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Soft x-ray absorption and pump-probe experiments of transient states using FEL sources

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Dynamics of phase transitions has been a long interest in the material science community, while recent studies on the transient states of the nanomaterials have opened a new window into the new whelm of the topological properties. It is now known that the phase transitions in low-dimensional materials are significantly modified by the effect of the shape and size [1]. This effect would have a significant practical impact if observed in extremely small organic and inorganic elements super-positioned within a continuous matrix such as silicon quantum dots in silicon oxide matrix or the metal nanoparticle functionalized within the organic carbon based matrices. However, studying the dynamics of phase transitions and various transient states in these materials is an extremely difficult task which may be accomplished by advanced photon sources, like the new high-brightness of new free electron lasers (FELs).
A promising technique for future soft x-ray experiments is certainly the x-ray absorption spectroscopy (XAS), which is able to provide information about the structural and electronic properties. One of the main advantages of performing XAS experiments at FEL facilities like the prospected EuPRAXIA@SPARC_LAB is the number of photons per pulse, which may exceed 1012 photons/pulse, thus being still significantly higher than that currently achievable at HGG sources. The high intensity of the FEL pulses allows us to acquire data with a good signal-to-noise ratio from single-shots measurements. In this context, X-ray Absorption Spectroscopy (XAS) can be used as a tool to directly observe the local structure of the specimen with typical sub-picosecond time resolution. In particular, either by tuning the undulators to the appropriate energy, or exploiting the natural FEL bandwidth generated in SASE mode, the experiments performed at EuPRAXIA@SPARC_LAB can allow measurements of the informative, low-energy portion of the XAS spectrum, the so-called XANES (X-ray Absorption Near Edge Spectroscopy) region. Quantitative analysis tools of XANES data are nowadays available including those based on first principles calculations and can provide detailed information on the evolution of the local structure.
Therefore, FEL-XAS measurements will become a powerful tool to provide unique information on the local geometry (as well as on electron density and spin states) around selected atomic species. Soft x-rays absorption studies carried out at the EuPRAXIA@SPARC_LAB include the K edge of elements such as C, N and O, and the L edge of 3d transition metals. Examples of pioneering soft L-edge FEL-XAS transmission experiments include measurements of Al, Ge and Ti thin films for variable fluence (see, for example, our previous works carried out at Fermi@Elettra [2–4]). In those experiments, ultrafast electron heating pumping matter at extremely high temperatures, as well as saturable absorption effects were observed. FEL experiments were found to be extremely useful to explore highly uniform warm dense matter (WDM) conditions, a regime exceedingly difficult to reach in present laboratory studies, but relevant to various fields, including high-pressure and planetary science, astrophysics, and plasma production. Various FEL-based ultrafast techniques can be used to probe WDM properties at electron temperatures in the 1–10 eV range and beyond.
The previous studies naturally call for further challenging experiments at the EuPRAXIA@SPARC_LAB FEL as well as for parallel developments of suitable interpretation schemes for modelling and understanding the X-ray absorption cross section under high-fluence conditions (see [5,6] and refs. therein).

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