

## Study of the cluster formation dynamics and its affect on generation of THz and X-Ray radiation in the expanding gas jet.

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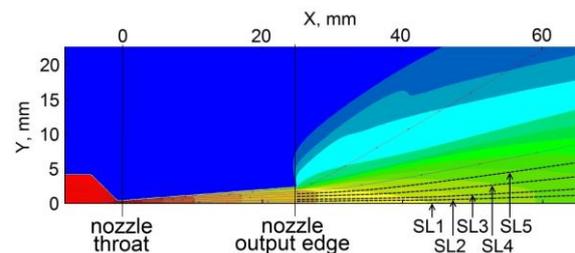
Presently the interaction of intense femtosecond laser pulses with cluster target is a subject of active researches. Laser-cluster interaction proceeds with high efficiency and is accompanied with a plenty of nonlinear effects [1-3]. That makes it very attractive and promising as the basis for elaboration of a source for generation of intense coherent electromagnetic pulses in a wide spectral range from X-ray up to THz.

For detailed understanding and interpretation of the processes occurring in the gas-cluster nanoplasma, as well as for further optimization of their effectivity, a detailed information about properties of the gas-cluster jet is required. This information include distributions of the clusters size, cluster concentration, condensation degree and average atomic density along the spatial coordinates. In general, the process of the clusters formation in the gas jet is quite complex and possesses the probabilistic nature. The efficient method to get detailed information regarding the properties and parameters of the gas-cluster jet is the straight numerical simulation of the clusterization process.

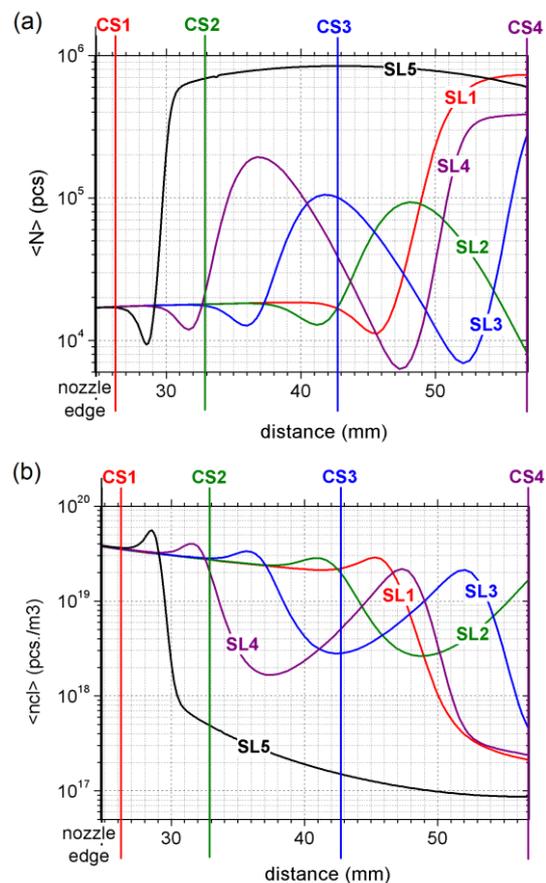
In this work, we have carried out the numerical simulation and computing of dynamic picture of clusterization of argon atoms passed through the supersonic conical nozzle and future propagation of the jet into vacuum at a distance of up to 60 mm below the nozzle throat. The result of numerical simulation has demonstrated that ratio between argon monomers, small and large clusters fractions dramatically changes both as along the jet propagation direction, and as across the jet when the distance from the nozzle throat increase.

Some results of the numerical simulation of cluster formation process are shown on Fig. 1,2. The following parameters of the conical nozzle which was applied in our experiments were used for simulation: throat diameter 0.7 mm, output diameter 4.7 mm, and the nozzle length 24.7 mm. Backing pressure of argon was 2 Mpa. Fig.1 depicts spatial distribution of the average argon atoms density inside and outside of the nozzle. The direction along the axis of symmetry of the nozzle is denoted as an axis of abscissa (X-axis), that coincides with the jet propagation direction as well. The nozzle throat position is noted as X=0 mm, and X=24.7 mm corresponds to position of the nozzle output edge. Radial direction, which is perpendicular to the axis of the symmetry, is denoted as Y-axis. There are five stream lines (SL) indicated by dashed lines on the Fig. 1. Distributions of mean cluster size and mean cluster concentration through the stream

lines as a function of distance from the nozzle are presented on Fig.2.



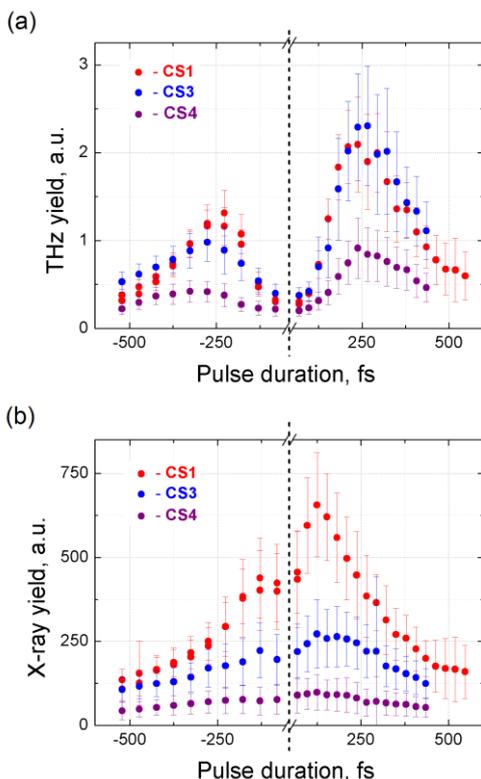
**Fig. 1.** Distribution of Ar atom density inside and outside of the conical nozzle (Y = 0 corresponds to the axis of symmetry of the nozzle, SL1-SL5 represent five stream lines). The magnitude of the density is represented by a color scale:  $\sim 5 \text{ kg/m}^3$  (red),  $\sim 0.3 \text{ kg/m}^3$  (yellow),  $\sim 10^{-2} \text{ kg/m}^3$  (green),  $\sim 3 \times 10^{-4} \text{ kg/m}^3$  (blue), and  $\sim 10^{-5} \text{ kg/m}^3$  (dark blue).



**Fig. 2.** Distributions of (a) mean cluster size  $\langle N \rangle$  and (b) mean cluster concentration  $\langle n_{cl} \rangle$ , along five stream lines (SL1-SL5) as a function of the distance from the nozzle throat.

The graphs shown on Fig. 1,2 clearly demonstrate that the distance from the nozzle throat is an important parameter which defines the properties of the gas-cluster jet. We suggest that this fact can be effectively used for efficient control over X-ray and THz emission yields produced from argon gas-cluster jet under irradiation with high-intense laser pulses.

In our experiments on laser-cluster interaction we used the setup described in details in our previous paper [4], which was modified to provide a possibility of focusing the laser beam into the gas-cluster jet at various distances below the output edge of conical supersonic nozzle. The focus point was located at the axis of symmetry of the nozzle and could be positioned discretely in the range between 1.5 mm to 32.3 mm below the nozzle edge that corresponds to the locations of CS1-CS4. Our laser system provided pulses with energy up to 30 mJ at 10 Hz repetition rate, central wavelength was 810 nm, the pulse duration could be tuned in the range of 50–600 fs by chirping the laser pulse in a vacuum grating compressor.



**Fig. 3.** X-Ray (a) and THz (b) yields from an Ar gas-clusters jet as a function of the temporal duration of the excitation laser pulses recorded at the cross-sections of CS1 (red dots), CS3 (blue dots), and CS4 (purple dots). The vertical dotted line in the center represents the pulse duration for a Fourier limited pulse.

Let us consider the experimental results. THz and X-Ray yields from Ar gas-clusters jet as a function of temporal duration of exciting laser pulse are presented on Fig. 3. Measurements have been performed for both positively (right side) and negatively (left side) chirped optical pulses. Pulse duration of around 55fs corresponds to Fourier-limited pulse and is indicated by related vertical line on Fig. 3. The symbols of dif-

ferent colors depict experimental data measured for three cases of position of laser beam focus relatively to the nozzle, and correspond to CS1, CS3 and CS4 cross-sections.

It can be seen from Fig. 3 that THz yield strongly decreases in the region of minimum pulse durations whereas X-Ray emission intensity demonstrates maximum values under these conditions. Maximal value X-ray signal monotonously decreases as the distance between excitation area and the nozzle throat increases from CS1 to CS4. In contrast with this behaviour, THz signal demonstrate roughly equal values in the CS1 and CS3, but it decreases in the CS4 position. As it can be seen from Fig. 1,2 there are mainly small-size clusters fractions are contained in cross-section CS1, and predominantly large-size clusters are in cross-section CS4.

In conclusion, we carried out numerical simulations of the cluster formation process in a supersonic jet of Ar. We have shown that the distance from the nozzle output edge is an important parameter describing the properties of the gas-cluster target, which should be taken into account when developing the effective sources of THz and X-ray radiation based on cluster nanoplasma.

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## References

1. Krainov V., and Smirnov M. Cluster beams in the super-intense femtosecond laser pulse // Phys. Rep. 2002. V. 370, P. 237-331.
2. Nagashima T., Hirayama H., Shibuya K., Hangyo M., Hashida M., Tokita S., and Sakabe S. Terahertz pulse radiation from argon clusters irradiated with intense femtosecond laser pulses // Opt. Express 2009 V. 17, P. 8907
3. Alexeev I., Antonsen T.M., Kim K.Y., and Milchberg H.M. Self-focusing of intense laser pulses in a clustered gas // Phys. Rev. Lett. 2003 V. 90, P. 103402
4. Balakin A.V., Dzhidzhoev M.S., Gordienko V.M., Esaulkov M.N., Zhvaniya I.A., Ivanov K.A., Kotelnikov I.A., Kuzechkin N.A., Ozheredov I.A., Panchenko V.Y., Savel'ev A.B., Smirnov M.B., Solyankin P.M., Shkurinov A.P. IEEE Trans. Terahertz Sci. Technol. 2017 V. 7, P. 70-79