Progress in x-ray diagnostics of extreme laser plasma states

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Outstanding progress in high power laser engineering paved the way to examine the matter under unprecedented energy concentration in space and time. It makes possible to investigate as novel fascinating phenomena as to reach deeper understanding of various practical aspects of laser plasma applications. However, none of these opportunities could be practically implemented without corresponding development in diagnostics capabilities. The latter is far challenging as it should resolve on the processes and phenomena lasting not longer than picoseconds, with micron scale spatial gradients, and in strongly vibrant environment. As recent experiments testify, significant part of that challenges can be overcome with use of newly developed high resolution X-ray emission and radiography approaches.

X-ray spectroscopy and imaging methods prove their capabilities starting from early ICF experiments with kJ ns lasers. In the next age, the spectral and spatial resolutions merged into X-ray imaging spectroscopy allowing to address dynamic, non-equilibrium and non-uniform conditions. Due to sub-ps emission time and escaping capability of K-shell characteristic X-rays they may deliver the insight into the most interesting early phase of a dense and deeply ionized extreme plasma states. Corresponding methods of multicharged ion emission and absorption analysis considering resonance spectral line intensities, line profiles, satellite structures, exotic states emission etc. were developed and ensembled. They were successfully applied all-round in HED experiments with high power and high-intensity lasers, heavy ion beams, ion traps, X-ray lasers, delivering the data on ultra-intense X-rays and EM-fields generation, charge particle acceleration and stopping, X-ray radiative properties and opacities, exotic atomic kinetics and ionization mechanisms, warm dense and isochorically heated matter, supersonic plasma flows and shock waves.

Nowadays, ultra-relativistic plasma created by (multi)PW lasers commonly have few-micron scales and gradients that unlikely could be spatially resolved in the measured X-ray spectra data. Accordingly, several modern approaches have been developed based on the discrimination of spectral components exclusively emitting at particular stages and/or specific conditions of extreme plasma states. Their implementation particularly allows to trace the plasma ionization mechanisms at ultra-relativistic intensities and fs times, and to address the demand on the measurement of peak laser intensities exceeding 1e22 W/cc.

Similar challenges have to be overcome in X-ray radiography diagnostics. The method is often non-alternative in studies of various hydrodynamic phenomena in laser plasma, including inertial fusion implosions and plasma instabilities, shock waves and equation-of-state measurements, or astrophysically-relevant supersonic plasma flows. They are dynamic, short-lived, low-contrast, containing micron features of interest, while fully opaque for a visible light.

Considering nanosecond timescale of the plasma hydrodynamics, it has been conventionally probed with X-rays emitted from picosecond high-power laser plasma backlighter in a point-projection geometry. Taking into account the demand to provide quantitative measurements on plasma density or compression, some monochromatic and quasi-monochromatic radiography schemes has been developed and widely used. They deliver important part of a puzzle in plasma hydrodynamic studies, however, remain limited in spatial resolution and object contrast sensitivity.

Today, with the advent of X-ray free-electron lasers, the most of such complexities can be addressed in a pack. Femtosecond duration of XFEL probe pulses provides a high temporal resolution far exceeding a common nanosecond timescale of plasma hydrodynamics. Then, an ultra narrow spectral bandwidth, high coherence and extreme brightness of the source enable diffraction-enhanced imaging of objects with low density gradients. XFEL capabilities in plasma radiography became even more remarkable when accompanied with an appropriate high-resolution fluorescent crystal detector. As a particular results, a Rayleigh–Taylor unstable system can be now studied and tracked with ~1 um resolution down to dissipation phase, and the laser-induced shock wave propagation can be mapped in such a detail like a paired plastic-elastic structure directly observed.

Together, X-ray imaging and spectroscopy diagnostics has been capable to progress in parallel with laser engineering and HED physics successfully addressing all the demands and sometimes inspiring the progress in studies of matter under extreme conditions.