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Coulomb explosions of deuterium clusters studied by compact design of Nomarski interferometer

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Abstract. Interactions of high-intensity femtosecond lasers with deuterium clusters leading to Coulombic explosions and subsequent production of fusion neutrons attracted considerable attention. In order to maximize the neutron yield finding a dependence of clusters size and their spatial distribution on experimental conditions became very important. In this paper a possibility to measure the deuterium clusters spatial distributions experimentally was analyzed. In combination with experiments recently performed in the Laboratory of Quantum Optics at the Korea Atomic Energy Research Institute (KAERI) interferometry was identified as the diagnostics suitable for such measurements.

1. Introduction
In recent years interactions of high-intensity femtosecond laser pulses with deuterium clusters leading to Coulombic explosions and subsequent production of fusion neutrons attracted considerable attention [1]–[4]. From experiments performed it became clear that in order to optimize fusion neutrons production it would be very important to find a dependence of clusters size and their spatial distribution in the expanding deuterium gas on experimental conditions, in particular the backing gas pressure and temperature. This information would provide a deeper insight into the process of clusters creation, their ionization, and fusion neutrons production efficiency. For this purpose various diagnostics were employed, e.g. Rayleigh scattering or Taylor-Sedov blast wave. However, these diagnostics were able to determine the information required only a qualitative way. Therefore, some new approach would need to be looked for and applied. Such an ambitious project would need some rather sophisticated diagnostics to be implemented.

2. Preliminary experiments performed at KAERI
Several years ago experiments aimed to repeat/verify the results reported earlier were performed also in the Laboratory of Quantum Optics at the Korea Atomic Energy Research Institute (KAERI) using the Ti:Saphire laser system (30 fs, $I > 10^{16}$ W/cm$^2$). Successful production of fusion neutrons was achieved [5]–[7]. In these experiments optical interferometry was employed mainly to visualize the experimental conditions of the interaction process. This was followed by a
series of experiments where interferometry was already used as a potentially valuable diagnostics in providing important information concerning the clusters spatial distributions. In order to test its limits the experimental setup illustrated in the Fig. 1 was used.

![Figure 1. Experimental setup for testing sensitivity of interferometry diagnostics. The gas is injected into the vacuum chamber from the top. Very close resemblance of various structures in the signal free/low areas of individual interferograms is clearly visible.](image1)

It was confirmed that even if the diagnostic laser beam cross section was not exactly homogeneous and along its trajectory to CCD through various optical elements gradually accumulated some local disturbances, its structure from shot to shot remained practically the same. This feature allowed for a very effective usage of the reference shots (either the background ones or those without the action of the main laser) to be incorporated into FFT based interferogram analysis [8]–[10], thus providing results with a degree of accuracy potentially sufficient for clusters spatial profiles reconstruction. One example of the results obtained is demonstrated in the Fig. 2.

![Figure 2. Interferograms from the left: background (vacuum); partially clusterized D$_2$ gas (injected from the top); laser interaction with partially clusterized D$_2$ gas. On the right: reconstructed phase shift of laser produced plasma (dark and bright regions - corresponding to positive and negative phase shifts - are the result of the compact interferometer design (for more details about this particular design see Ref. 10).](image2)

3. Theoretical analysis of clusters distribution measurement by interferometry

Encouraging results of the experiments performed at KAERI so far triggered further interest into preparation of a new series of experiments dedicated solely to the application of optical interferometry for determination of the actual clusters spatial distributions. In this Section some specific comments to this topic will be presented. It should be understood from the very beginning that this diagnostics does not provide any means how to determine the actual sizes of the clusters. Only some average values can be worked with contributing to the total phase shift of the probing part of the diagnostic beam along its path through the expanding gas/clusters jet according to the clusters respective spatial distribution.
Let’s consider the situation when the injected deuterium gas is expanding into vacuum. In the ideal case of the pure gas (without any clusters created) the density profile in the cross-section perpendicular to the gas jet axis of symmetry at the distance \( z \) from the nozzle can be described by some function \( f_1(r, z) \) where \( r \) represents the distance from the axis of symmetry. Now let’s take into consideration that in the real case a certain part of the gas will participate in generation of clusters. Let’s denote this density as \( f_2(r, z) \) thus giving rise to the corresponding clusters density \( f_C(r, z) \). When \( N \) would be the effective number of deuterium molecules in one cluster then \( f_C(r, z) = f_2(r, z)/N \). Let’s also presume that clusters and gas have different values of their respective molar refractivity. Under these assumptions the resulting phase shifts can be obtained from the following expressions:

\[
\varphi_1(y, z) = k_1 A[f_1(r, z)],
\]

\[
\varphi_2(y, z) = k_1 A[f_1(r, z)] - (Nk_1 - k_C)A[f_C(r, z)],
\]

where \( \varphi_1(y, z) \) is the phase shift corresponding to the pure gas; \( \varphi_2(y, z) \) is the phase shift of the gas/clusters mixture; \( k_1 \) and \( k_C \) are appropriate constants specific for the deuterium gas and the clusters, respectively; \( A[f(r)] \) stands for the Abel integral transformation of the function \( f(r) \) [11]. Provided that both the phase shifts \( \varphi_1(y, z) \) and \( \varphi_2(y, z) \) would be known, as well as the parameters \( k_1, k_C, \) and \( N \), the resulting clusters spatial distribution can be found from the expression:

\[
f_C(r, z) = \frac{A^{-1}[\varphi_1(y, z) - \varphi_2(y, z)]}{Nk_1 - k_C},
\]

where \( A^{-1}[\varphi(y)] \) denotes the Abel inversion of the function \( \varphi(y) \).

This theoretical analysis requires some important comments to be made from the point of its practical applicability. The first comment concerns the actual knowledge of various parameters needed for such analysis to be performed. The experimentally measured phase shift \( \varphi_2(y, z) \) should pose no major problems. Also, the algorithm used for these data analysis should guarantee the required level of precision. One example of such analysis if provided in the Fig. 3. Somewhat different situation concerns the phase shift \( \varphi_1(y, z) \). However, \( \varphi_1(y, z) \) can actually be determined only indirectly as for the appropriate experimental conditions the partial clusterization already occurs thus the measured quantity would always be \( \varphi_2(y, z) \). Hence, ways must be found to obtain this \( \varphi_1(y, z) \) from measurements performed under slightly different conditions when no clusterization would occur combined with necessary extrapolation based on suitable theoretical analysis. As for the remaining parameters assembled in the denominator of the formula (3) they play only the role of the multiplicative factor. Therefore, if only the relative spatial distribution of clusters would be of some concern (and indeed in many cases such knowledge might be quite sufficient) they could be selected rather arbitrarily. For the knowledge of their absolute values, however, these parameters would need to be determined. Out of them \( k_1 \) is the easiest to obtain as it is directly related to \( D_2 \) gas molar refractivity. The average number of atoms in one cluster \( N \) can be approximately evaluated using the Hagena number [4]. The remaining parameter \( k_C \) related to molar refractivity of deuterium clusters is the most difficult to find. It might need to be obtained experimentally.

4. Conclusion
It this paper it was demonstrated that for the experimental conditions available in KAERI the optical interferometry diagnostics should be suitable for determination of deuterium clusters density spatial distribution assuming the effective size of clusters averaged over their size distribution (at least in the case when knowledge of relative density profiles would be sufficient).
Figure 3. Interferograms of (a) partially clusterized D$_2$; (b) background (vacuum); (c) 2D reconstructed phase shift corresponding to (a) using (b) as a reference. 3D graph represents the same data as in (c).

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