FEL induced acceleration of light ions in methane clusters

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We have studied the acceleration dynamics of light hydrogen ions in methane, deuterated methane and mixed methane-xenon clusters interacting with very intense and very short soft X-ray pulses at FLASH. We found that light ions (hydrogen, deuterium) in methane clusters can gain high energies, up to 300 eV, depending on the cluster size, beam intensity. In methane clusters doped with xenon the energy gain is substantial (reaching 600 eV), due to higher charge states created. The results offer new avenues in the exploitation of free-electron lasers for the acceleration of ions to high energies.

The experiments were performed at FLASH facility at DESY in Feburary 2008. The targets were methane (CH4) and deuterated methane (CD4) clusters, with an optional doping with Xenon to created core-shell clusters. These were irradiated by intense (10^{13}-10^{15} W/cm^2), 15 femtosecond long soft X-rays at a wavelength of 13.5 nm, corresponding to an energy of 92 eV. The methane clusters were produced with a helium cooled clusterjet using a piezoelectric nozzle for cluster creation. The maximumg cluster size possible with this setup was 10^6 atoms per cluster. Doping with Xenon was done in a mixing chamber attached to the main vacuum chamber and the amount of doping was controlled by using different backpressures for the gas. The experimental setup as well as a short description of the time-of-flight (TOF) measurements can be seen in Figure 1. Each measurement contained approximately 40,000 shots on clusters with the FEL.

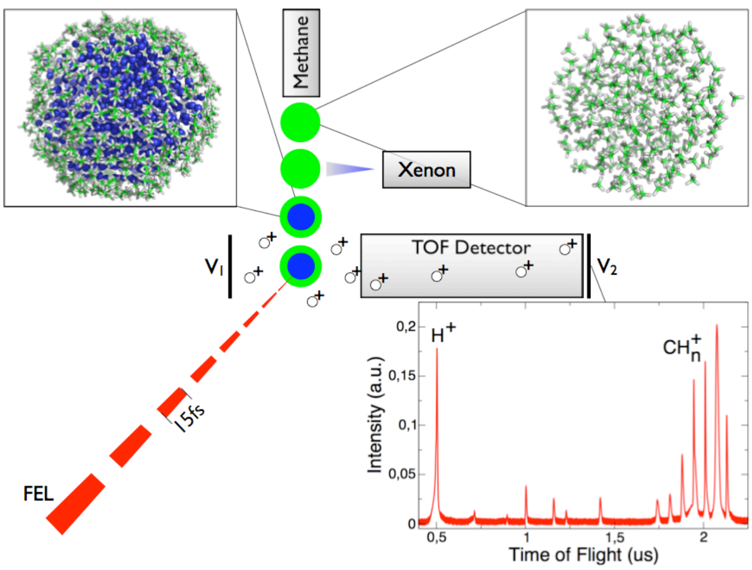

Fig. 1: Experimental setup. Methane clusters are produced by a cryo-cooled cluster source (upper right), and then pass through a doping cell for producing mixed clusters with Xe (upper left). They travel towards the interaction region located between the repulsion plate and the drift tube of a time-of-flight (TOF) detector where they will be intersected by 15 fs long soft X-ray pulses, 13.5 nm wavelength. The pulses deposit a high amount of energy into the clusters leading to their ionization and subsequent disintegration. Positively charged ions are attracted towards the multi-channel plate (MCP) detector at the end of the TOF tube, recorded by an oscilloscope and analyzed. V_1 and V_2 are the voltages on the repulsion plate and the MCP.

The recorded TOF spectra were analyzed to answer questions about the dominant ionization and ion acceleration mechanism at the wavelength of 13.5nm and possible energy gain of light ions (predominantly hydrogen) in dependency of cluster size, Xenon doping pressure and beam intensity. The software package SIMION was used to perform simulations for the time of flight of light ions in the TOF detector, and obtain the energy distribution of the ions.

Our findings showed that the general behaviour of the clusters while interacting with the soft X-rays is similar to the case in the optical regime (Last 1997, Ditmire 2000). The ion energies show a clear size-dependency, intensity dependence and doping dependece, as can be seen in Figure 2, mainly due to a high number of charges in the cluster driving the Coulomb explosion.

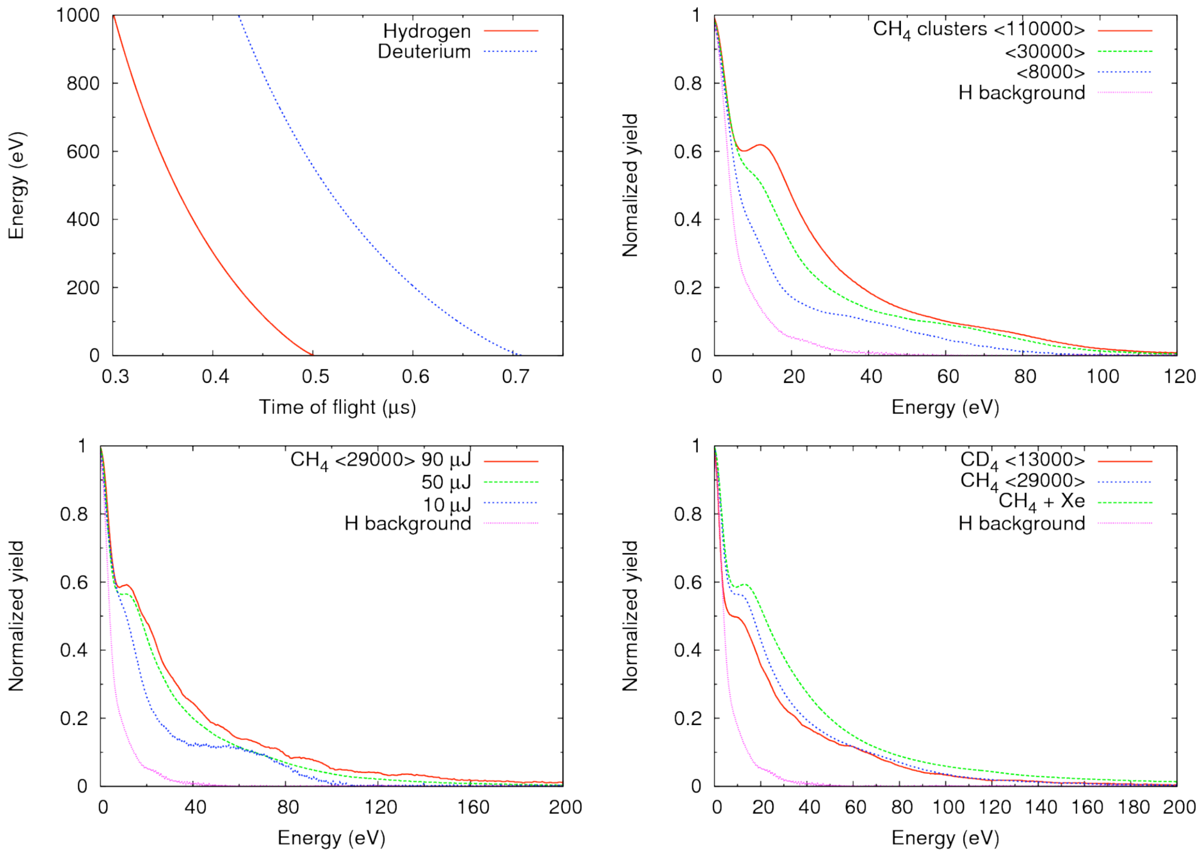

Fig. 2: a) Simulated relations between energy and flight time for H and D ions, **b)** Energy distributions of H ions as a function of methane cluster size. Average X-ray pulse intensity is 30 µJ, 15 fs long, and . **c)** Energy distribution of H ions from a 29000 CH4 cluster as a function of X-ray beam intensity. **d)** Comparison of energy distribution of light ions from methane clusters, deuterated methane clusters and Xe-doped methane clusters. Average X-ray pulse intensity is 40 µJ.

Irradiation of heteronuclear clusters with soft X-ray laser pulses leads to light ion acceleration that is not as energetic as in the optical case. Our results show that the maximum energy hydrogen ions could gain is approximately 300 eV in the undoped case and 600eV with Xe doping, and depends strongly on the experimental conditions like doping pressure, beam intensity and cluster size. Therefore, the best result could be obtained by a methane cluster consisting of 30,000 atoms, doped with high-Z material, Xenon, at a pressure of 72mbar and with a FEL pulse intensity peaking at approximately 80 µJ outrunning even the bigger, undoped methane cluster with 110,000 atoms.

The energy range can be increased by using more energetic laser pulses and bigger clusters doped with high-Z material. Focusing the laser beam down to only a few micrometer as has been done in microfocusing experiments would increase the beam intensity and thus push the accessible energy range. Bigger methane clusters can be doped with more Xenon before the integrity of the cluster breaks down which would also allow us to reach higher light ion energies. Those approaches are taken in consideration and will be pursuit in our next experiments at FLASH.

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