found with the longest pulse duration giving about $10^8$ neutrons, while the highest plasma ion kinetic energies were found with the shortest pulse duration and lower neutron yields of the order of $10^7$.

In figure 2 (a) we show the signals obtained from the t
and b FC and (b) the typical signals obtained from the TP (b): p, d and the six charge states of C are visible. For this shot, h=3.6 µm, r=150 µm, and laser pulse duration 0.5 ns. The distribution plotted in fig.2a demonstrates that we obtained kinetic energy of protons (p) (an impurity of the CD$_2$ target) and deuteriums (d) of the order of MeV.

For the moment we would like to focus on the fact that long laser pulses, say 3 ns, produce high ion yields with kinetic energies of the order of 1 keV, while short pulses produces >100s keV ions with small yield.

In a CD$_2$ target, fusion reactions might occur if the kinetic energy of the colliding deuterium ions is sufficient to overcome the Coulomb barrier. An optimal energy for this system is of the order of tens to hundreds of keV. Our attempts above changing the lasers pulse duration, had the intent to optimize the resulting ions kinetic energies and maximize the number of fusions. In the plasma, the main fusion channel reactions are

\[ d + d \rightarrow t + p \quad Q = 4.03 MeV \]
\[ d + d \rightarrow ^3He + n \quad Q = 3.27 MeV \]

These reactions occur with the same probability, and we refer to these as two body fusion reactions $N_2$. The yield is given by:

\[ N_2 = N_i \left( \prod_{dt} / 2 \right) \]

$N_i=\rho_0 V$ is the total number of ions which can be calculated from the CD$_2$ initial density $\rho_0$ and volume $V$ of the target given by the cylinder of thickness $h$ and radius $r$, (fig.1b). $\left( \prod_{dt} \right)$ is the average of eq.(1), and it depends on the ion kinetic energy distribution. If the plasma is in thermal equilibrium, the factor 2 is needed for identical ions. The energetic neutrons (2.45 MeV) can be measured using the ND. The produced t and $^3$He have kinetic energy slightly below 1 MeV and the probability of fusion for such energies ($\sigma(dt)=0.4b=4e^{-25cm^2}$) is quite large and well known from the literature. Thus we can have ternary fusion processes i.e.:

\[ t + d \rightarrow \alpha + n \quad Q = 17.59 MeV \]
\[ ^3He + d \rightarrow \alpha + p \quad Q = 18.35 MeV \]

This is the onset of nuclear catastrophic reactions, i.e. reactions that can release large energy in the plasma and warm it up. The number of fusions $N_3$ can be easily calculated as above:

\[ N_3 = N_2 \left( \prod_{dt} \right) = N_2 \left( 1 - e^{-\Delta \rho dt} \right) \]

similarly for the other reaction. Notice that in this case we have no average sign, in fact the t($^4$He) has 1.01 MeV kinetic energy and the plasma kinetic energy is relatively low (about 1 keV in the best cases) and can be neglected. Using the ND we can measure the 14.1 MeV ($N_3$), the 2.45 MeV neutrons ($N_2$), see methods. Since all the quantities entering equation (3) are known or measured, we can invert the equation and derive the areal density $\Delta \rho$ shot by shot. Thus with this method we use nuclear reactions to measure the areal density at the time of maximum compression where we expect the ternary yield to be highest. In the scenario described here we got a ratio $N_2/N_3\approx5$ in some shots revealing a tremendous compression! In these cases the total energy release from ternary fusion reactions is comparable to the two body fusion reactions taking advantage of the large Q-value. This is an extremely important result since further compressions (with more laser energy or other features) might decrease the ratio even more[32], thus fuel targets might be prepared with smaller concentration of the radioactive tritium for applications.

An example of the neutron measurement is displayed in figure (c), obtained using a plastic scintillator BC420, with 5cm thick lead shielding, located at $L=3.3$ m from the target. For this shot, the target thickness $h=79$ µm, focalization $r=300$ µm, total laser energy 18.7 kJ and pulse duration 3 ns. The raw time of flight (TOF) spectrum (opportune divided by the detector distance L) is given in the inset. It shows a strong EMP for very short times, followed by a small bump corresponding to the 14.1 MeV neutron and a huge bump at longer times (2.45 MeV). The decay time of the EMP is a characteristic of the detector.
and associated electronics and can be parameterized as an exponential decay. A ‘clean’ spectrum can be obtained after subtracting the exponential decay and it is plotted in the figure. The TOF/L is converted in neutron energy in the top axis. The two neutrons peaks are clearly visible showing that the 14.1 MeV peak is quite comparable to the 2.45 MeV, a signature of the high compression. An important feature is that the first peak seems shifted from the 14.1 MeV birth value suggesting that neutrons collide with other ions before exiting the dense plasma. Thus quaternary collisions are important as well and we will examine them more in detail below.

Figure 3: (color online) Fusion yield as function of laser energy. Different experimental results Ditmire-2004 [50], UT-2011 [20], UT-2016 [19], Fu-2015 SGII [11], Dittrich-1994 [15], NIF-2014 [44] Osaka-2001 [22], Osaka-2004 [43], OMEGA-shot5241 [37] and SGIIIpro2017 [38] are indicated in the inset.

In optimal conditions to warm up the plasma, we need the neutrons to release most of their kinetic energy, thus $N'_{3} < N_{3}$ which after some simple algebra leads to the condition: $\Lambda \rho_{\sigma}(nC;nD;...) > \ln 2$. The reaction cross-section of $n$ with C, D, H and other ions are known. We can define an average reaction cross-section over the C and D content of our CD$_{2}$ target taking into account their concentrations. For the 14.1 MeV, we obtained a total cross section, $\sigma_{TCD} = \sigma_{nC} + 2\sigma_{nD} = 1.5 b + 2 \times 0.85 b = 3.2 b$. From the quaternary collisions we can also obtain an estimate of the areal density using the Down Scattering Ratio (DSR), the ratio of the number of neutrons with energy between 10 and 12 MeV ($N_{3}$) divided by the total number of ternary fusion reactions ($N_{3}-14.1$ MeV neutrons): $\rho_{\Lambda} = (20.4 \pm 0.6)\text{DSR}$. The temperature can be obtained assuming, for sake of comparison to other data, that at the time when neutrons are mostly produced (at the highest compression) the plasma is in equilibrium. From the number of two body fusions and the ratio of ternary to two body fusions we can obtain the average dd fusion cross section, see the appendix. In figure 4 we plot the quantity $\Lambda \rho_{\sigma}/\ln 2$ obtained from eq. (4) vs T from eq. (1) and eq. (2). If this quantity is much larger than one then most of the 14.1 MeV neutrons: $\rho_{\Lambda} = (20.4 \pm 0.6)\text{DSR}$. The NIF results are located one, apart one shot obtained with the smallest laser energy and pulse duration. The NIF results are located one, apart one shot obtained with the smallest laser energy and pulse duration. The NIF results are located one, apart one shot obtained with the smallest laser energy and pulse duration.
In conclusion, in this paper we demonstrated the reaching of record areal high densities in laser compressed plasmas adopting cylindrical symmetry. The ratio of the 14.1 MeV and the 2.45 MeV neutrons gives a direct information of the areal density $\Delta \rho_D$ [39, 40], confirmed by the DSR method mostly in use at the Omega and the NIF laboratories. If we further assume that the range is equal to the thickness of the target at maximum compression, similar to the UT results [15, 19], we can write $\Lambda \approx N_1^{1/3}/\rho_D^{1/3}$ apart a coefficient of the order of one. The maximum observed areal density in our shots was $\Delta \rho_D = 4.8 \pm 1.5$ g/cm$^2$, $N_1 \approx 2.3 \times 10^{18}$ thus $\Delta \rho_D = 2.0 \pm 0.9$ kg/cm$^3$, using the relation between $\Lambda$ and $\rho_D$. The ions kinetic energy is about 0.6 keV from which we can obtain an average velocity $v = \sqrt{2T/m_d}$; a characteristic time $\Lambda/v = 52 \pm 9$ ps can be associated with the plasma lifetime at maximum compression or the beam-beam crossing time. It can be compared with the bang time obtained at NIF [21] of the order of 150 ps. Longer plasma lifetimes imply more fusion reactions and this must be balanced with the higher densities obtained with our geometry. An optimal determination of all these factors may optimize the efficiency of nuclear fuel burning.

Appendix

From eq.(1) and eq.(2), we can derive

$$\langle \sigma \rangle_T = -\ln \left(1 - \frac{N_2}{2N_1}\right) / \Delta \rho.$$  \hspace{1cm} (5)

Since $N_2$ (from ND), $\Delta \rho$ (from the ratio $N_3/N_2$) and $N_1$ (from geometry) are known, we can derive $\langle \sigma \rangle_T$ for each shot. Assuming that the cross-section is not modified by the plasma environment, we can derive the corresponding $T$ [2] if we assume the plasma to be in equilibrium or the C.M. energy of the colliding ions if it is out of equilibrium [22]. In the case of beam-beam collisions, half of the ions travel in one direction and half in the opposite one, thus a further factor of 2 is needed in eq.(3) and the average is over very narrow ion distributions in energy and angle as in our case. Since we are going to use this result for the purpose of comparison to other experiments, we derive an effective $T$ from $\langle \sigma \rangle_T$ obtained inverting eq.(1) (the x-axis in figure 4), as expressed by eq.(4) and shown in figure 5. Using the steepest descent method, one can get the average cross section as function of temperature from the Maxwell-Boltzmann distribution [31].

$$\langle \sigma \rangle_T = \frac{4 \cdot S}{\sqrt[3]{\pi}} e^{-\frac{3E_G}{T}}.$$  \hspace{1cm} (6)

For $d + d \rightarrow ^3He + n$ reaction, a constant S-factor $S = 54.4$ keVb is set and $E_G = (\frac{3E_G}{2})^2$ is the Gamow energy. The ratio $N_2/N_3$ is obtained by integrating the neutron signal from 14.1 MeV to 2.5 MeV ($N_3$) and below 2.5 MeV up to 1.0 MeV for $N_2$. The largest error comes from the minimum energy adopted to estimate the 2.45 MeV. This is due to the fact that 14.1 MeV and 2.45 MeV might be shifted down below 2.45 MeV. Furthermore, some neutrons might be bounce back neutrons of any energy depending on their trajectory and detector distances. Thus we estimated the 2.45 MeV by integrating the signal down to 1 MeV in one case and to 0.25 MeV in another case. We averaged the results and estimated the resulting error in about 30%.

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References

[1] E. M. Burbidge, G. R. Burbidge, W. A. Fowler, F. Hoyle, Rev. Mod. Phys. 29 (1957) 547.
