X-ray spectroscopic diagnosis of hot electron production in laser-irradiated Cu targets

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Generation of suprathermal electrons accompanying interaction of high-intensity lasers with solid targets and their transport through the near-solid density matter [1] have attracted significant interest due to their potential to study the behaviour of matter in extreme conditions. In the same time, hot electrons (hereafter HE) represent one of the key issues for realization of inertial confinement fusion [2]. In the shock ignition approach (SI), a role of hot electrons is ambiguous: they contribute to laser energy transport into pellets and enhancement of ablation pressure but they may also preheat targets. A detailed knowledge of the fast electron generation and transport is therefore of paramount importance for optimization of the SI concept.

A survey of previous HE studies based on x-ray diagnostics can be found, e.g., in paper [3]. Non-Maxwellian electrons affect properties of emitting plasma systems, collisional processes result in creation of holes in inner electronic shells of target atoms and their subsequent filling via radiative transitions. In particular, the $2p\rightarrow 1s$ K-shell fluorescence from relatively cold targets (i.e., Kα emission) studied by advanced x-ray methods provides a direct experimental technique for HE investigation. Here we report on a non-conventional approach to HE diagnosis using a combination of monochromatic x-ray imaging and high-resolution K-shell spectroscopy. This novel method has been developed within a series of experiments being performed at PALS laser facility [4] where laser-plasma coupling is studied at intensities up to 5×10^{16} W/cm^2, i.e., at parameters of the laser spike envisaged to launch the shock wave igniting the fusion reaction. After a brief description of the experiment, we interpret selected x-ray images and K-shell spectra in terms of HE generation by using a detailed ray-tracing analysis of the implemented instruments and Monte Carlo modelling of HE deposition in targets. Implications of this procedure for routine HE diagnosis are discussed. The reported research contributes to development of advanced diagnostic methods for SI-relevant plasmas.

The experiment was carried out using the fundamental (1ω) and frequency tripled (3ω) radiation of the iodine laser (wavelength λ = 1315/438 nm, pulse duration 0.3/0.25 ns, energy 440/170 J focused to intensities $I = 2\times10^{16}/9\times10^{15}$ W/cm^2 for 1ω/3ω, respectively) striking massive or thin-foil Cu targets at normal incidence. In several shots, an additional 1ω laser beam (60 J, 1×10^{14} W/cm^2) preceding the main pulse by 1.2 ns was used to create a long-scale pre-plasma simulating the compression phase of shock ignition. The diagnostic complex is schematically shown in Fig. 1 and fully described elsewhere [3], here we concentrate on high-resolution x-ray diagnosis with emphasis on high-collection efficiency imaging.

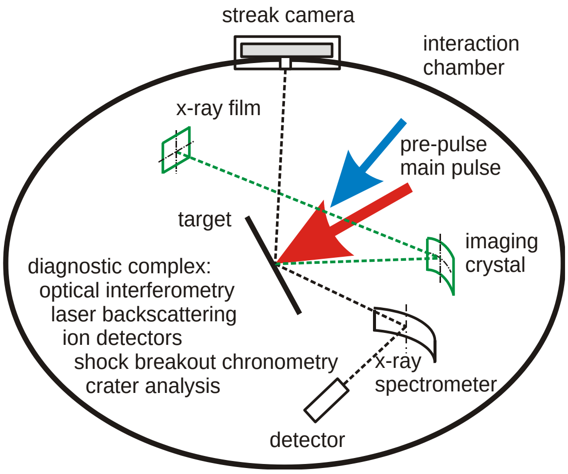

Fig. 1. Scheme of the x-ray experimental setup and complementary diagnostics used.

The time-integrated 2D-resolved images of the Cu Kα emission produced by HE interaction with near-surface copper ions were taken at quasi-normal incidence using the crystal of quartz (422) spherically bent to a radius of 380 mm. Images recorded on x-ray film Kodak Industrex AA400 were digitized and converted to incident photon fluxes with respect to the characteristic curve of the film and filter transmission. The range of photon energies ΔE_i reflected from the crystal surface was rather narrow (ΔE_i=3.86 eV), whereas the range of photon energies relevant for HE diagnosis covers ΔE_s=8–8.265 keV [5]. To correct the recorded signal for the limited spectral coverage, the imaging was complemented by information obtained via high-resolution spectroscopy. The K-shell spectra were observed by using the x-ray spectrometer equipped with the crystal of quartz (223) spherically bent to a radius of 150 mm. The spectra were again recorded on x-ray film, calibrated with respect to dispersion relation of the experimental geometry used and cross-checked via tabulated dominant Cu K-shell transitions. The signal was recalculated to an intensity scale with respect to a variable crystal reflectivity and transmission through filters.

The quantitative interpretation of K-shell spectral emission leans on models correlating the yield of the characteristic x-ray radiation with the action of laser-generated HE [6]. In contrast to our previous estimates of the HE production based on a thin target approximation [7], here the 3D electron trajectories inside the target, generation and transport of x-ray photons were simulated using the Monte Carlo code PENELOPE [8].

The interpretation of K-shell images in terms of the HE generation proceeded in three steps. First the Cu Kα signal recorded above the detector background was recalculated to the source emission. This intermediate result was corrected with respect to the limited spectral range of the imaging by using the information following from the simultaneously recorded x-ray spectrum and finally the resulting K-shell emission was related to the number of suprathermal electrons propagating through the Cu target.

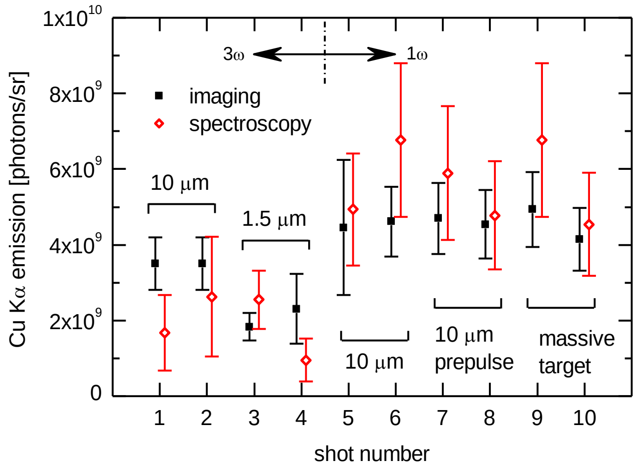

Fig. 2. Comparison of photon fluxes recorded at diverse Cu targets by x-ray imaging and spectroscopy in the spectral window of 3.86 eV at the maximum of the Cu Kα_1 emission.

The performance of the instruments used was analysed via ray-tracing procedure [9] and tested by comparing photon fluxes measured close to the Cu Kα maximum in the spectral window ΔE_i. Comparison of intensities emitted from different-thickness Cu targets under irradiation conditions indicated in Fig. 2 demonstrates that the found fluxes of 1–6×10^{10} photons/4π were identic for imaging and spectroscopy within the error bars (~40%).

The full number of K-shell photons emitted into the energy range of 8–8.265 keV was determined from imaging records by multiplying their integrated signal with a corrective factor relating spectral intensities measured within the above defined ranges of ΔE_s and ΔE_i. These fluxes were subsequently related to the number of generated HE using the independently measured values of HE temperature T_{HE} and the PENELOPE code predictions. The results recalculated to conversion efficiency η of the laser energy in HE are presented in Fig. 3.

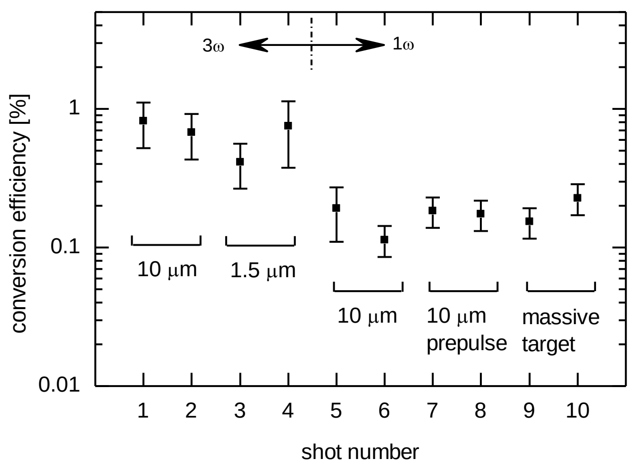

Fig. 3. Conversion efficiency of laser energy in hot electrons at two different laser wavelengths, Cu target thicknesses and the plasma scale-length modified by the pre-pulse.

The found values η are within 0.1-0.2% and 0.2-0.8% for 1ω and 3ω shots, respectively. Absolute values of these fractions are comparable with the previously published data measured at similar laser intensities, see e.g. [10]. Minimum deviations of η observed for different-thickness targets are explained by the low T_{HE}≈30 keV found for current experimental conditions, i.e., by limited penetration of suprathermal electrons inside the targets. Indeed, the stopping length of hot electrons with the energy of 30 keV can be estimated using the continuous-slowing-down-approximation to 3.3 μm [11]. This means that most of electrons deposit their energy within the 1.5-μm-thick near-surface layer due to repeated scattering processes. On the other hand, the higher values of conversion efficiency found at 3ω in comparison with 1ω are rather counter-intuitive. The results of our measurements can tentatively be explained by diverse mechanisms of hot electron generation at 1ω and 3ω. The higher values of conversion efficiency found for frequency tripled radiation support a theoretical conjecture of enhanced laser energy absorption by resonance mechanisms and its transport to a flow of fast electrons [12], however the quantitative confirmation of this conclusion is to be done. The detailed interpretation of the experimentally observed data, in particular the role of different plasma scale-lengths and variable laser coupling parameters including their comparison with theoretical models can be found elsewhere [5].

To conclude, relatively easy-to-align and high-collection-efficiency K-shell imaging combined with the high resolution x-ray spectroscopy offers a novel approach to hot electron diagnosis. The correction introduced by spectroscopic information is of paramount importance for quantitative evaluation of recorded quasi-monochromatic images. The described technique is particularly suitable for a routine monitoring of hot electron generation in the partly ionized matter and can be used even at non-plastic-coated targets. The sample results obtained at variable-thickness Cu targets irradiated by laser beams with two different wavelengths demonstrate viability of this method for characterization of suprathermal electron generation in shock-ignition-relevant plasmas.

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References

[1] M.H. Key et al, Phys. Plasmas **5**, 1966 (1998)
[2] S.Yu. Guskov, Plasma Phys. Reports **39** (2013) 12013.
[3] P. Köster et al, Plasma Phys. Control. Fusion **55** (2013) 124045.
[4] K. Jungwirth et al, Phys. Plasmas **8** (2001) 2495.
[5] O. Renner et al, New Journal of Physics, submitted.
[6] O.F. Kostenko, N.E. Andreev, Quantum Electronics **43** (2013) 237.
[7] M. Šmíd et al, Phys. Scr. **T145** (2014) 014020.
[8] F. Salvat et al, PENELOPE-2008, http://www.nea.fr/html/science/pubs/2009/nea6416-penelope.pdf.
[9] S.G. Podorov et al, J. Phys. D: Appl. Phys. **34** (2001) 2363.
[10] B. Yaakobi et al., Phys. Plasmas **19** (2012) 012704.
[11] M.J. Berger et al, NIST ESTAR database, http://physics.nist.gov/PhysRefData/Star/Text/ESTAR.html.
[12] S.Yu. Guskov et al, Laser Part. Beams 32 (2014) 177.