Pulsed neutron source from interaction of petawatt femtosecond laser with pitcher-catcher

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Abstract

Production of pulsed neutron sources from petawatt-class femtosecond laser interacting with pitcher-catcher target is studied by comprehensively using radiation hydrodynamic, particle-in-cell and monte-carlo simulations. We find that the preplasma from the ablation of laser prepulse is beneficial for increasing the neutron yield. Be converter as the catcher layer could offer superior performance in improving the quality of neutron source. For the experimental consideration, a novel converter with LiH ceramic wrapping Be material is designed to maintain emissions within safety limits and achieve high retention rate. With a laser of intensity 4\$×1021$W/cm2,duration30fsandpower1.45PW,onecanobtainaforward-peakedneutronsourceofyield1.95\times$\$1010, duration 150 ps and maximum energy ~70 MeV. This high-quality pulsed neutron source can be produced at a high repetition rate, and is promising for industrial non-destructive tests and related applications.

Full Text

Preamble

Pulsed Neutron Source from Interaction of Petawatt Femtosecond Laser with Pitcher-Catcher Target

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We investigate the production of pulsed neutron sources from petawatt-class femtosecond laser interaction with pitcher-catcher targets through comprehensive radiation hydrodynamic, particle-in-cell, and Monte Carlo simulations. Our findings reveal that preplasma generated by laser prepulse ablation significantly enhances neutron yield. Beryllium converters as catcher layers demonstrate superior performance in improving neutron source quality. For experimental implementation, we design a novel converter featuring LiH ceramic wrapping Be material to maintain emissions within safety limits while achieving high retention rates. With a laser intensity of 4×10^{21} W/cm^2, pulse duration of 30 fs, and power of 1.45 PW, one can obtain a forward-peaked neutron source with yield of 1.95×10^{10}, duration of 150 ps, and maximum energy of 70 MeV. This high-quality pulsed neutron source can be produced at high repetition rates and shows promise for industrial non-destructive testing and related applications.

Keywords: Petawatt femtosecond laser pulse; pitcher-catcher target; preplasma; converter

Introduction

Neutron sources serve as essential tools for interdisciplinary research and find extensive applications in material structure analysis, biomedicine, industrial non-destructive testing and safety monitoring, and nuclear energy research [?]. High-flux pulsed neutron sources have emerged as critical platforms for advancing cutting-edge scientific and industrial innovations.

Currently, high-flux pulsed neutron sources primarily rely on spallation reactions, such as the China Spallation Neutron Source, where 1.6 GeV protons bombard tungsten or uranium targets [?]. In this process, each proton generates approximately 20–30 neutrons, with output pulse durations ranging from 4 to 30 ns and peak flux reaching 10^{16}-10^{17} n/cm^2/s [?]. To achieve higher temporal-spatial resolution, there remains a need to develop high-quality neutron sources with greater flux and shorter pulse durations.

The development of chirped pulse amplification (CPA) [?] and optical parametric CPA [?] technologies has significantly advanced ultraintense, ultrashort laser systems. Laser pulses with intensities of 10^{18}-10^{23} W/cm^2 and durations ranging from picoseconds to femtoseconds are now available in laboratories [?, ?]. When such pulses interact with matter, they generate energetic charged-particle beams and bright secondary radiations with extremely high number densities and short pulse durations within compact spatial scales \cite{8-12}. By inducing various nuclear reactions, it becomes possible to produce pulsed neutron sources with peak flux exceeding 10^{18} n/cm^2/s, durations from hundreds of picoseconds down to femtoseconds, and focal spots at the centimeter scale \cite{13-16}. Among all laser-based neutron production schemes \cite{17-23}, the pitcher-catcher target configuration proves particularly promising for developing compact, high-flux pulsed neutron sources \cite{24-27}. In this scheme, protons or ions (e.g., deuterium ions) are first accelerated when a laser pulse irradiates the pitcher layer, and subsequently strike the catcher layer (i.e., converter), where neutrons are produced through various nuclear reactions [?]. To achieve high neutron yields, sub-picosecond or multi-picosecond petawatt (PW) laser pulses are typically employed in experiments because they can deliver tens to hundreds of joules of laser energy \cite{27,29-34}. Additionally, the energy conversion efficiency from laser to ions can reach relatively high levels of up to 10% [?, ?].

However, for practical applications, PW femtosecond laser systems may offer greater advantages in neutron source production, as they can simultaneously achieve high repetition rates and high yields while maintaining device compactness. Recently, numerous PW-fs laser facilities have become operational worldwide [?], providing the foundation for developing compact, high-flux, high-repetition-rate pulsed neutron sources.

For PW-fs laser-driven neutron sources, two key factors require special attention: preplasma and converter design. Modern PW-fs laser systems can focus laser pulses to intensities ranging from 10^{21} to 10^{23} W/cm^2 [?]. Using advanced laser cleaning techniques [?] such as plasma mirror methods \cite{37-39}, the laser contrast (the intensity ratio between the main pulse and amplified spontaneous emission pedestal) can exceed 10^{10} [?]. Nevertheless, prepulse intensities may still surpass 10^{11} W/cm^2 [?, ?], with a steep temporal rising edge before the main pulse. This can induce preplasma with a certain scale length in front of the target [?, ?], potentially affecting laser ion acceleration and subsequent neutron production [?]. The converter represents another critical factor, as its design must be optimized for specific ion beam energy characteristics to achieve high nuclear reaction cross-sections and strong radiation resistance.

In this paper, we investigate neutron production from PW-fs laser pulses interacting with pitcher-catcher targets in the presence of prepulses, emphasizing the detailed influence of preplasma and converter materials on neutron quality. We find that the laser prepulse significantly alters the density profile of the pitcher layer, with preplasma from prepulse ablation leading to remarkable increases in neutron yield. Among common converter materials, beryllium offers advantages for high-yield neutron production. Considering experimental safety requirements, we design a novel converter structure with LiH ceramic wrapping Be material to maintain high nuclear reaction cross-sections and strong irradiation resistance. Under typical PW-fs laser irradiation parameters, one can obtain a forward-peaked neutron pulse with yield $>10^{10}$, duration 150 ps, and maximum energy in the tens of MeV range. Such a high-quality neutron source shows promise for industrial non-destructive testing and related applications.

The paper is organized as follows. Section 2 introduces the laser and pitcher-catcher target parameters along with the simulation methodology. Section 3 presents preplasma formation from laser prepulse ablation of the pitcher layer and the interaction of the main pulse with the ablated pitcher layer. Section

4 characterizes neutron sources produced through nuclear reactions as the accelerated proton and ion beams transport through converters, discussing the effects of preplasma and converter material. Section 5 proposes a novel converter optimized for typical PW-fs laser pulses. Finally, Section 6 provides a summary.

II. Simulation Model and Laser-Target Parameters

We comprehensively employ the radiation hydrodynamic (RHD) code FLASH [**?**], particle-in-cell (PIC) code EPOCH [**?**], and Monte Carlo (MC) code GEANT4 [**?**] to investigate preplasma formation, laser-target acceleration, and neutron generation, respectively. A schematic of the laser pulse interaction with a pitcher-catcher target is shown in Fig. 1 [Figure 1: see original paper].

Considering the actual power of current PW-fs laser pulses striking the target, particularly for high-repetition-rate operation, we simulate four different power scenarios: P = 0.18 PW, 0.36 PW, 0.72 PW, and 1.45 PW. These laser pulses, with a wavelength of 0.8 μm and period T_0 = 2.67 fs, are linearly polarized (LP) and focused onto the front surface of the target at a 5° incidence angle. Their temporal and spatial profiles follow Gaussian distributions, with a pulse duration of 30 fs and focal spot diameter of 4.8 μm. The corresponding laser intensities are 5×10^{20} W/cm^2, 1×10^{21} W/cm^2, 2×10^{21} W/cm^2, and 4×10^{21} W/cm^2, with normalized amplitudes $a = eE_0/m\,\omega_0 c$ = 15, 22, 31, and 43, respectively. Here, $-e$ and m are the electron charge and mass, E_0 and ω_0 are the laser electric field amplitude and angular frequency, and c is the speed of light in vacuum. For all scenarios, the contrast ratio remains constant at 10^{10}, referencing the SILEX-II laser system [**?**].

The target consists of a CD_2 pitcher layer with thickness d_0 = 5 μm and a catcher layer (converter) with thickness d_2 = 3 cm, separated by a distance L_0 = 1 cm. A natural contamination layer behind the pitcher layer is modeled as an ultrathin carbon-hydrogen-oxygen film with thickness d_1 = 20 nm. The ion density ratio of this contamination layer is C:H:O = 2:4:1, corresponding to an electron density of 3×10^{22} cm^{-3} [**?**]. The converter is designed as a cubic structure with 10 cm edge length.

The FLASH simulation is performed in a two-dimensional Cartesian coordinate system, with laser deposition achieved through ray-tracing projection [**?**]. The Courant-Friedrichs-Lewy (CFL) time limit is set to 0.4, and equation-of-state and multi-group opacity tables are obtained from PROPACEOS. The FLASH code employs an adaptive mesh refinement (AMR) scheme with coarsest/finest mesh sizes of 0.04/0.026 μm in the axial (x) and radial (y) directions.

Preplasma profiles obtained from FLASH simulations are fully incorporated into PIC simulations as the initial density distribution of the pitcher layer. The pitcher and contamination layers are considered fully ionized due to laser prepulse ablation. In EPOCH simulations, the simulation box measures x × y = 100 μm × 30 μm with 10,000 × 1,500 cells and 36 macro-particles per cell.

Open boundary conditions are applied for both particles and fields at all boundaries. The pitcher layer is initially positioned between $x = 21$ μm and $x = 26$ μm. Subsequently, all position, momentum, energy, and particle weight information for ions from the EPOCH simulation is imported into the GEANT4 post-processing program within the MC framework. Only ions with momentum $p\ > 0$ are considered valid, as ions with $p\ < 0$ cannot reach the converter. The neutron reaction module is activated to invoke the relevant nuclear reaction cross-section database for simulating neutron generation. In GEANT4 simulations, laser-accelerated ion beams can be treated as a point source since their spatial size is much smaller than the converter. To investigate prepulse effects on neutron production, we also conducted full-process simulations without laser prepulses. The role of converter material is discussed by comparing three common materials: LiF, LiD, and Be. In these simulations, we vary one parameter at a time while keeping others constant.

III. Petawatt Femtosecond Laser-Driven Ion Acceleration

Figure 2 [Figure 2: see original paper] shows the density distribution of the CD_2 pitcher layer at $t = 120$ ps under different laser powers P from FLASH simulations. The preplasma primarily appears within the transverse range of the laser focal spot region due to prepulse ablation of the pitcher layer. As P increases, the radiation heat wave becomes stronger, drilling deeper into the pitcher layer. The peak density of the CD_2 layer correspondingly increases, and the preplasma in front of the pitcher layer expands to a larger spatial scale along the $-x$ direction. From the axial density distribution, we observe that the density profile becomes less steep with disturbances appearing in the high-density region. Overall, the laser prepulse significantly alters the density distribution of the pitcher layer, particularly creating a preplasma of certain scale length that may affect energy absorption of the main laser pulse.

PIC simulations investigate the dynamics of the main laser pulse interacting with the ablated pitcher layer. Figure 3 [Figure 3: see original paper] shows electron density distributions, spectra, and longitudinal electric fields at $t = 60T_0$ for cases with and without preplasma from prepulse ablation. Dense oscillating bunches are generated through betatron-like resonance \cite{51-53} as relativistic self-focusing occurs within the preplasma [?]. These electrons transport through the high-density region to the rear of the pitcher layer, with most moving forward and possessing much higher energies than in the case without preplasma. The hot electron temperature even exceeds the Wilks ponderomotive scaling $T\ = ((\surd(1 + a_0{}^2/2) - 1)m\ c^2$ [?]. Originating from these "superponderomotive" electrons \cite{55-58}, a stronger (at least 1.5 times) sheath electric field E is induced, as its amplitude is proportional to T and increases with P [?]. The longitudinal electric field in front of the pitcher exhibits a distinct zonal structure attributed to interference between incident and reflected laser light.

Figures 4(a)-4(f) show density and spectral distributions of protons (H^+) and deuterium (D^+) ions at $t = 100T_0$ for different P values. The ion densities exhibit a layered structure. Due to their relatively large charge-to-mass ratio [?, ?], protons can be accelerated to higher velocities by the sheath electric field through the target normal sheath acceleration (TNSA) mechanism [?], concentrating at the front. In contrast, heavier D^+ ions have lower energy per nucleon and distribute toward the rear, acting as a buffer layer that creates small quasi-monoenergetic spikes in the proton spectra [?], as shown in Figs. 4(e)-4(h). Notably, D^+ ions also separate into two layers, a phenomenon that becomes particularly prominent at higher P. The first layer consists of high-energy D^+ ions accelerated in the sheath electric field established by energetic electrons in the preplasma, while the second layer comprises lower-energy D^+ ions contributed by hot electrons from J × B heating [?, ?] when the main laser pulse interacts with the compressed high-density pitcher layer. Preplasma facilitates ion acceleration, increasing D^+ ion and proton energies by 2 times and 1.5 times, respectively.

The angular distribution dN /d for both ion species in cases with and without preplasma is presented in Figs. 4(i)-4(l). Proton divergence (= 20°) is slightly larger than D^+ ion divergence (_D = 12°) due to strong Coulomb repulsion from D^+ ions on front protons. This repulsion becomes more pronounced at higher P (e.g., 1.45 PW), causing significant increases in while proton numbers at = 0° decrease substantially, as shown by the green lines in Figs. 4(k) and 4(l). Regardless of preplasma presence, the divergence angles of both ion species remain essentially identical because the thermal diffusion depth [?] L = 5.23 × 10^{-3} µm is much smaller than d_0 = 5 µm, where $\alpha = 2.28 \times 10^{-7}$ m^2/s is the thermal diffusion coefficient and τ_{prepulse} = 120 ps is the prepulse duration. During prepulse ablation, heat remains confined to the front of the pitcher layer without penetrating it, so the CD_2 layer avoids damage from thermal expansion and performs similarly to the case without preplasma. The number of protons around = 0° is much smaller than D^+ ions because protons originate only from a very thin contamination layer, and the electrons contributing to their acceleration mainly come from preplasma with quantities far below those of hot electrons from the pitcher layer in the absence of preplasma.

IV. Neutron Production in Converters of Different Materials

When proton and D^+ ion beams strike LiF, LiD, and Be converters, neutrons are produced through different nuclear reaction channels. For LiF converters, the channels are $^7Li(d,n)^8Be$ and $^7Li(p,n)^7Be$; for LiD converters: $D(d,n)^3He$, D(p,n+p)p, $^7Li(d,n)^8Be$, and $^7Li(p,n)^7Be$; and for Be converters: $^9Be(d,n)^{10}B$ and $^9Be(p,n)^9B$. During nuclear reactions, neutron yield can be approximated as Y Σ n · σ · Φ [?], where n is target nucleus density, σ is the reaction cross-section for the i-th incident ion, and Φ is their flux. With increasing P or when preplasma is considered, Y is remarkably enhanced due to improved Φ , as shown in Figs. 5(a)-5(c). For LiF, LiD, and Be converters, n values are 6.11 × $10^{22}/cm^3$, 1.208 × $10^{23}/cm^3$, and 1.235 × $10^{23}/cm^3$, respectively.

When proton and D^+ ion energies exceed 2 MeV and 3 MeV, respectively, σ for Be material are the highest among all reaction channels [**?**]. Consequently, Be converters should yield the highest Y , followed by LiD, with LiF lowest, which agrees well with Figs. 5(a)-5(c). Figures 5(d)-5(f) show neutron spectral distributions for the three converter materials with and without preplasma at different P. Maximum neutron energy E ,max correlates positively with P, and neutron numbers at specific energies increase as more protons and D^+ ions are accelerated to higher energies. Be converters are most beneficial for obtaining high neutron energies, particularly at higher P (e.g., P = 1.45 PW).

Figure 6 [Figure 6: see original paper] shows neutron angular distribution dN /d for both cases. Regardless of preplasma presence, the distribution remains roughly the same since dN /d shows no significant difference in Figs. 4(i)-4(l). Interestingly, with increasing P, these neutron sources exhibit excellent forward-peaked characteristics. Counting neutrons with P > 0 reveals they account for 70% ± 5% of total neutrons, primarily consisting of high-energy neutrons (for Be converter at P = 1.45 PW, E reaches 75 MeV). This phenomenon can be qualitatively understood through impulse-mass coupling in nuclear reaction dynamics. During nuclear reactions, momenta of incident ion (p), target nucleus (p), residual nucleus (p), and neutron (p) must satisfy momentum conservation: p + p = p + p . Since the target nucleus is essentially at rest (v   0) and the residual nucleus velocity is extremely small (v   0), we have p   p , meaning the neutron inherits the incident ion’ s direction of motion. If v ≠ 0, the neutron may deviate from the incident ion direction.

We quantitatively estimate the proportion of forward neutrons. In the center-of-mass frame, the angular distribution of nuclear reaction differential cross-section is strictly described by quantum scattering theory [**?**, **?**]. Its Legendre series expansion form can be written as dσ/dΩ = Σ $_0$^∞ (2 + 1)P (cos _c)exp[− (+ 1)/ ^{2}], where P (cos _c) is Legendre polynomial, _c is neutron scattering angle, and   is the partial wave angular momentum channel. $_0$ = kR is the angular momentum cutoff parameter determined by nuclear geometric structure. The reduced wave number k = √(2 E)/ħ, where   is reduced mass, E is incident ion energy, and ħ is reduced Planck constant. R = 1.25A^1/^{3} fm and A are target nucleus radius and mass number, respectively.

In the high-energy region (E > E), dσ/dΩ exhibits a pronounced forward peak since $_0$ = √ ^{2} E [**?**], where E   = |Q|(1 + m /m) is nuclear reaction threshold energy, Q is net energy released, and m and m are incident ion and target nucleus masses. This forward peak originates from constructive interference of all partial waves with angular momentum up to $_0$ [**?**]. The number of contributing partial waves increases with energy ($_0$ √E), leading to a narrower peak. Such partial waves correspond to borderline collisions (b_{max}   R), with maximum angular momentum _{max}ħ = pb_{max} = ħkR. Analysis reveals that the   = 0 partial wave, which is isotropic [P_0(cos _c) = 1], accounts for 70% ± 5% of total reaction cross-section, as obtained from Geant4 simulations. The pronounced forward peak in differential cross-section is therefore primarily generated by constructive interference of the remaining 30% higher- partial waves (≥ 1). For low-energy incident ions ($E < E$), multiple Coulomb scattering causes ion direction deviation [?]. The differential cross-section follows the Rutherford scattering formula, showing that low-energy ions are responsible for large-angle neutron scattering. Events with small impact parameters could even produce backward neutrons (angle between p and p $> \pi/2$). As shown by red curves in Fig. 6, ion energy is not high and neutron emission is nearly isotropic when $P = 0.18$ PW.

Neutron source duration Δt is a key quality indicator for practical applications. For instance, wide durations Δt s can satisfy spectral integration requirements for resonance capture, while short durations $\Delta t < 100$ ps benefit high temporal resolution in time-resolved imaging [?]. Figures 7(a)–7(f) show temporal evolution of neutron production rate $P(t)$ under all conditions. $P(t)$ exhibits Gaussian-like distributions except for LiF converters, matching precisely the temporal structure of incident ions. Neutron source duration [full width at half maximum (FWHM)] ranges from 100 to 200 ps, approaching requirements for high time-resolved imaging. As P increases or preplasma is considered, $P(t)$ also increases since $P(t) \quad \Phi(t) \cdot \sigma[E(t)]$ [?]. For Be converters at $P = 1.45$ PW, maximum $P(t)$ reaches 1.4×10^{20} s^{-1}, representing a 2.42-fold increase compared to cases without preplasma. Interestingly, Figs. 7(a) and 7(d) show a two-peak structure for LiF converters, attributed to different flight times for the two ion species over $L_0 = 1$ cm distance. The first peak originates from protons and the second from D^+ ions. For LiF material with lowest volumetric reaction rate R, the two-peak feature from flight time difference is retained. However, for Be material with higher R and broader σ , the typical two-peak structure gradually transforms into a single peak.

V. A Wrapped-Type Converter Based on LiH Ceramic Wrapping Be Material

We have demonstrated that Be material is highly suitable as a converter for typical PW-fs laser pulses. However, this material is extremely toxic and exists in powdered form. For operational safety, a wrapping layer is typically used to isolate highly active Be material from the experimental environment.

The essence of the wrapping structure lies in decoupling the selection of embedded material (Be) and wrapping material. The wrapping material should have low neutron absorption cross-section, high mechanical strength, and good environmental stability. Aluminum is a common choice (Al+Be), but its nuclear reaction cross-section is very low, disadvantageous for neutron production. Moreover, bright γ-rays are emitted when intense electron beams transport through it, affecting neutron diagnostics. Optimization of wrapping material is therefore essential.

Considering that LiD has rapid deliquescence (weight gain rate 5 wt%/h at RH = 50%) and LiF lacks sufficient bending strength (polycrystalline ceramics

45 MPa) [?], neither is suitable as wrapping material. To maintain emissions within safety limits while achieving high retention rates, we designed a novel converter with LiH ceramic wrapping Be material (LiH+Be), as shown in Fig. 8 Figure 8: see original paper. LiH ceramic can achieve >99% density through temperature isostatic pressing [?], with bending flexural strength over 110 ± 10 MPa and surface passivation ensuring hydrolysis rate <0.01 wt%/day [?]. The melting point of LiH ceramic is 688°C, slightly higher than Al (660°C), indicating stronger particle beam irradiation tolerance [?]. Furthermore, LiH ceramic density is only 0.77 g/cm^3, much less than Al' s 2.7 g/cm^3. Ion beam stopping power in LiH ceramic is thus far below that in Al \cite{82-84}, resulting in lower energy loss. Compared to Al+Be converters, LiH+Be is therefore more beneficial for neutron production.

To evaluate LiH+Be converter performance, we employ Geant4 code to simulate neutron production, comparing results with pure Be and Al+Be converters. The side and front/back plates of LiH and Al wrapping layers both have thickness $d_0 = d_1 = 0.1$ cm. In LiH+Be, Al+Be, and pure Be converters, all Be materials are cubic with 3 cm thickness and 10 cm side length. Figures 8(b)-8(f) show neutron spectrum, yield, and angular distribution for the three converters. The spectral structures are almost identical, demonstrating that wrapping layers do not induce spectral distortion. At low P (e.g., P ≤ 0.36 PW), differences in E , Y , and dN /d among converters are significant. For LiH+Be, E and Y are only slightly inferior to pure Be and much higher than Al+Be. With increasing P, differences gradually decrease since two-species ions are accelerated to higher energies and their energy loss ratio in the wrapping layer becomes lower. This indicates LiH+Be converters can achieve higher retention rates of pure Be performance. With a laser intensity of 4×10^{21} W/cm^2, duration 30 fs, and power 1.45 PW, a forward-peaked neutron pulse with yield 1.95×10^{10}, duration 500 ps, and maximum energy 70 MeV can be obtained using the LiH+Be converter.

VI. Summary

In summary, we have investigated laser prepulse ablation, laser-driven ion acceleration, and neutron production through nuclear reactions during PW-fs laser interaction with pitcher-catcher targets using full-process simulations. We find that preplasma formation in front of the pitcher layer benefits neutron production. Converter material selection is crucial, with Be converters as catcher layers offering superior performance in improving neutron source quality. Considering experimental operational requirements, we propose a novel converter with LiH ceramic wrapping Be material to maintain emissions within safety limits while achieving high retention rates. Specifically, with a laser intensity of 4×10^{21} W/cm^2, duration 30 fs, and power 1.45 PW, simulations demonstrate that a forward-peaked neutron pulse with yield 1.95×10^{10}, duration 500 ps, and maximum energy 70 MeV can be obtained using the novel converter. Our results should prove helpful for current experiments on PW-fs laser-driven pulsed neutron sources and their related applications.

References

[1] M. C. Scott, Neutron sources for basic physics and applications. Ann. Nucl. Energy 10, 501 (1983). doi: 10.1016/0306-4549(83)90033-6

[2] J. Y. Tang, A. Qi, H. Y. Bai et al., China' s first high-performance white neutron source: CSNS back-n white neutron source and application. Nucl. Sci. Tech. 30, 1 (2019). doi: 10.7538/yzk.2019.youxian.0431

[3] Y. Chen, Progress in the measurement of the neutron-induced fission cross-section at CSNS Back-n. EPJ Web Conf. 322, 08003 (2024). doi: 10.1051/epjconf/202532208003

[4] D. Strickland, G. Mourou, Compression of amplified chirped optical pulses. Opt. Commun. 55, 447–449 (1985). doi: 10.1016/0030-4018(85)90151-8

[5] X. Zeng, K. Zhou, Y. Zuo et al., Multi-petawatt laser facility fully based on optical parametric chirped-pulse amplification. Opt. Lett. 42, 2014–2017 (2017). doi: 10.1364/OL.42.002014

[6] G. A. Mourou, T. Tajima, S. V. Bulanov, Optics in the relativistic regime. Rev. Mod. Phys. 78, 309–371 (2006). doi: 10.1103/RevModPhys.78.309

[7] C. N. Danson, C. Haefner, J. Bromage et al., Petawatt and exawatt class lasers worldwide. High Power Laser Sci. Eng. 7, e54 (2019). doi: 10.1017/hpl.2019.36

[8] A. Macchi, M. Borghesi, M. Passoni, Ion acceleration by superintense laser-plasma interaction. Rev. Mod. Phys. 85, 751–793 (2013). doi: 10.1103/RevModPhys.85.751

[9] H. Daido, M. Nishiuchi, A. S. Pirozhkov, Review of laser-driven ion sources and their applications. Rep. Prog. Phys. 75, 056401 (2012). doi: 10.1088/0034-4885/75/5/056401

[10] E. Esarey, C. B. Schroeder, W. P. Leemans, Physics of laser-driven plasma-based electron accelerators. Rev. Mod. Phys. 81, 1229–1285 (2009). doi: 10.1103/RevModPhys.81.1229

[11] U. Teubner, P. Gibbon, High-order harmonics from laser-irradiated plasma surfaces. Rev. Mod. Phys. 81, 445–479 (2009). doi: 10.1103/RevModPhys.81.445

[12] S. Corde, K. Ta Phuoc, G. Lambert et al., Femtosecond x rays from laser-plasma accelerators. Rev. Mod. Phys. 85, 1–48 (2013). doi: 10.1103/RevModPhys.85.1

[13] J. Alvarez, J. Fernández-Tobias, K. Mima et al., Laser driven neutron sources: characteristics, applications and prospects. Phys. Procedia 60, 29–38 (2014). doi: 10.1016/j.phpro.2014.11.006

[14] S. N. Chen, F. Negoita, K. Spohr et al., Extreme brightness laser-based neutron pulses as a pathway for investigating nucleosynthesis in the laboratory. Matter Radiat. Extremes 4, 054402 (2019). doi: 10.1063/1.5081666

[15] W. Qi, S. K. He, Research progress of beam-target neutron source and applications driven by ultra-short pulse lasers (Invited). Chin. J. Lasers 51, 0101004 (2024). doi: 10.3788/CJL231292

[16] F. Canova, I. Cohen, S. Gales et al., High power laser drivers and fast neutron sources towards green energy applications. J. Phys. Conf. Ser. 688, 012001 (2016).

[17] J. Zweiback, T. E. Cowan, R. A. Smith et al., Characterization of fusion burn time in exploding deuterium cluster plasmas. Phys. Rev. Lett. 85, 3640 (2000). doi: 10.1103/PhysRevLett.85.3640

[18] Y. Zhang, W. M. Wang, Y. Li et al., Effects of internal target structures on laser-driven neutron production. Nucl. Fusion 59, 076032 (2019). doi: 10.1088/1741-4326/ab1cda

[19] I. Pomerantz, E. McCary, A. R. Meadows et al., Ultrashort pulsed neutron source. Phys. Rev. Lett. 113, 184801 (2014). doi: 10.1103/PhysRevLett.113.184801

[20] Y. L. Yao, S. K. He, Z. Lei et al., High-flux neutron generator based on laser-driven collisionless shock acceleration. Phys. Rev. Lett. 131, 025101 (2023). doi: 10.1103/PhysRevLett.131.025101

[21] X. R. Jiang, F. Q. Shao, D. B. Zou et al., Energetic deuterium-ion beams and neutron source driven by multiple-laser interaction with pitcher-catcher target. Nucl. Fusion 60, 076019 (2020). doi: 10.1088/1741-4326/ab91f9

[22] X. R. Jiang, D. B. Zou, Z. J. Zhao et al., Microstructure-assisted laser-driven photonuclear pulsed neutron source. Phys. Rev. Appl. 15, 034032 (2021). doi: 10.1103/PhysRevApplied.15.034032

[23] H. X. Deng, R. Sha, L. X. Hu et al., Pulsed neutron source from interaction of relativistic laser pulse with micro-structure assisted pitcher-catcher target. Plasma Phys. Control. Fusion 64, 085004 (2022). doi: 10.1088/1361-6587/ac7253

[24] K. L. Lancaster, S. Karsch, H. Habara et al., Characterization of ^{7}Li(p,n)^{7}Be neutron yields from laser produced ion beams for fast neutron radiography. Phys. Plasmas 11, 3404–3408 (2004). doi: 10.1063/1.1756911

[25] L. Willingale, G. M. Petrov, A. Maksimchuk et al., Comparison of bulk and pitcher-catcher targets for laser-driven neutron production. Phys. Plasmas 18, 083106 (2011). doi: 10.1063/1.3624769

[26] M. Roth, D. Jung, K. Falk et al., Bright laser-driven neutron source based on the relativistic transparency of solids. Phys. Rev. Lett. 110, 044802 (2013). doi: 10.1103/PhysRevLett.110.044802

[27] A. Yogo, Z. Lan, Y. Arikawa et al., Laser-driven neutron generation realizing single-shot resonance spectroscopy. Phys. Rev. X 13, 011011 (2023). doi: 10.1103/PhysRevX.13.011011

[28] M. Zimmer, T. F. Rösch, S. Scheuren et al., Assessing the potential of upcoming laser-driven neutron sources and their practical applications for industry and society. Eur. Phys. J. Plus 139, 1107 (2024). doi: 10.1140/epjp/s13360-024-05879-5

[29] D. P. Higginson, J. M. McNaney, D. C. Swift et al., Laser generated neutron source for neutron resonance spectroscopy. Phys. Plasmas 17, 100701 (2010). doi: 10.1063/1.3484219

[30] D. P. Higginson, J. M. McNaney, D. C. Swift et al., Production of neutrons up to 18 MeV in high-intensity, short-pulse laser matter interactions. Phys.

Plasmas 18, 100703 (2011). doi: 10.1063/1.3654040
[31] S. Kar, H. Ahmed, R. Prasad et al., Guided post-acceleration of laser-driven ions by a miniature modular structure. Nat. Commun. 7, 10792 (2016). doi: 10.1038/ncomms10792
[32] A. Alejo, A. G. Krygier, H. Ahmed et al., High flux, beamed neutron sources employing deuteron-rich ion beams from D_2O-ice layered targets. Plasma Phys. Control. Fusion 59, 064004 (2017). doi: 10.1088/1361-6587/aa684a
[33] A. Kleinschmidt, V. Bagnoud, O. Deppert et al., Intense, directed neutron beams from a laser-driven neutron source at PHELIX. Phys. Plasmas 25, 053101 (2018). doi: 10.1063/1.5006613
[34] M. Zimmer, S. Scheuren, A. Kleinschmidt et al., Demonstration of non-destructive and isotope-sensitive material analysis using a short-pulsed laser-driven epi-thermal neutron source. Nat. Commun. 13, 1173 (2022). doi: 10.1038/s41467-022-28756-0
[35] J. Fuchs, P. Antici, E. d' Humières et al., Laser-driven proton scaling laws and new paths towards energy increase. Nat. Phys. 2, 48–54 (2006). doi: 10.1038/nphys199
[36] L. Robson, P. T. Simpson, R. J. Clarke et al., Scaling of proton acceleration driven by petawatt-laser-plasma interactions. Nat. Phys. 3, 58–62 (2007).
[37] C. Thaury, F. Quéré, J. P. Geindre et al., Plasma mirrors for ultrahigh-intensity optics. Nat. Phys. 3, 424–429 (2007). doi: 10.1038/nphys595
[38] B. Dromey, S. Kar, M. Zepf et al., The plasma mirror—a subpicosecond optical switch for ultrahigh power lasers. Rev. Sci. Instrum. 75, 645–649 (2004). doi: 10.1063/1.1646737
[39] A. Lévy, T. Ceccotti, P. d' Oliveira et al., Double plasma mirror for ultrahigh temporal contrast ultraintense laser pulses. Opt. Lett. 32, 310–312 (2007). doi: 10.1364/OL.32.000310
[40] P. Neves, M. Arronte, R. Vilar et al., KrF excimer laser dry and steam cleaning of silicon surfaces with metallic particulate contaminants. Appl. Phys. A 74, 191–199 (2002). doi: 10.1007/s003390100868
[41] A. Jullien, S. Kourtev, O. Albert et al., Highly efficient temporal cleaner for femtosecond pulses based on cross-polarized wave generation in a dual crystal scheme. Appl. Phys. B 84, 409–414 (2006). doi: 10.1007/s00340-006-2334-7
[42] X. P. Feng, P. X. Lu, Z. Z. Xu, Effect on LPX radiation characteristics with a laser prepulse irradiated binary-layer target. Chin. J. Lasers 18, 9 (1991).
[43] J. Lu, X. Lan, X. Xi et al., Influence of laser prepulse on proton acceleration using ultra-short laser interaction with thin-foil. At. Energy Sci. Technol. 47, 637–640 (2013). doi: 10.7538/yzk.2013.47.04.0637
[44] P. Varmazyar, S. Mirzanejhad, T. Mohsenpour, Effect of pre-plasma on the ion acceleration by intense ultra-short laser pulses. Laser Part. Beams 36, 226–231 (2018). doi: 10.1017/S0263034618000241
[45] B. Fryxell, K. Olson, P. Ricker et al., FLASH: An Adaptive Mesh Hydrodynamics Code for Modeling Astrophysical Thermonuclear Flashes. Astrophys. J. Suppl. Ser. 131, 273 (2000). doi: 10.1086/317361
[46] T. D. Arber, K. Bennett, C. S. Brady et al., Contemporary particle-in-cell

approach to laser-plasma modelling. Plasma Phys. Control. Fusion 57, 113001 (2015). doi: 10.1088/0741-3335/57/11/113001
[47] S. Agostinelli, J. Allison, K. Amako et al., Geant4—a simulation toolkit. Nucl. Instrum. Methods Phys. Res. A 506, 250–303 (2003). doi: 10.1016/S0168-9002(03)01368-8
[48] W. Hong, S. He, J. Teng et al., Commissioning experiment of the high-contrast SILEX-II multi-petawatt laser facility. Matter Radiat. Extremes 6, 064402 (2021). doi: 10.1063/5.0016019
[49] Z. Lécz, J. Budai, A. Andreev et al., Thickness of natural contaminant layers on metal surfaces and its effects on laser-driven ion acceleration. Phys. Plasmas 27, 013102 (2020). doi: 10.1063/1.5123542
[50] C. Orban, M. Fatenejad, D. Q. Lamb, Code-to-code comparison and validation of the radiation-hydrodynamics capabilities of the FLASH code using a laboratory astrophysical jet. Phys. Plasmas 29, 053901 (2022). doi: 10.1063/5.0079493
[51] A. Pukhov, Z. M. Sheng, J. Meyer-ter-Vehn, Particle acceleration in relativistic laser channels. Phys. Plasmas 6, 2847–2854 (1999). doi: 10.1063/1.873242
[52] D. B. Zou, H. B. Zhuo, X. H. Yang et al., Enhanced target normal sheath acceleration based on the laser relativistic self-focusing. Phys. Plasmas 21, 063108 (2014). doi: 10.1063/1.4882245
[53] T. P. Yu, Z. M. Sheng, A. Pukhov et al., Betatron-like resonance in ultra-intense laser mass-limited foil interaction. Plasma Phys. Control. Fusion 55, 085021 (2013). doi: 10.1088/0741-3335/55/8/085021
[54] S. C. Wilks, A. B. Langdon, T. E. Cowan et al., Energetic proton generation in ultra-intense laser-solid interactions. Phys. Plasmas 8, 542–549 (2001). doi: 10.1063/1.1333697
[55] A. P. L. Robinson, A. R. Bell, R. J. Kingham, Effect of target composition on proton energy spectra in ultraintense laser-solid interactions. Phys. Rev. Lett. 96, 035005 (2006). doi: 10.1103/PhysRevLett.96.035005
[56] A. P. L. Robinson, A. V. Arefiev, V. N. Khudik, The effect of superluminal phase velocity on electron acceleration in a powerful electromagnetic wave. Phys. Plasmas 22, 083103 (2015). doi: 10.1063/1.4928893
[57] J. H. Bin, M. Yeung, Z. Gong et al., Enhanced laser-driven ion acceleration by superponderomotive electrons generated from near-critical-density plasma. Phys. Rev. Lett. 120, 074801 (2018). doi: 10.1103/PhysRevLett.120.074801
[58] D. B. Zou, D. Y. Yu, M. Y. Yu et al., Efficient generation of 100 MeV ions from ultrashort 10^{21} W/cm^2 laser pulse interaction with a waveguide target. Nucl. Fusion 59, 066034 (2019). doi: 10.1088/1741-4326/ab1121
[59] P. Mora, Plasma expansion into a vacuum. Phys. Rev. Lett. 90, 185002 (2003). doi: 10.1103/PhysRevLett.90.185002
[60] V. T. Tikhonchuk, A. A. Andreev, S. G. Bochkarev et al., Ion acceleration in short-laser-pulse interaction with solid foils. Plasma Phys. Control. Fusion 47, B869 (2005). doi: 10.1088/0741-3335/47/12B/S69
[61] S. G. Bochkarev, V. Y. Bychenkov, V. T. Tikhonchuk, Investigation of ion acceleration in an expanding laser plasma by using a hybrid

Boltzmann-Vlasov-Poisson model. Plasma Phys. Rep. 32, 205–221 (2006). doi: 10.1134/S1063780X06030032

[62] S. P. Hatchett, C. G. Brown, T. E. Cowan et al., Electron, photon, and ion beams from the relativistic interaction of Petawatt laser pulses with solid targets. Phys. Plasmas 7, 2076–2082 (2000). doi: 10.1063/1.874030

[63] T. Z. Esirkepov, S. V. Bulanov, K. Nishihara et al., Proposed Double-Layer Target for the Generation of High-Quality Laser-Accelerated Ion Beams. Phys. Rev. Lett. 89, 175003 (2002). doi: 10.1103/PhysRevLett.89.175003

[64] P. Gibbon, Short pulse laser interactions with matter: an introduction. World Scientific, 2005.

[65] Y. Sentoku, W. Kruer, M. Matsuoka et al., Laser hole boring and hot electron generation in the fast ignition scheme. Fusion Sci. Technol. 49, 278–296 (2006). doi: 10.13182/FST06-A1149

[66] O. A. Ezekoye, Conduction of heat in solids. In: SFPE handbook of fire protection engineering. Springer, 2016: 25–52. doi: 10.1007/978-1-4939-2565-0_2

[67] R. D. Evans, The atomic nucleus. McGraw-Hill, 1955.

[68] ENDF, https://www-nds.iaea.org/exfor/endf.htm.

[69] L. P. Horwitz, Y. Lavie, Scattering theory in relativistic quantum mechanics. Phys. Rev. D 26, 819 (1982). doi: 10.1103/PhysRevD.26.819

[70] J. R. Taylor, Scattering theory: the quantum theory of nonrelativistic collisions. Courier Corporation, 2012. doi: 10.13182/NT73-A31305

[71] J. M. Blatt, V. F. Weisskopf, Theoretical nuclear physics. Springer, 2012. doi: 10.1119/1.1933407

[72] R. J. Glauber, G. Matthiae, High-energy scattering of protons by nuclei. Nucl. Phys. B 21, 135–157 (1970). doi: 10.1016/0550-3213(70)90511-0

[73] P. E. Hodgson, E. Gadioli, E. G. Erba, Introductory nuclear physics. Clarendon Press, 1997.

[74] G. R. Satchler, Introduction to nuclear reactions. In: Introduction to Nuclear Reactions. Palgrave Macmillan, 1990: 21–88. doi: 10.1007/978-1-349-20531-8_2

[75] P. Sigmund, K. B. Winterbon, Small-angle multiple scattering of ions in the screened Coulomb region: I. Angular distributions. Nucl. Instrum. Methods 119, 541–557 (1974). doi: 10.1016/0029-554X(74)90805-2

[76] E. Rutherford, The scattering of α and β particles by matter and the structure of the atom. Philos. Mag. 21, 669–688 (1911). doi: 10.1080/14786440508637080

[77] G. A. Yi, Y. Zheng, X. Qi et al., Applicability and limitation of pulsed neutron source method for subcritical assembly. Chin. J. Comput. Phys. 42, 224 (2025). doi: 10.19596/j.cnki.1001-246x.8865

[78] Total Materia, https://www.totalmateria.com/.

[79] L. Peng, D. Zhou, W. Zhang et al., Temperature effect on short-term strength of lithium hydride with tensile and three-point bend specimens. Crystals 12, 840 (2022). doi: 10.3390/cryst12060840

[80] D. Poeth, The evaluation of lithium hydride for use in a space nuclear reactor shield, including a historical perspective. Knolls Atomic Power Lab.,

2005.
[81] V. K. Golubev, K. G. Rabinovich, L. V. Polyakov, The effect of pressing conditions on the strength of lithium hydride upon compression. J. Appl. Mech. Tech. Phys. 38, 961–962 (1997). doi: 10.1007/BF02467963
[82] J. F. Ziegler, J. P. Biersack, The stopping and range of ions in matter. In: Treatise on heavy-ion science: volume 6. Springer, 1985: 93–129. doi: 10.1007/978-1-4615-8103-1_3
[83] P. Sigmund, Particle penetration and radiation effects volume 2. Springer, 2014. doi: 10.1007/978-3-319-05564-0
[84] H. Paul, http://www.exphys.uni-linz.ac.at/stopping/

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