STUDY OF EXTREME HYDRODYNAMIC PHENOMENA IN LASER PLASMA BY HIGH-RESOLUTION COHERENT X-RAY RADIOGRAPHY: POSSIBILITIES AND LIMITATIONS

S. S. Makarov

Joint Institute for High Temperatures, Russian Academy of Sciences, Moscow, Russia

National Research Center "Kurchatov Institute", Moscow, Russia

X-ray radiography is a key imaging technique in a wide range of laser-plasma experiments in High Energy Density Physics (HEDP), including laboratory astrophysics and inertial confinement fusion research. It provides a two-dimensional density distribution over the entire volume of an object and enables the study of the temporal evolution of rapidly evolving hydrodynamic phenomena such as laser-induced shock waves or plasma jets, blast waves or hydrodynamic instabilities, which are often opaque to visible light.

The simplest and most widely used probe radiation is an X-ray source based on laser plasma. Typical resolutions achieved today are in the order of 10–20 μm in space and picoseconds in time. As the visibility of the recorded X-ray pattern depends on the brightness, monochromaticity and coherence of the radiation source, the images from laser plasma sources are blurred.

The advent of free-electron lasers (FELs) opened new possibilities and even a new era for X-ray radiography in HEDP experiments. In 2009, the first step was taken at FLASH facility to implement phase-contrast imaging (PCI) in the soft X-ray spectral range at a photon energy of 155 eV [1]. However, the real progress in the development of X-ray methods is associated with hard X-ray FELs (XFELs). These sources offer a unique opportunity for decisive success in the study of extreme hydrodynamic phenomena in laser plasmas by implementing the coherent phase-contrast radiography approach. Firstly, the femtosecond duration of the XFEL probe pulses provides a high temporal resolution, far beyond the usual nanosecond timescale of plasma hydrodynamics. In addition, the extremely high spectral resolution, coherence and extreme brightness of the source enable the acquisition of high-contrast images of objects with low density gradients using the phase-contrast radiography approach.

There are currently three XFEL facilities (LCLS – USA, SACLA – Japan, EuXFEL – Germany) in which stations for investigating the HEDP are in operation. Each station is capable of simultaneously delivering an X-ray pulse and optical pulses of nanosecond and femtosecond duration into the experimental chamber. The combination of an XFEL beam (with probe energy photons of several keV) with powerful optical lasers in a laboratory pump-probe experiment opens unique possibilities for solving problems in laboratory astrophysics, condensed matter physics, laser nuclear fusion and other fields.

In this report, the capabilities and limitations of coherent phase-contrast radiography with an XFEL pulse to study hydrodynamic phenomena in laboratory experiments with laser plasma are discussed in detail [2, 3]. An overview of the latest outstanding studies on laser-induced Rayleigh-Taylor instabilities and elastic-plastic shock waves in nanosecond laser plasmas is given [4–6]. This is particularly relevant in the context of the construction of the "mega-science" class facility "SyLa" (Synchrotron and Laser) in the Russian Federation, which includes an accelerator-storage complex with a 4th generation synchrotron source and an XFEL. The expected parameters and the structure of the complex are described in detail in a recently published work [7]. It is important to underline that in the frame of the project an experimental station at the XFEL dedicated to the study of matter in extreme states (MEC) is being developed. Comprehensive studies of laser plasmas performed in such experiments require the development of suitable X-ray diagnostic techniques.

References

1. **Rosenhahn, A.** Digital In-line Holography with femtosecond VUV radiation provided by the free-electron laser FLASH [Text] / A. Rosenhahn, F. Staier, Th. Nisius et al. // Opt. Expess. – 2009. – Vol. 17. – P. 8220.

2. **Makarov, S. S.** Possibilities of the Phase-Contrast X-Ray Method in a Laboratory Astrophysical Experiment on the Study of Plasma Instabilities [Text] / S. S. Makarov, S. A. Pikuz // Astron. Rep. – 2023. – Vol. 67. – P. 61–70.

3. **Faenov, A. Y.** Advanced high resolution x-ray diagnostic for HEDP experiments [Text] / A. Y. Faenov, T. A. Pikuz, P. Mabey et al. // Sci Rep – 2018. – Vol. 8. – P. 16407.
4. **Rigon, G.** Micron-scale phenomena observed in a turbulent laser-produced plasma [Text] / G. Rigon, B. Albertazzi, T. Pikuz et al. // Nat Commun – 2021. – Vol. 12. – P. 2679.
5. **Makarov, S.** Direct imaging of shock wave splitting in diamond at Mbar pressure [Text] / S. Makarov, S. Dyachkov, T. Pikuz et al. // Matter Radiat. Extrem. – 2023. – Vol. 8. – P. 066601.
6. **Katagiri, K.** Transonic dislocation propagation in diamond [Text] / K. Katagiri, T. Pikuz, L. Fang et al. // Science – 2023. –Vol. 382. – P. 69-72.
7. **Kovalchuk, M. V.** Fourth-Generation Synchrotron Radiation Source with X-ray Free-Electron Laser SILA: Concept of Accelerator–Storage Complex [Text] / M. V. Kovalchuk, A. E. Blagov, O. S. Naraikin et al. // Crystallogr. Rep. – 2022. – Vol. 67. – P. 676–683.