Postprint: Advances in Short-Pulse Laser Laboratory Astrophysics

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Abstract

With the rapid development of Chirped Pulse Amplification (CPA) technology, laser power density has achieved a dramatic increase, rendering the conditions for conducting laboratory astrophysics research using short-pulse lasers increasingly mature. The interaction between short-pulse lasers and targets can produce relativistic particles (electrons and positrons, protons, neutrons, etc.) and high-energy electromagnetic radiation (X-rays, γ-rays), and the generation processes of these particles and radiation correspond to certain physical phenomena in astrophysics. This paper introduces the research progress in laboratory astrophysics using short-pulse lasers, focusing on nuclear astrophysics, hollow ion spectroscopy, relativistic collisionless shock waves, and plasma diagnostics.

Full Text

Research Progress in Laboratory Astrophysics Using Short-Pulse Lasers

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Abstract: With the rapid development of Chirped Pulse Amplification (CPA) technology, laser power density has achieved a leapfrog enhancement, making it increasingly feasible to conduct laboratory astrophysics research using short-pulse lasers. Interactions between short-pulse lasers and targets can produce relativistic particles (electrons, positrons, protons, neutrons) and high-energy electromagnetic radiation (X-rays, gamma rays), with these generation processes corresponding to certain physical phenomena in astrophysical environments. This paper reviews the research progress in laboratory astrophysics us-

ing short-pulse lasers, focusing on nuclear astrophysics, hollow ion spectroscopy, relativistic collisionless shock waves, and plasma diagnostics.

Keywords: laboratory astrophysics; nuclear astrophysics; hollow ion spectroscopy; relativistic collisionless shock waves; plasma diagnostics

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High-energy-density laboratory astrophysics is an emerging interdisciplinary field that originated in the 1990s, primarily relying on high-power lasers, magnetic pinch devices, and tokamaks to construct extreme physical conditions in the laboratory for simulating astrophysical processes and addressing related questions. In laboratory astrophysics research, the relationship between laboratory and astrophysical parameters can be categorized into three types based on their ranges and the degree of analogy in physical processes: "identical," "similar," and "analogous." The "identical" category refers to environments where astrophysical and laboratory conditions match, such as creating plasmas in the laboratory with temperatures and densities consistent with stellar interiors or atmospheres to study equations of state, high-temperature X-ray emissivity, and opacity. The "similar" category applies when some parameters cannot reach "identical" levels as in astrophysical environments but can be scaled proportionally. For instance, while the spatial and temporal scales of certain astrophysical motions far exceed laboratory scales, the governing hydrodynamic equations are identical, allowing physical parameters to be connected through scaling transformations under appropriate conditions. The "analogous" category describes situations where no scaling law has been identified, but the phenomena are similar and involve the same atomic and nuclear processes, enabling comparative studies between astrophysical and laboratory plasmas. Today, laboratory astrophysics encompasses a broad range of research objectives, including nuclear reactions in stellar interiors, equations of state, astrophysical opacity, photoionized plasma spectra near strong radiation sources, hydrodynamic instabilities and collisionless shock waves in supernova remnants, jets from compact objects, and magnetic reconnection in solar flares.

[Figure 1: see original paper] shows several international high-power laser facilities with powers exceeding terawatts (10^{12} W, TW). Laser systems can be divided into two categories based on pulse duration: long-pulse lasers (nanosecond scale) and short-pulse lasers (picosecond to femtosecond scale, 10^{-12} s to 10^{-15} s). Physicists typically characterize laser intensity by power density, defined as I [W/cm^2] = laser power / focal spot area S. In recent years, short-pulse laser power has reached terawatt or even petawatt levels, with target surface intensities of 10^{18}-10^{20} W/cm^2 or higher. At such intensities, electrons oscillate in the laser field at velocities approaching the speed of light, entering a relativistic regime. Consequently, these lasers are also called relativistic lasers. Compared with long-pulse lasers, current laboratory astrophysics research using short-pulse lasers primarily focuses on the "identical" and "analogous" aspects, including nuclear physics, atomic physics, and relativistic physics studies. Additionally, short-pulse laser-driven high-energy particles and radiation serve as effective plasma diagnostics. This paper will review these developments.

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1. Laboratory Nuclear Astrophysics

Nuclear astrophysics helps us understand stellar evolution and explain the origin and abundance of elements in the universe, yet many questions remain unresolved. For example, the standard Big Bang nucleosynthesis model predicts ^{7}Li isotopic abundances 3–4 times higher than observed values, and the enrichment mechanism of metal-poor carbon-enhanced stars remains uncertain. Furthermore, nuclear reaction studies of isotopes with half-lives between 10 and 10^{6} years have attracted considerable interest, as these timescales correspond well to different evolutionary stages of astrophysical objects. Compared to the characteristic evolution time of the Milky Way (~10^{10} years), some isotopic half-lives are negligible. Reproducing these nucleosynthesis processes in the laboratory and studying physical processes that significantly affect reaction cross-sections are crucial for addressing these nuclear astrophysics questions. Experimental platforms for nuclear astrophysics research include heavy-ion accelerators, tandem accelerators, long-pulse lasers, and radioactive beam facilities. This review focuses on studies conducted using short-pulse laser facilities.

Regarding the cosmic lithium problem, relevant nuclear reactions such as ^{3}He(d,p)^{4}He, ^{7}Li(p,α)^{4}He, ^{6}Li(d,α)^{4}He, and ^{11}B(p,3α) have been realized at the 10 TW picosecond Neodim laser facility at the Russian Federal Nuclear Center. Proton spectra, deuteron energy spectra, and neutron signals were observed. Assuming isotropic neutron emission, the neutron yield per laser pulse corresponds to approximately 700 neutrons over 4π steradians [3]. Similar experiments at Moscow State University' s femtosecond laser facility observed the D(γ,n)H reaction with a threshold energy of 2.23 MeV, achieving a neutron yield of 0.1 per pulse at a laser pulse energy of 15 mJ. These results demonstrate that plasmas produced by short-pulse intense lasers can provide fast particles to initiate nuclear fusion reactions.

The high-power laser system HPLS at the European ELI-NP facility (center wavelength 815 nm, peak power up to 10 PW for pulse durations below 22 fs) is planned for studying the influence of plasma environments on astrophysically relevant nuclear reactions. This will help understand screening effects and other observable changes in nuclear physics, such as decay modes and half-lives of unstable states. Screening effects refer to modifications of reaction cross-sections due to electron clouds surrounding nuclei in hot plasma environments. Debates about screening effects have persisted for decades, sometimes requiring their inclusion to explain experimental data. Recently, it has been proposed that screening effects may actually reflect clustering effects in nuclear reactions, particularly those involving light nuclei. Experiments at ELI-NP are expected to clarify this issue.

Laboratory nuclear astrophysics is a rapidly developing research branch. Using short-pulse laser facilities with powers above terawatts makes it possible to achieve the energy densities required for nuclear reactions, enabling us to reproduce Big Bang nucleosynthesis processes and study plasma environment effects on nuclear reactions under laboratory conditions.

2. Spectroscopy of Hollow Ions in Laser Plasmas

The spectral properties of hollow ions have attracted increasing attention in recent years. Hard X-rays with complex power-law spectra emitted from active galactic nuclei can produce hollow ion plasmas through photoionization, and hollow ion plasmas are also closely related to planetary nebulae and X-ray binaries. The definition of hollow ions is not unique but generally refers to ions with vacancies in inner-shell orbitals (K or L shells) that are ionized before valence electrons. Typically, valence electrons tend to become free through collisional processes, while for inner-shell electrons, the photoionization cross-section is inversely proportional to the principal quantum number n^3. When photon energies exceed inner-shell electron binding energies, these electrons can be photoionized. Consequently, complex hollow ion spectra are produced when low-temperature plasmas are exposed to strong radiation fields. This section reviews research on hollow ion spectroscopy using short-pulse laser-target interactions.

Experiments using the Vulcan petawatt laser interacting with 1.5 m and 20 m thick aluminum foils have conducted high-resolution spectroscopic studies. The experiments employed 160 J laser energy with a center wavelength of 1054 nm, pulse duration of 0.7 ps, and focal spot diameter of 8 m, achieving a maximum laser intensity of 3$×10^{20}$ W/cm^2, sufficient to produce photons with energies exceeding aluminum' s K-shell ionization energy (~1.5 keV). Spatially resolved spectra were measured in the range of 7.0–8.4 Å, covering K-shell spectra of aluminum in multiple ionization states. Spectral lines between 7.3–7.7 Å primarily originated from ions with no K-shell electrons, i.e., KK hollow ions, while lines between 7.9–8.3 Å mainly came from KL hollow ions with one vacancy each in the K and L shells. Using the same laser power with two different target thicknesses, observed spectral lines primarily resulted from n=1$→$2 inner-shell transitions, with significantly reduced hollow ion emission lines for the thicker target.

[Figure 2: see original paper] shows experimental spectra from Vulcan PW (black and blue curves corresponding to 1.5 m and 20 m targets) along with theoretical counterparts (pink curves) and experimental spectra from LCLS. Analysis revealed that during interaction of high-intensity (e.g., 10^{20} W/cm^2) laser fields with 1.5 m targets, megaelectronvolt-scale electrons were produced. Under the influence of target surface fields, some high-energy electrons oscillated between the front and back surfaces of the foil—a process called refluxing. The 1.5 m thin foil is essentially transparent to these relativistic electrons, which rapidly lose energy through Thomson scattering and bremsstrahlung processes in the surface plasma fields, generating X-rays and forming a kiloelectronvolt radiation field with intensity exceeding 5$×10^{18}$ W/cm^2. X-ray photons ionized inner-shell electrons to form hollow ions. For the 20 m thick foil, the refluxing time was longer, reducing the frequency of interaction between fast electrons and the laser/plasma fields, thereby decreasing X-ray generation efficiency. Consequently, Figure 2 shows clear differences in self-emission spectra between the two target thicknesses due to different radiation field intensities irradiating the plasma, confirming that this experiment was dominated by radiation processes.

In addition to optical lasers, accelerator-based short-pulse free-electron lasers have also been used to study hollow ions. Using LCLS, 80 fs X-ray short-pulse quasi-monochromatic laser pulses were focused onto 1 m thick aluminum foils with a focal spot area of 9.1$\pm 0.8\mu m^{\{2\}.Photonenergiesrangedfrom1560–1830eVatanintensityof1.1\times10}${17}$ W/cm^2, with observed spectra covering 1460–1680 eV. The laser pulse duration, along with timescales for electron heating, photoionization, and Auger processes, were fast compared to atomic motion and hydrodynamic expansion of the target. For example, aluminum ions at 150 eV temperature could only move 5 nm in 100 fs, far less than the target thickness, while hydrodynamic expansion time for a 1 m thick target was roughly estimated at 20 ps. Considering electron-ion equilibration times are expected to be less than 10 ps, the experimental conditions can be considered to produce uniform, warm dense matter. Kα spectral lines were observed, and analysis showed that absorption in the aluminum foil was dominated by K-shell photoionization, as the K-shell photoionization cross-section is more than ten times larger than those for L-shell and valence electrons. After K-shell vacancy formation, filling was primarily completed by KLL Auger processes, creating two vacancies in the L shell. The X-ray photons served not only as the energy source for photoionization but also as a selective probe. The narrow photon energy range of free-electron lasers only affects ions whose ionization energies fall within this range, making the observed spectra from free-electron laser experiments appear cleaner than those from Vulcan experiments (Figure 2).

For hollow ion spectroscopy experiments using short-pulse lasers, laser parameters, target materials, and thicknesses significantly affect the generated radiation field. Appropriate combinations can produce large quantities of high-energy photons (exceeding target atom K- or L-edge ionization energies). Hollow ion spectra are generally complex because numerous outer-shell electron configurations must be considered, resulting in a large number of configurations in calculations. Even with today' s substantially improved computational capabilities, this remains a considerable challenge for theoretical spectral calculations.

3. Relativistic Collisionless Shock Waves

Shock waves are ubiquitous in astrophysical environments, including the solar-terrestrial space, supernova explosions, and gamma-ray bursts. Due to low densities and high ejecta velocities in astrophysical environments, most observed astrophysical shock waves are collisionless, meaning their spatial scales are much smaller than Coulomb collision scales between ions. Based on shock velocity, shock waves can be classified as non-relativistic or relativistic. For example, shock waves in solar-terrestrial space and supernova explosions have velocities of approximately 1000–10000 km/s and are non-relativistic, while those in gamma-ray bursts propagate near light speed and are relativistic. Astronomical observations reveal that shock formation is accompanied by production of high-energy particles and even cosmic rays. It is widely accepted that cosmic rays with energies below $10^{15 \cdot 5}$ eV in the power-law spectrum originate primarily from non-relativistic shock acceleration within the Milky Way (e.g., supernova explosions), while those above $10^{15 \cdot 5}$ eV mainly come from relativistic shock acceleration outside the Milky Way (e.g., gamma-ray bursts). Recent rapid developments in short-pulse laser technology have made laboratory studies of relativistic shock waves possible.

Theoretical studies indicate that relativistic shock waves are generated when upstream incident particles are confined to localized regions under the influence of Weibel self-generated magnetic fields until discontinuities in density, temperature, velocity, and pressure emerge. During shock formation, incident charged particles can gain energy by repeatedly crossing the shock upstream and downstream while constrained by turbulent magnetic fields—this is the Fermi acceleration mechanism proposed to explain cosmic ray formation. To study relativistic shock generation and acceleration processes in the laboratory, stable Weibel shocks must first be obtained. According to the Weibel instability growth rate, it is evident that the growth rate depends on beam particle species, beam velocity, and density. Beams with higher density, higher velocity, and lower particle mass more easily excite Weibel instability and induce Weibel shock formation. Positron-electron plasma beams provide the most ideal environment for laboratory studies of relativistic Weibel shocks. However, limited by current short-pulse laser intensities, beam velocity (i.e., relativistic electron energy) is difficult to substantially increase. Increasing positron-electron yield to raise beam density represents a promising research approach.

[Figure 3: see original paper] shows the relationship between positron yield and laser energy [12], while Figure 4 presents simulated positron yield versus laser intensity [12]. Short-pulse laser interactions with high-Z solid targets can produce megaelectronvolt-scale positron-electron pair plasma beams through the Bethe-Heitler (BH) process. In this mechanism, relativistic electrons generated at the target front surface produce high-energy X-rays via bremsstrahlung, which then irradiate the high-Z metal target to create positron-electron pairs near high-Z atomic nuclei, with each pair reaching energies of several to tens of megaelectronvolts. Experiments at the Titan, Orion, and Omega EP short-pulse laser facilities have increased positron yields by 30 times to 10^{11}/kJ using the BH method. However, the number of relativistic positron-electron pairs still falls short of requirements for relativistic collisionless shock wave studies. Data analysis revealed a non-linear relationship between positron yield and laser energy, with yield proportional to the square of energy within the experimental parameter range. Using two lasers with different pulse durations, shorter pulses were found to produce higher intensities and more positrons (Figure 3). Theoretical analysis of experimental results predicts that higher-energy laser facilities will increase positron-electron pair yields. Simulations using different models show that for 1 mm thick gold targets, positron-electron pair yield increases with laser intensity, reaching maximum at 2$×10^{20}$ W/cm^2. As laser intensity continues to increase, although overall positron yield still rises, the efficiency of positron production decreases because the initially generated relativistic electrons have excessively high energies (Figure 4).

Currently, laboratory research on relativistic collisionless shock waves is focused on "how to achieve the physical conditions required for relativistic collisionless shock waves," with stage-wise progress and promising results. Chen et al.' s work [12] predicted positron yields near 10^{20} W/cm^2 intensity through simulations, and we anticipate data on positron yields at higher intensities from future theoretical or experimental studies.

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4. Laser Plasma Diagnostic Methods

Using radiation sources produced by short-pulse laser-target interactions for plasma radiography provides rich physical information. Two common radiography techniques are currently used for laboratory plasma diagnostics: X-ray backlighting and proton radiography. The former is more sensitive to plasma density and temperature, primarily measuring density and temperature variations caused by hydrodynamic instabilities and shock wave propagation. The latter is more sensitive to electromagnetic fields, enabling diagnosis of dynamic electromagnetic field processes such as magnetic field generation (Biermann battery effect), magnetic field dissipation, and energy conversion (magnetic reconnection). The temporal and spatial resolution of plasma radiography depends on the physical processes of short-pulse laser-target interactions. Temporal resolution is generally comparable to the laser pulse duration (femtosecond or picosecond), while spatial resolution depends on the radiation source size, approximately tens of micrometers.

Table 1 lists the photon energies of Kα lines emitted by different target materials when interacting with lasers. For molybdenum (Mo), copper (Cu), and other materials, the Kα photon energies are 4.95 keV, 8.04 keV, 17.4 keV, and 58 keV respectively.

Below we describe the working principles and applications of these two radiography techniques. First, X-ray backlighting technology: short-pulse laser-target interactions produce intense X-ray radiation with conversion efficiency of approximately 10^{-4}–10^{-5}. When X-rays propagate through optically thick media (high-density plasmas), some X-rays are deposited due to penetration depth limitations, causing intensity changes. By comparing transmitted intensity with initial intensity, plasma density and temperature information can be obtained. For example, at the LULI2000 facility, researchers simulated the physical process of material flows from a white dwarf's accretion companion colliding with the white dwarf surface. Picosecond short-pulse lasers interacting with different target materials generated Kα lines at various energy bands as backlighter sources (Table 1) to image plasma dynamic evolution. High-Mach-number (M=5–10) plasmas interacting with aluminum planar targets produced reverse shocks, while small-scale structures (tens of micrometers) were also observed. These fine structures could be resolved because the X-ray backlighting technique employed achieved spatial resolution better than 30 m.

When X-rays pass through optically thin media, their intensity remains essentially unchanged, but their phase undergoes significant modification. Using X-ray phase changes to diagnose plasma density distribution is called X-ray Phase-Contrast Imaging (XPCI). XPCI is based on phase changes of X-ray photons induced by density gradients, making synchrotron radiation and free-electron lasers ideal platforms because these facilities can generate high-flux, high-energy coherent radiation. With the advent of short-pulse lasers, XPCI can also be implemented using incoherent X-rays. At the PHELIX laser at GSI, researchers used short-pulse laser-generated X-ray sources for XPCI measurements of shock wave structures. A 25 J, 0.5 ps, 1.06 m short-pulse laser focused to a 5 m spot on a tungsten wire produced target surface intensities of approximately 6$×10^{19}$ W/cm^2. Relativistic electrons transmitted through the wire generated X-rays via bremsstrahlung. Another laser beam (25 J, 2 ns, 1.06 m) interacting with a plastic target produced shock waves propagating into the target. Experimental results clearly revealed phase changes at density interfaces, while traditional X-ray imaging under the same conditions could not provide comparable detail. This demonstrates that XPCI is more sensitive to density variations than conventional X-ray imaging, enabling detection of different density regions in a single measurement and observation of fine details in shock wave structures even at low X-ray flux. This is highly valuable for studying interfacial hydrodynamic processes such as Richtmyer-Meshkov and Kelvin-Helmholtz instabilities.

In addition to X-rays, short-pulse laser-target interactions can produce high-energy protons (tens of megaelectronvolts). Proton radiography utilizes these energetic protons passing through plasma regions with electromagnetic fields, where their trajectories are altered by these fields and recorded by detection media. By analyzing spatial distributions of proton flux on the recording medium, changes in transmission trajectories can be reconstructed, ultimately revealing electromagnetic field configurations and intensity distributions. The most common method for generating proton sources is target normal sheath acceleration (TNSA), where short-pulse lasers focused on planar targets accelerate protons to megaelectronvolt energies. Researchers used a 1 ps, 300 J short-pulse laser at OMEGA EP interacting with a 20 m thick copper target to generate a proton radiography source, successfully imaging self-generated magnetic fields from long-pulse laser interactions with high resolution and observing ring-shaped magnetic fields around the target area produced by the Biermann battery effect [10]. Based on magnetic field topology in magnetic reconnection, researchers cleverly designed experiments using these ring-shaped magnetic fields to measure magnetic reconnection processes with high-resolution proton radiography, revealing typical characteristics of laser-driven magnetic reconnection.

Using short-pulse lasers as plasma diagnostic tools offers high spatiotemporal resolution and plays an irreplaceable role in diagnosing rapidly evolving processes. In laboratory astrophysics, these techniques enable not only fine observations of fluid motion, shock wave structures, and instability development but also hold diagnostic potential for radiation processes.

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5. Conclusions and Outlook

Short-pulse lasers possess unique advantages in laboratory astrophysics. Compared to long-pulse lasers, reducing pulse duration while maintaining the same laser energy can increase laser power to petawatt levels and intensities to 10^{23} W/cm^2, substantially enhancing energy and power densities in laboratory environments. Short-pulse laser-target interactions produce relativistic electrons, subsequently generating X-rays, gamma rays, high-energy protons, and positron-electron pairs, significantly expanding research objects and parameter ranges in laboratory astrophysics. The areas discussed in this paper—nuclear astrophysics, hollow ion spectroscopy, relativistic collisionless shock waves, and diagnostic methods—are currently in a rapid development phase. We should seize this opportunity to combine short-pulse lasers with other experimental facilities to fully exploit their advantages for theoretical and experimental research. Internationally, higher-power short-pulse lasers are under construction, such as Europe' s ELI, China' s 10 PW facility (Shanghai Zhangjiang High-Tech Park), and 100 PW facility (Guangdong Zhongshan Photon Science Center). The advent of next-generation higher-power short-pulse lasers will further expand laboratory parameter ranges, enabling studies of more extreme astrophysical environments.

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Note: Figure translations are in progress. See original paper for figures.