Laser-matter interaction in magnetized plasmas: x-ray diagnosis of enhanced hot electron energy deposition

O. Renner[1,2,3], S. Agarwal[1,4], J. Badziak[5], M. Červeňák[1], T. Chodukowski[5], J. Cikhardt[1,6], J. Domański[5], R. Dudžák[1,2], D. Ettel[2], P. Gajdoš[1,2], M. Krupka[1,2,7], M. Krus[1], V. Munzar[6], Z. Rusiniak[5], S. Singh[1,2,6], and T. Pisarczyk[5]

[1] *Institute of Plasma Physics, Czech Academy of Sciences, Prague, Czech Republic*
[2] *FZU-Institute of Physics, Czech Academy of Sciences, Prague, Czech Republic*
[3] *ELI ERIC Beamlines Facility, Dolní Břežany, Czech Republic*
[4] *Faculty of Mathematics and Physics, Charles University, Prague, Czech Republic*
[5] *Institute of Plasma Physics and Laser Microfusion, Warsaw, Poland*
[6] *Faculty of Electrical Engineering, Czech Technical University, Prague, Czech Republic*
[7] *Faculty of Nuclear Sci and Phys Engineering, Czech Technical University, Prague, Czech Republic*

Recent progress in the development of strong laser-driven magnetic field generators at high energy laser facilities paves the way to new sort of experiments benefitting from application of well controlled external B-fields. In addition to basic research oriented investigation of fundamental phenomena in extreme parameter plasmas, these experiments also contribute to a design of alternate schemes of inertial confinement fusion where the plasma magnetization might increase the fusion yield [1]. Here we report on investigation of an increased deposition of hot electrons in laser irradiated targets due to external magnetic fields produced near the target surface. The experiment was performed at Prague iodine laser facility PALS, its setup is presented in Fig. 1. The random phase plate smoothed main laser beam (wavelength 1.315 μm,

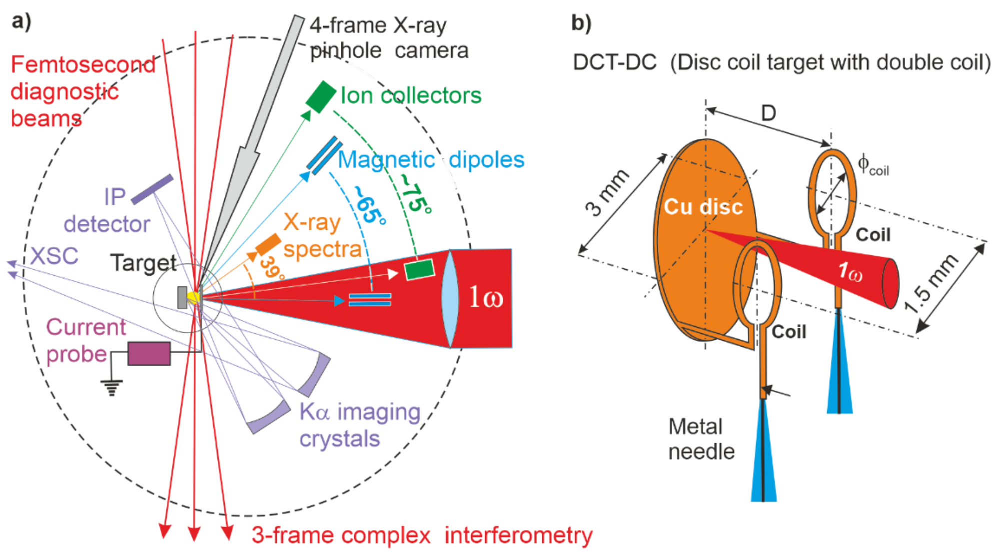

Fig. 1. Diagnostic complex used for studies of hot electron deposition in solids affected by magnetized plasmas (a) and a scheme of target irradiation and magnetic field production with force lines parallel to its surface (b).

pulse energy 550 J, duration 350 ps, intensity 2×10^{16} W/cm^2) was focused onto the 50-µm-thick Cu disc connected with two grounded single-turn coils positioned perpendicularly to its surface (DCT-DC targets). The return current through the disc-coil holder circuit generated the magnetic field parallel to the target surface, its strength was varied by using the coils with different diameters $\varnothing_{coil}$ (1 and 1.5 mm) and distances D from the disc surface (0.8 and 1.2 mm). Based on data from inductive target current probes, the peak values of the magnetic field at midplane between the coils was assessed to about 0.8-1 T. The effects of this field on properties of the laser-created plasma were studied by using the previously described diagnostic complex [2]. Hereafter we concentrate on x-ray diagnosis of the enhanced energy deposition of hot electrons (HE) inside Cu discs via K-shell emission spectroscopy and $K\alpha_1$ monochromatic imaging, both based on diffraction from spherically bent quartz crystals.

The $K\alpha$ photons originate from creation of vacancies in inner atomic shells of quasi solid-state near-surface plasmas by impact of HE or photon fluxes with energies above the Cu K 1s ionization limit (8979 eV) and subsequent $2p \rightarrow 1s$ transitions resulting in $\hbar\omega_{K\alpha}$ fluorescence

$$K^1L^xM^yN^z \rightarrow K^2L^{x-1}M^yN^z + \hbar\omega_{K\alpha}$$

where x, y, and z characterize the electron configuration in L, M, and N atomic orbitals. The frequency of the emitted photons shifts in dependence on environmental conditions of emitting plasmas which burdens their interpretation [3]. These problems are minor when investigating the $K\alpha$ group emission from Cu N-shell (imaging) and M-shell (spectroscopy) charge states which exist for bulk electron temperatures up to 100-200 eV and densities about 0.1 g/cm^3 in several tens of micrometers thick layer near the original target surface [4]. At such parameters, the contributions of the plasma corona self-emission and non-radiative Auger transitions are negligible and the $K\alpha$ radiation can be applied for characterization of the total population and energies of HEs propagating into the dense moderately ionized material of the target.

A design of the low aberration HE imagers benefits from a near-coincidence between the wavelength of the HE-induced Cu $K\alpha_1$ emission (1.5406 Å) and the 2d interplanar spacing (1.5414 Å) of the quartz (422) crystals, here with the bending radii of 360 mm for time integrated and 500 mm for time resolved imaging. In the former case, the 2D-resolved magnified images (M = 1.73) mapping the distribution of the HE interaction inside targets were observed at the angle of ψ = 29º from the surface of the laser-irradiated Cu discs. The images were recorded on the absolutely calibrated imaging plates (IP) Fuji BAS SR and digitized using the scanner with the pixel size 25×25 µm^2. In the latter case, the magnified images (M = 4.81) were observed at the angle of ψ = 55º, projected on the entrance slit of the X-ray Streak Camera (XSC) and recorded with temporal and spatial resolution of 5.35 ps/px and 3.22 µm [2].

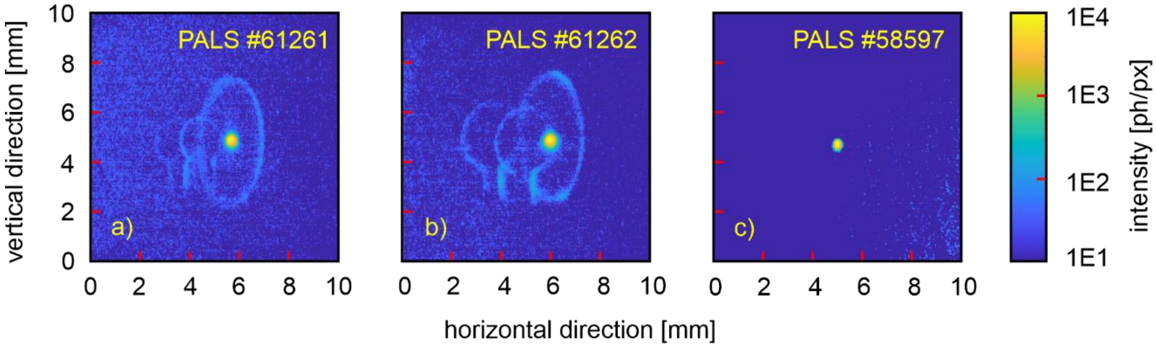

Fig. 2. 2D-resolved time integrated images of the Cu $K\alpha_1$ emission characterizing the HE energy deposition in DCT-DC targets with coil diameter 1 mm, disc-coil distance 0.8 mm (a) and 1.2 mm (b), and bare Cu disc (c).

Selected 2D-resolved images presented in Fig. 2 visualize a principal difference between the HE generation and interaction in DCT-DC and simple Cu disc targets. The FWHM width of the bright central spot at DCT-DC targets is distinctly larger (about 20 µm) than that observed at bare Cu disc and also the HE energy deposited in the central spot of disc coil targets grows by a factor of 1.2-1.4. The second remarkable feature is the increased x-ray emission from the rim of the disc coil targets. Both these phenomena are qualitatively ascribed to the HE deflection from the transverse magnetic field created close to the target surface and, in the case of the rim emission, to the enhanced flux of HEs sliding along the target and its visualization at the Cu disc edge. A distinct Cu $K\alpha_1$ emission from the coils is ascribed to the fluorescence due to the counter-streaming HE and x-ray fluxes. The time resolved images confirmed spatial broadening of the HE affected area in dependence on the target geometry and indicated earlier raise of the HE deposition at the level of several tens of ps. However we should note that all these effects have been investigated without absolute XSC calibration and in a rather limited number of the laser shots, their validation requires further experiments and detailed theoretical interpretation.

The x-ray spectra emitted from disc coil targets were observed with the Johann type spherical crystal spectrometer combining spectral and 1D spatial resolution [5]. The spectrometer was equipped with the quartz (223) crystal ($2d$ = 2.024 A) bent to the radius 150 mm and dispersed

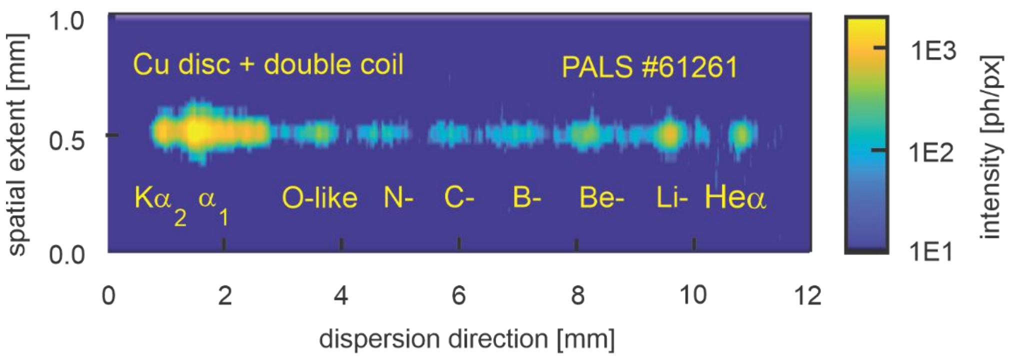

Fig. 3. Raw spectrum recorded with the spherically bent crystal spectrometer. Positions of dominant spectral groups emitted from the Cu K- and M-shell charge states are identified.

the Cu K-shell emission in the vertical plane at an angle of $\psi = 51°$. The time integrated spectra were again recorded on absolutely calibrated SR IP with magnification $M = 0.40$, both spectral and spatial resolution were partly limited by the IP resolution at the level of 60 μm.

An example of the recorded spectrum is depicted in Fig. 3. The covered photon energy range 7950-8500 eV surveys the emission at bulk electron temperature ranging from a cold target material to the hot corona plasma which means that full spectrum cannot be modelled using a single set of plasma parameters. The analysis of the HE action was therefore limited to Cu $K\alpha$ group including M-shell charge states emission. as these states exist only for bulk electron temperature lower than ~200 eV. This temperature is too low to ionize the inner-shell of mid-Z elements, and, consequently, x-ray lines are mostly induced by HEs [6].

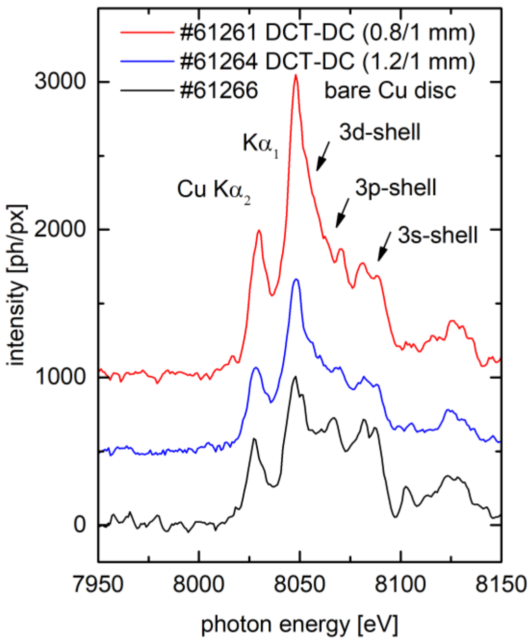

Fig. 4. Magnetic field affected Cu M-shell charge states emission from disc-coil and bare Cu discs.

Intensity distribution in $K\alpha$ and M-shell group measured at different type targets is shown in Fig. 4. Based on collisional-radiative code FLYCHK calculations [7], the emissivity integrated over the range of 8020-8100 eV is proportional to a mg field affected fraction of HEs interacting with the target. Compared to bare Cu disc, emissivity observed at DCT-DC targets grows by a factor up to 1.6 which agrees well with imaging data. The detailed interpretation of the measured Cu $K\alpha$ profiles and 3s,p,d levels redistribution proceeds.

To conclude, the x-ray diagnostics confirm the magnetic field effect on enhanced conversion of the laser energy to HEs and their flux inside the DCT-DC targets. Further studies of the HE generation and interaction with quasi-solid plasmas require detailed modeling of plasma kinetics as well as relevant atomic physics phenomena [3].

The authors acknowledge the CMEYS funding of the PALS facility operation under the grant No. LM2023068.

References

[1] C. Vlachos et al, *Phys. Plasmas* **31**, 032702 (2024).
[2] T. Pisarczyk et al, *Plasma Phys. Control. Fusion* **66**, 115007 (2024).
[3] F. B. Rosmej , V. A. Astapenko , V. S. Lisitsa: *Plasma Atomic Physics*. Springer Switzerland 2021.
[4] M. Šmíd et al, *Nature Communications* **10**, 4212 (2019).
[5] O. Renner, F.B. Rosmej, *Matter Radiat. Extremes* **4**, 024201 (2019).
[6] F.P. Condamine et al, *High Energy Density Phys.* **32** (2019) 89.
[7] H.-K. Chung et al, *High Energy Density Phys.* **1**, 3 (2005).