Investigation on Dynamics of Nano-Plasma of Rare-Gas Clusters by EUVFEL Pump – NIR Laser Probe Measurements

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Abstract: Via extreme ultraviolet free electron laser pump and near infrared laser probe experiments for rare-gas clusters, we found clear enhancement of highly charged ions when EUVFEL and NIR pulses overlap, indicating efficient heating of nano-plasma.
OCIS codes: (020.2649) Strong field laser physics, (020.4180) Multiphoton processes

1. Introduction

Recent developments of the free electron laser (FEL) light sources based on self-amplified spontaneous-emission (SASE) invoke new research fields on the interaction of matters with intense laser pulses in the short wavelength region. Rare-gas clusters are one of the ideal samples to investigate the interaction of matters with the intense laser because of their simple electronic structure and the size controllability. Electron spectra of rare-gas clusters measured in the extreme ultraviolet (EUV) spectral region [1-3] suggested the formation of nano-plasma state as a result of intense EUVFEL irradiation, and molecular dynamics (MD) simulation studies give the microscopic insight into the mechanisms of nano-plasma formation by the intense FEL pulses [4-7]. MD simulations for small rare-gas clusters [8] also suggested a scheme to investigate the dynamics of nano-plasma using pump-probe techniques with near infrared (NIR) laser, by seeing the enhanced energy absorption due to the resonant surface plasma resonance. Triggered by these pioneering works, we carried out EUVFEL pump - NIR laser probe experiments at the SPring-8 compact SASE source (SCSS) test facility [9], which delivers intense FEL pulses in the EUV spectral region of λ=51~ 61nm.

2. Experiment

We have carried out time-of-flight (TOF) measurements of fragment ions from xenon clusters (N~5,000) and neon clusters (N~5,000) as a function of delay time between the EUVFEL pulse (λ=51nm for xenon clusters and 61nm for neon clusters) and the NIR laser pulse (λ=800nm).

Figure 1 is the schematics of experimental apparatus. Our apparatus is equipped with velocity map imaging (VMI) spectrometer for ion and electron detection, and a pulsed cluster source. The cluster beam is produced by the supersonic expansion of sample gas. The focusing system consists of a pair of elliptical and cylindrical mirrors coated with SiC. We have installed two sets of light baffles between the mirror system and the detection chamber, to remove scattered light from focus mirrors. Spatial overlap between EUVFEL and NIR laser has been achieved by seeing the ion image of xenon atom using the imaging detector. In order to find the temporal overlap, we observed the increase of He^+ (@51nm) and Ne^{2+} (@61nm) ions in TOF spectra.

3. Results and discussions

Figure 2 shows the ion TOF spectrum for the xenon clusters. We found notable enhancement of ion yields especially in the highly charged ions when the EUVFEL pulses temporally overlapped with the NIR laser pulses. We confirmed the emission of energetic highly charged xenon ions up to around Xe^{15+} for xenon clusters from the analysis of TOF spectra, suggesting the enhanced heating of nano-plasma due to surface plasma resonance. The presence of surface plasma resonance gives an evidence for the nano-plasma formation from rare-gas clusters by intense EUVFEL irradiation.

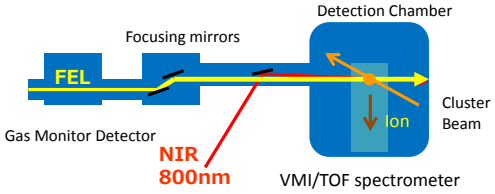

Figure 1. Schematics of experimental apparatus

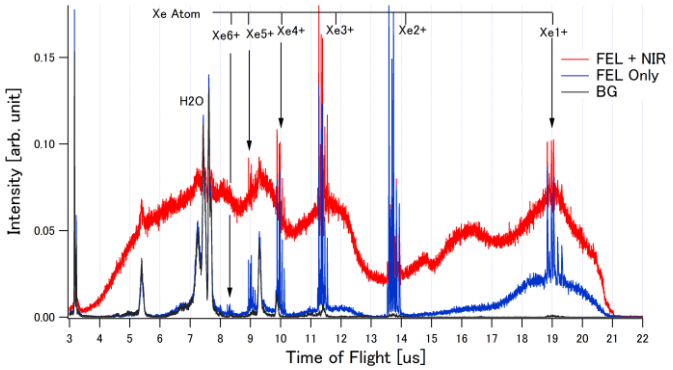

Figure 2. Ion TOF spectra of xenon clusters recorded by EUVFEL pump – NIR probe measurements. Blue line: TOF spectrum recorded by only FEL irradiation, red line: TOF spectrum by FEL + NIR laser with a delay time of 2ps, black line: background spectra recorded without the cluster beam.

We found similar enhancement of highly charged ions for neon clusters. In addition, clear difference is found in the delay time response of ion yields between xenon clusters and neon clusters. Ion TOF spectra of xenon clusters showed the increase of highly charged ions until ~20 ps after the irradiation of EUVFEL pulse, whereas highly charged ions from neon clusters vanished quickly (<2ps). Such difference could be associated to the difference of the nature of nano-plasma created by EUVFEL irradiation. We discuss the FEL-induced dynamics of rare-gas clusters based on our experimental data.

Acknowledgement

We are grateful to SCSS Test Accelerator Operation Group at RIKEN for continuous support in the course of the studies. This study was supported by the X-ray Free Electron Laser Utilization Research Project and the X-ray Free Electron Laser Priority Strategy Program of Ministry of Education, Culture, Sports, Science, and Technology of Japan (MEXT), by Grants-in-Aid (No. 23241033 and No. 23600006) from the Japan Society for the Promotion of Science (JSPS).

References

[1] C. Bostedt *et al*., ”Multistep Ionization of Argon Clusters in Intense Femtosecond Extreme Ultraviolet Pulses” Phys. Rev. Lett. **100**, 133401 (2008).

[2] C. Bostedt *et al*., ”Fast electrons from multi-electron dynamics in xenon clusters induced by inner-shell ionization” New J. Phys. **12** (2010) 083004.

[3] S. Yase *et al*., ”Crossover in the photoionization processes of neon clusters with increasing EUV free-electron-laser intensity” Phys. Rev. A **88**, 043203 (2013).

[4] U. Saalmann, Ch. Siedschlag, and J. M. Rost, ”Mechanisms of cluster ionization in strong laser pulses” J. Phys. B: At. Mol. Opt. Phys. 39, R39 (2006).

[5] B. Ziaja, H.Wabnitz, F.Wang, and E.Weckert, T. Moeller, ”Energetics, Ionization, and Expansion Dynamics of Atomic Clusters Irradiated with Short Intense Vacuum-Ultraviolet Pulses” Phys.Rev. Lett. 102, 205002 (2009).

[6] Th. Fennel , K.-H. Meiwes-Broer, J. Tiggesbaumker, P.-G. Reinhard, P. M. Dinh, E. Suraud, ”Laser-driven nonlinear cluster dynamics” Rev. Mod. Phys., **82**, 1793 (2010).

[7] M. Arbeiter and Th. Fennel, ”Ionization heating in rare-gas clusters under intense XUV laser pulses” Phys. Rev. A 82, 013201 (2010).

[8] C. Siedschlag and J. M. Lost, ”Surface-plasma resonance in small rare-gas clusters by mixing ir and vuv laser pulses” Phys. Rev. A 71, 031401(R) (2005).

[9] H. Shintake *et al*., ”A compact free-electron laser for generating coherent radiation in the extreme ultraviolet region” Nature Photon. 2, 555 (2008).