Probing ultrafast dynamics of a cluster nanoplasma by a combination of time resolved ion spectroscopy and x-ray scattering techniques

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Within femtoseconds, intense light pulses are able to transform matter into a highly excited non-equilibrium state. Clusters, as nanometer-sized particles with the density of bulk solids isolated in free space, are ideal to study light-matter interaction and to develop our understanding of the underlying physics. The ionization and relaxation dynamics of such sample in the FEL focus is rather complex and is expected to proceed on several different time scales [1].

Figure 1: Scheme of the experimental setup: Within the interaction region single clusters are interacting with the pump and temporally delayed probe pulses. X-ray scattered light as well as cluster fluorescence photons are recorded with a multichannel plate detector. The ions created during the cluster disintegration are detected by a time-of-flight mass spectrometer.

Recently we have studied the expansion and disintegration dynamics of Xe gas clusters using the autocorrelator setup at FLASH. The final fragment ion distribution collected over an ensemble of clusters in the focus volume shows substantial changes towards higher charge states with the increase of a time-delay between first pump and second more intense probe x-ray pulses [2]. The results of this study show that the cluster plasma changes significantly on the time scale of 1-3 ps depending on the cluster size. Also, the development of ultrafast x-ray scattering techniques on single clusters allows studies on geometric configuration and cluster morphology [3] as well as provides insight into cluster growth processes (to be published). Moreover, x-ray diffraction patterns of single clusters carry information about the optical constants of the irradiated object, and, thus, the transient electronic configurations of highly excited states of matter have now become accessible [4].
Figure 2: Distribution of the fluorescence yield (a - NIR only) and intensity of the x-ray scattering patterns (b - FEL only) together with the corresponding ion spectra. Dramatic changes in the ion yield spectra and of the intensity of single-shot images are mostly explained by the different position of a single cluster within the focus of the NIR or FEL beam, respectively. This effect would be smeared by the integration over intensity of focal volume and cluster size distribution.

In our last beamtime at FLASH we have combined the capability of single-shot single particle imaging with ion spectroscopy in time resolved manner. A scheme of the experimental geometry is shown in Figure 1. This new class of experiments allows studies of dynamics of a spatially restricted nanoplasma under well defined experimental conditions. Figure 2 shows the dramatic changes of the intensity of single shot images as well as of the ion yield distributions depending on the position of a single cluster within the focal volume. This demonstrates the advantage of single-shot single particle experiments, because otherwise the nanoplasma dynamics becomes substantially smeared by the integration over irradiation intensity and cluster size distribution. On the other hand, such approach requires intelligent filters and data processing algorithms.

Our ongoing data analysis shows, that the impact of near-infrared (NIR) laser or FEL pulse on a single cluster can be disentangled, even though the power density of both pulses is comparable. This is because the characteristic nanoplasma parameters (i.e. electron temperature and average charge) as well as the coupling of the transient states differs substantially. While a soft x-ray pulse is still able to produce changes in the ion yield spectra even nanoseconds after the irradiation of the cluster with a NIR pulse, the transient nanoplasma excited by the soft x-ray pulse is most effectively influenced by the NIR field under the resonance conditions, when the nanoplasma eigenfrequency approaches the oscillation frequency of the NIR field. Moreover, as the soft x-ray pulse produces snap-shot images of clusters, a new insight into the evolution of transient states of matter becomes accessible.

References