Coulomb cluster explosion boosted by a quasi-dc pulse—diagnostic tool and ultimate test of laser fusion efficiency in clusters

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To greatly enhance output of nuclear fusion produced neutrons in a laser-initiated Coulomb explosion of Deuterium clusters, we propose to subject the ions produced by the explosion to quasi-dc electrical pulse, to accelerate them to the energies where the \( D^+ + D \) collision cross-section is the highest. With \( D^+ \) ions shepherded then to bombard a Deuterium-rich solid-state cathode, this allows one to solve a few problems simultaneously by (a) completely removing electron cloud hindering the Coulomb explosion of ionic core, (b) utilizing up to 100% of the cluster ions to collide with the high-density packed nuclei, and (c) reaching maximum cross-section of neutron production in a single \( D^+ + D \) collision. We also consider the use of E-pulse acceleration for diagnostic purposes.

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Nuclear fusion reactions in solid-deuterium laser-produced plasma were first observed 45 years ago [1]. Recent development in laser technology and generation of neutrons is laser-induced explosions, ionization in very localized objects, such as deuterium clusters [2] with a conversion efficiency up to \( \sim 2 \times 10^6 \) neutrons/J [3]. A major mechanism there is Coulomb explosion, CE [2-5] of e.g. deuterium \( (D) \) nano-clusters resulting in sufficiently high energy ions colliding with each other. The CE occurs when an irradiated cluster undergoes rapid and high ionization of its atoms, while free (ionized) electrons ideally almost instantly swept away by the laser. The ionic core is then torn apart by repulsive Coulomb forces resulting in CE, part of which is formation of shock-shells in expanding ionic cloud predicted in [6], explored in detail in [7] and most recently observed experimentally with an individual cluster in [8]. In general, however, there could be some other mechanisms of cluster explosion, such as e.g. the quasineutral microplasma model [8], hydrodynamic model [9], etc., more characteristic for lower laser intensities \( (\sim 10^{15} W/cm^2) \). While the generation of neutrons indicating nuclear fusion reaction due to ion collisions have been successfully observed in experiment [1-3], the results are still far from the goal of decades-long quest for an elusive efficient nuclear fusion for energy-producing application, whereby the energy of generated neutrons exceeds that of the input.

Three major and persistent problems apparently block the road to significant advance in using laser-induced explosions in clusters: insufficient kinetic energy of most of produced ions resulting in greatly reduced collisional cross-section (typically a few KeV vs \( 50 - 100 \text{KeV} \) for maximum cross-section [10]); too low atomic density of surrounding plasma (typically \( \sim 10^{-18} \text{cm}^{-3} \) vs \( \sim 10^{23} \text{cm}^{-3} \) in solid state) resulting in low utilization of produced ions, hence insufficient number of collisions resulting in fusion reaction vs total number of produced ions, and finally, an inevitable free electron cloud that at some point neutralizes the ion cloud and greatly hampers Coulomb explosion. Earlier predicted [6] and very recently experimentally observed [8] shock-shells in Coulomb explosion may increase the collision rate [6] by having ions collide in the higher-density area near original cluster, but this enhancement may still be insufficient to attain required efficiency.

This Letter has a two-fold goal: to propose (1) the way of overcoming all of those problems by using a laser for initial ionization of clusters and simultaneously applied electrical pulse for acceleration of produced ions \( D^+ \) to energies sufficiently high to maximize the collisional cross-section for the neutron production \( (\sim 70 - 100 \text{KeV} [11]) \), and smashing them against a deuterium (or tritium)-rich solid-state target (cathode); this would not only allow to greatly enhance neutron output, but essentially provide an ultimate test of laser+cluster nuclear fusion for energy production applications, and (2) a diagnostic tool for exploration of the intrinsics of cluster structure and explosion for research purposes as well as for such applications as an efficient neutron source.

This proposal may be viewed as a cross between laser-induced CE and basic electrostatic generation of neutrons [12] providing substantial cross benefits. One of them is that there is no need anymore to strive for as powerful laser irradiation as possible, in particular to remove the electron cloud, the laser energy has to be just enough to attain a reasonably high ionization, not to produce high ion energies or blow electron cloud away. Ionized electrons in a ”double-action” system are quickly removed from the expanding cloud, which prevent them from neutralizing the ions in the cloud and hindering/suppressing the main useful effect of Coulomb explosion. Similarly by using a laser as an ionization trigger, this may allow to use lower E-field than in electrostatic generators. The system also simplifies the analysis and diagnostics of the entire process: once all electrons are removed, the dynamics of remaining cloud of positively charged ions is strictly due to a repulsive Coulomb explosion, which now may differ from an ideal CE only in that in each
case the radial density distribution of the ions may be non-uniform, which would depend on their initial distribution. The latter one can thus be elicited by using segmentation of the cathode into a few electrically isolated sections/rings and recording the time-dependant current from each one of them, see below.

In a common arrangement for such a system, either a single cluster or a cloud (or jet) of clusters is injected between two electrodes – an anode for collecting ionization produced electrons, and a cathode covered by deuterium or tritium-rich material, as a target for $D^+$ ions accelerated by a strong dc-like electrical ($E$) pulse applied to the electrodes. The ion energy then can be much higher than that produced by CE and readily reach the optimum domain of up to 100 KeV; it can also be easily controlled by the $E$-pulse amplitude. At the same time, a solid-state target insures a high probability of collisions resulting in fusion. An $E$-pulse has to be much longer than the laser pulse, since it needs to be maintained till all the ions reach the cathode. Its duration for e. g. 50 KeV voltage and 2 cm electrode spacing, has to be $>10$ ns, while the laser pulse is typically sub-ps long; the formation time of ion cloud is even much shorter. For a laser with intensity $\gg 10^{15} W/cm^2$, free electrons are taken away from the core faster than a laser cycle [6], after which they will be swept away by the $E$-pulse and brought to the anode.

Specific electrodes geometries may vary, from parallel plates to concentric spheres or cylinders, and to co-axis cones, yet all of them have common major features. Parallel configuration provides for a simple experimental arrangement and allows to easily elucidate those features. Consider an individual cluster initially at the distance $z_0$ from a cathode with a potential between them being $U_0 = qV_0$, where $V_0$ is the respective voltage and $q$ – an ionic charge (for deuterium or tritium, $q = e$); the cluster is a subject to a strong and very short laser pulse sufficient to substantially ionize it. Due to laser and $E$-pulses’ “vacuum-cleaning”, all free electrons get removed and attracted to the anode. The ensuing CE would then typically result in a shock at the edges of a CE cloud [6-8], yet very soon, at the distance of about $10R_0$, where $R_0$ is the radius of an original cluster, the density of over-run ions rapidly vanish. Then in the case of almost ideal CE, the further cloud expansion proceeds as if it is a sphere with ideally uniform ion density distribution in the momentum space.

In general, however, we will assume that the picture could be more complicated and the expanding cloud is originally either the result of other processes, e. g. thermal explosion, secondary collisional ionization, or compositions, such as e. g. radially non-uniform or heterogeneous clusters [3,13], consisting of different ionic species, or mixed clusters [9] formed by depositing layers of atoms upon a cluster initially made of different atoms, etc. that may result in distinctly different initial non-uniform ion kinetic energy distribution along the radius, with the same maximum energy $T_{0\text{max}}$, see below. (In the case of an ideal CE, whereby the initial density is almost uniform, we have $T_{0\text{max}} = q^2 N_\Sigma / R_0$ [6], where $N_\Sigma$ is a total number of ions in a cluster.) When $R_{cl} >> R_0$, where $R_{cl}(t)$ is a cloud radius, the ion motion is unaffected by ion collisions, and the ion movement is inertial in the frame of the center of mass (COM), while COM accelerates toward a cathode with its $z$-speed being $v_{\text{COM}}(t) = -U_0 t / z_0 M$, with $t = 0$ at the moment of explosion. Similarly to the Hubble expansion then, the ion radial distance $\rho$ from COM is proportional to their original velocity, $\rho = \rho_0 v_0$, $\rho_0 \leq \rho_{\text{max}} = \sqrt{2 T_{0\text{max}} / M}$.

We introduce a potential/kinetic energy ratio, $\chi = U_0 / T_{0\text{max}}$, and a dimensionless time, $\tau = t / t_0$, where $t_0 = z_0 \sqrt{2 M / U_0}$ is a time for COM to reach a cathode due to $dc$-like potential $U_0$ alone. The first ions would reach the cathode in time $\tau_{\text{min}}$ and the last ones – in $\tau_{\text{max}}$, where

$$\tau_{\text{min,max}} = \sqrt{1 + \chi^{-1}} \pm \Delta \tau / 2; \quad \Delta \tau = 2 / \sqrt{\chi} \quad (1)$$

and $\Delta \tau$ is total duration of ion flow. Ions with the same starting energy $T_0$ make an expanding sphere (for the outer edge, see insert, Fig. 1); all these spheres fall down to a cathode with the same acceleration, $-U_0 / z_0 M$. Straightforward calculations yield then the rate number of ions hitting the cathode at $\tau_{\text{min}} < \tau < \tau_{\text{max}}$ as:

$$\frac{1}{N_\Sigma} \frac{dN}{d\tau} = \frac{3 \sqrt{\chi}}{8} \left(1 + \frac{1}{\tau^2}\right) F(\tau); \quad F = \int_{\xi_1}^{\xi_2} f(\xi) d\xi \quad (2)$$

FIG. 1: Full ion flow rate, $(dN / d\tau) / N_\Sigma$ vs dimensionless time, $\tau = t / t_0$, for various potential/kinetic energy ratios, $\chi = U_0 / T_{0\text{max}}$. Inset: the schematics of the proposed experiment, where dotted circles outline the edge of ion cloud resulting from a cluster explosion at two different moments of time. The expanding positively charged cloud moves down toward the deuterium-rich cathode and finally hit it under the action of high-voltage potential.
where $\xi = T_0/T_{0\text{max}}$ is a relative initial kinetic energies of ions, and function $f(\xi)$ describes a radial distribution of these energies that satisfies a condition

$$\int_{0}^{1} f(\xi) d(\xi^{3/2}) = 1. \quad (3)$$

In the case of ideal CE, we have $f_{CE} = \text{const} = 1$. To illustrate diagnostic potentials of this system, we will also consider two other distinctly different models of that distribution, in particular “hot ball”, $f_{HB} = 5\xi/3$, which has a hollow core, while its outer shell is populated by hottest ions, thus making it a sustained shock, and a “cool ball”, $f_{CB} = 5(1-\xi)/2$, with a dense cold core and a vanishing density of “hot” outer ions.

In Eq. (2), the integration limits $\xi_1(\tau)$ and $\xi_2(\tau)$ are determined by the area of the cathode engaged. If all the ions hitting cathode are included, we have $\xi_2 = 1$, and

$$\xi_1 = \xi_{\text{min}}(\tau) = \frac{\chi}{4} \left( \frac{1}{\tau} - \tau \right)^2 < 1, \quad (4)$$

which is a minimal initial energy of ions reaching a cathode at the moment $\tau$, so that for CE, $F_{CE} = 1 - \xi_{\text{min}}$, for hot ball, $F_{HB} = (5(1-\xi_{\text{min}})/6$, and for cool ball, $F_{CB} = 5(1-\xi_{\text{min}})^2/4$. For the CE case, the rate $dN/d\tau$ in units $N_\Sigma$ for $\chi$ from 2.5 to 25 is depicted in Fig. 1 (if $T_{0\text{max}} = 4KEV$, that would correspond to $U_0$ ranging from 10 to 100KEV). Notice that while initial kinetic energy of an ion is $T_0$, which increases to $T = U_0 + T_0$ when it hits a cathode, the total energy of the cloud delivered to the cathode during entire process in an ideal CE case, can be shown to be

$$T_\Sigma = N_\Sigma (U_0 + 3T_{0\text{max}}/5). \quad (5)$$

To prevent ions from hitting an anode, one needs to provide a sufficient overhead spacing, $z_{up}$, between clusters and anode with a total cathode-anode spacing being $z_{CA} = z_0 + z_{up} \geq z_{cr}$, and thus a sufficient voltage between the plates, $V_{CA} \geq V_{cr}$ which are shown to be

$$z_{cr}/z_0 = V_{cr}/V_0 = 1 + \chi^{-1}; \quad (6)$$

The maximum “hot spot” radius, $\rho_{sp}$, at the cathode is reached at the moment $\tau_{sp}$, which are respectively as:

$$\rho_{sp} = \frac{2\sqrt{1+\chi}}{\chi}, \quad \tau_{sp} = \sqrt{\frac{2}{\chi} + 1} \quad (7)$$

i. e. the spot gets tighter as ratio $\chi$ increases, as expected. This indicates also that the effect is sensitive to the distribution of ion energies $f(\xi)$ in the original explosion, and thus may offer a well-resolved time-of-flight diagnostics of that distribution.

This kind of diagnostic can be implemented by segmenting the cathode into isolated concentric rings or sub-cathodes, and recording dynamics of ion flow in each of them separately, as well as a total count of the ions hitting each of them, for various distributions $f(\xi)$. While in real experiment one can use as many rings as necessary, for simplicity purposes we consider here the set of just three rings, the central one being a disc with a radius $\rho < \rho_1$, a middle ring $\rho_1 < \rho_c < \rho_2$, and external ring $\rho_2 < \rho_c < \rho_{max}$, where we set the sizes in such a way that in the end of the process, the total ion flow in each of them be the same for all three sub-cathodes for the
ideal CE case, whereby they have to be $\rho_1/\rho_{sp} \approx 0.475$ and $\rho_2/\rho_{sp} \approx 0.709$. Fig. 2 depicts the time dynamics of the current/flow of ions through each ring and total ion count (see inserts) in each of those rings for each chosen model. It illustrate plentifully a great potential of such a system for spectroscopy and diagnostic purposes.

For various applications, the anode and cathode geometry can be modified using, e.g. spherical or cylindrical surfaces. Having in mind the optimization of neutron output, the latter configuration with a jet of nanoclusters injected into parallel to the cylinder axis, may be used with a scanning laser focus or a "slab" laser beam. The proof-of-principle experiments can be done with spherical electrodes and a few tens KeV potential.

In conclusion, we proposed to reach ultimately maximal yield of neutrons due to laser-driven explosion of deuterium clusters, by applying in addition to the laser electric field, and making a quasi-electrical pulse of a few tens Kev peak field, and making $D^+$ ions of Coulomb explosion collide with a negatively charged deuterium-rich cathode. The maximal yield is reached since free electrons are removed from the ion cloud, $D^+$ ions are fully utilized and made to collide with solid-state deuterium-rich target instead of plasma. By choosing appropriate configuration of the system, it can be made into a sensitive diagnostic tool to resolve an intrinsic structure of initial cluster.

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