Acceleration of light and heavy ions from solids by intense soft X-ray

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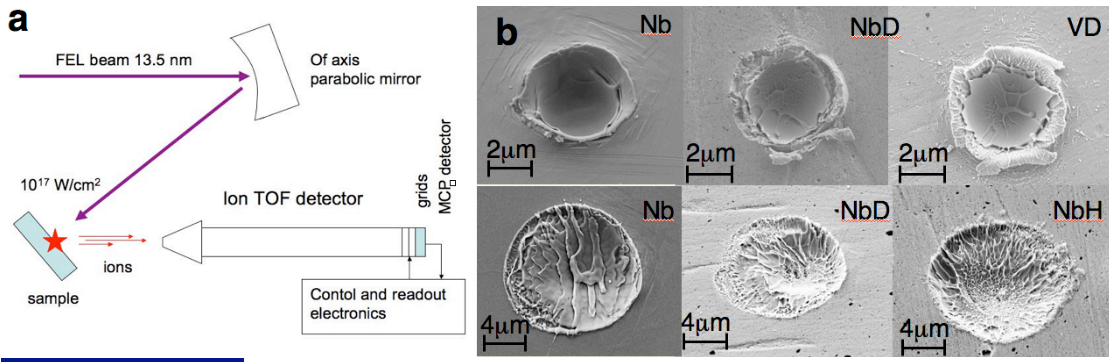
Studies on the interaction of ultra-short and extremely intense soft X-ray pulses with material can now be performed with free-electron lasers. We report here studies on the dynamics of ions ejected from bulk metals and their hydrides/deuterides when exposed to focused pulses of the FLASH FEL (pulse length 15 fs, λ=13.5 nm, pulse energy 7-70 μJ, energy flux ~10^{17} W/cm^2). We find that the interaction between a 15 fs pulse and the solid target can accelerate the light ions (hydrogen and deuterium) and highly ionized metal ions (up to 5+) to kinetic energies approaching 7 keV and 20 keV respectively. The results offer new avenues in the exploitation of free-electron lasers through the acceleration of ions to high energies at solid densities.

The experiments were performed at FLASH in April 2008. The targets were polished bulk samples of niobium (Nb) and vanadium (V) as well as deuterated niobium (NbD) and vanadium (VD) and hydrogenated niobium (NbH). FLASH was operating in single shot mode and an of axis parabolic mirror (Fig. 1 a) was used to control the focus of the free-electron laser (FEL) beam down to about 2 μm in diameter. The time of flight (TOF) detector was equipped with a high pass (HP) filter in the form of charged metal grids in front of the ion detector.



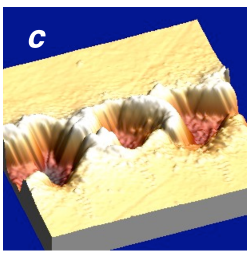


Fig. 1: **a)** Experimental setup. An of axis parabolic mirror focuses the FEL beam onto the sample. A fraction of the ejected ions travel through the TOF detector and are recorded by the MCP. Charged metal grids in front of the MCP act as a HP filter. **b)** SEM images of single shot craters in focus (top) and out of focus (bottom). **c)** AFM image of in focus craters in scan mode in deuterated vanadium.

The samples were exposed to the beam either in a single shot mode (Fig. 1 b) or in a scan mode (Fig. 1 c). In the scan mode the moving target was exposed to the FEL pulses with a repetition rate of about 5 Hz. This causes each pulse to hit partly in the crater of the previous pulse. Due to the slope of the crater edges this generates different local geometric environments in the interaction region when the sample is moved to the right, left, up or down. In the single shot mode the exposure rate was 1 Hz generating well separated craters.

Scanning Electron Microscope (SEM) images (Fig. 1 b) show that the craters in the samples loaded with H and D have pronounced microstructures while the surfaces in the un-treated samples are relatively smooth. This indicates that the interaction region in the deuterated and hydrogenated samples cool faster than in the untreated samples. This may be related to light ions from the bulk leaving the sample at an early stage of the interaction.

From the ion TOF data (Fig. 2.a and c) the charge states and maximum kinetic energies of the ejected ions can be determined. Under the influence of a particular HP filter setting each ion populations is cut at a characteristic flight time corresponding to the energy needed to pass the filter. Comparing the flight times where these cut offs occur with simulated relations between the kinetic energies and ion flight times (Fig. 2.a and b) Nb ions with charge states up to 5+ are identified. The leading edge of the Nb ion populations occur at about 3 μs (Fig. 2 c, dotted line) corresponding to an energy of 20 keV (Fig. 2 a, dotted line) . For the V samples we observe charge states up to 4+ and energies approaching 20 keV. At shorter flight times (between 0.5 and 4 μs) hydrogen (H^{+}), carbon (C) and oxygen (O) ions are frequently observed. These ions originate from surface contaminations. The C and O ions have relatively low energies and are not seen with the HP filter at 2.5 keV (Fig. 2 c).

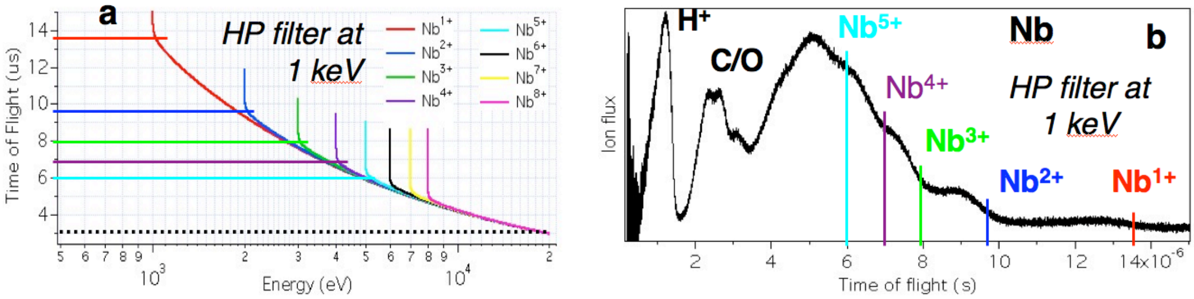
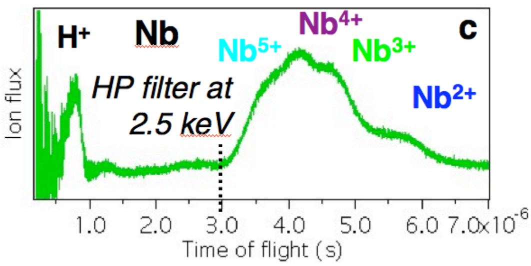


Fig. 2: a) Simulated relations between energy and flight time for Nb ions with different charge states, HP filter at 1 keV. **b)** Averaged ion TOF spectrum from Nb, HP filter at 1 keV. **c)** Averaged ion TOF spectrum from Nb, HP filter at 2.5 keV



When deuterated samples are exposed in the scan mode (Fig. 1.c), D^{+} ions are picked up by the detector together with H^{+} when the surface of the wall of the previous crater is tilted towards the TOF detector. (D^{+} ions are never observed in the single shot mode). Under in focus conditions we observe H and D populations extending to 0.5 and 0.7 μs respectively. These flight times correspond to kinetic energies of about 7 keV.

In conclusion, we have observed emission of protons and deuterons with energies approaching 7 keV and of metal ions up to 20 keV. Highly charged metal ions, up to Nb^{+5} and V^{+4} have been created and observed. We propose that the interaction region is cooling rapidly in metals loaded with H/D, as high energy light ions leave the bulk.

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