Laser-driven x-ray diagnostics for heavy-ion heated dense plasmas

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The internal upgrade project to construct a high-energy laser beamline from the PHELIX facility to the HHT cave behind the SIS18 is well underway [1], with first laser pulses on target expected towards the end of 2020. Upon completion, laser pulses with energies up to 200 J at the second harmonic (wavelength 527 nm) with nanosecond duration will become available at this experimental station. These will allow to drive intense x-ray sources based on laser-produced plasmas, which will enable state-of-the-art x-ray probing techniques commonly used at high-energy density facilities worldwide, and which are consequently foreseen as diagnostics for dense plasmas produced with intense heavy-ion pulses at FAIR.

In order to verify the performance of such laser-driven x-ray sources with the laser parameters projected for the HHT-cave, and to demonstrate their suitability for the foreseen diagnostic applications we have performed an experiment at the Z6 experimental area. Laser pulses from both the nhelix and the PHELIX laser systems were used, with pulse energies up to 40 J (in 8 ns) and 160 J (in 1 ns), respectively. Focused down to spot sizes of approx. 50 µm these yield intensities from 10^{14} to $6x10^{15}$ W/cm^2. A variety of mid- to high-Z targets were irradiated, producing hot (few keV) highly-charged plasmas. X-ray emission spectra were recorded by two crystal spectrometers, while the x-ray source size was measured by means of a pinhole camera.

A dual-channel focusing spectrometer based on two conically curved KAP-crystals (developed in collaboration with the university Jena) measured the x-ray emission in the spectral range around 1.6 keV. In this range, targets made from rare earth elements (Sm, Dy, Yb) exhibit strong M-band emission. The high density of emission lines results in a near continuous emission spectrum, suitable for x-ray absorption spectroscopy. As an example, fig. 1 a) shows a single-shot high-resolution absorption spectrum through a 5 µm thick aluminum foil in the vicinity of the Al K-edge. This XANES (X-ray Absorption Near Edge Spectroscopy) technique has a high diagnostic potential and can be used to infer electron temperatures in samples at warm-dense matter conditions, detect edge shifts and shell rebinding, and is sensitive to the local ionic structure [2].

The second spectrometer employing a highly-oriented pyrolytic graphite crystal covered the spectral range 4…9 keV, measuring the strong line emission from Helium-like ions from mid-Z metal targets (Ti, Fe, Ni, Cu). The x-ray yield into this line radiation increases strongly with laser intensity, with a more than 1000-fold increase from the lowest (nhelix) to the highest (PHELIX) energy laser pulses, underlining the need for high-energy laser pulses to efficiently drive these x-ray sources. At the highest intensities the conversion efficiency (laser to x-ray energy) reaches values of nearly 10^{-3}, yielding up to 10^{14} photons at 4.5 keV. A prominent diagnostic application of such intense narrow-band x-ray sources is x-ray diffraction, fig. 1b showing as an example the Debye-Scherrer rings from a 5 µm thick iron foil. For heavy-ion heated targets diffraction will allow to measure changes of the lattice constant due to thermal expansion, observe solid-solid phase transitions [3] and indicate melting. Furthermore, the diffracted intensity can be related to the lattice temperature via the Debye-Waller-factor.

The pinhole camera employed a 25 µm diameter high-Z pinhole, filtering was chosen to image x-ray energies > 4 keV. X-ray source sizes between 50 and 150 µm were measured, with a tendency to larger sizes at higher laser energies. A small source allows for point-projection x-ray imaging as was also experimentally demonstrated with using a test target (cf. fig. 1c). Radiographic imaging of heavy-ion driven samples would allow to observe evaporation and isentropic expansion, interface movement as a

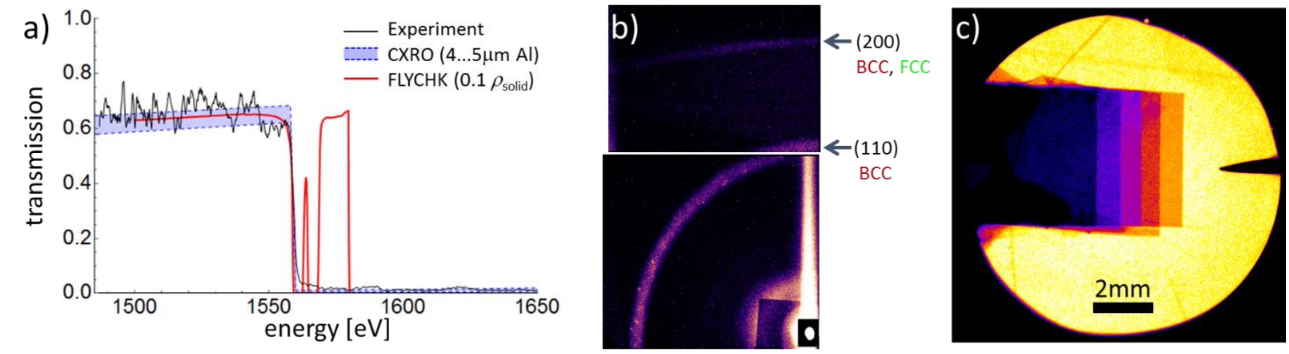

Figure 1: (a) Transmission spectrum around the Al K-edge. Measurements on an Al-sample at ambient conditions (black) are compared to tabulated transmission of solid Al (blue, CXRO [4]), and calculations of a hot, expanded Al-sample (red, FLYCHK [5]). (b) X-ray diffraction rings obtained from a Fe-foil. (c) X-ray image of plastic foil stack and steel needle.

heavy material pushes into a lighter tamper, or fracture and spallation events.

In summary, our proof-of-principle experiments demonstrate the feasibility of using the long-pulse mode of PHELIX to drive an x-rays source suitable for x-ray diffraction, absorption and imaging techniques. Our results on cold test samples show the potential of this laser-driven x-ray source for the investigation of heavy-ion heated states of matter.

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