Laser-Driven Micro-Pinch: A Pathway to Ultra-Intense Neutrons

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Abstract

Utilizing the laser-driven Z-pinch effect, we propose an approach to generate ultra-short intense MeV neutron source of femtosecond pulse duration. The self-generated magnetic field driven by a petawatt-class laser pulse compresses deuterium in a single nanowire to over 120 time of its initial density, achieving an unprecedented particle number density of $ 10^{25} cm^{-3}$. Through full dimensional kinetic simulations including nuclear reactions, we find these Z-pinches have the capacity to generate neutron pulses of high intensity and short duration, with a peak flux reaching $10^{27}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. Such laser-driven neutron sources are beyond the capability of existing approaches and paves the way for groundbreaking applications in r-process nucleosynthesis studies and high precision Time-of-Flight neutron data measurement.

Full Text

Laser-Driven Micro-Pinch: A Pathway to Ultra-Intense Neutron Sources

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Abstract: We propose a novel approach to generate ultra-short, intense MeV neutron sources with femtosecond pulse durations by harnessing the laser-driven Z-pinch effect. The self-generated magnetic field induced by a petawatt-class laser pulse compresses deuterium in a single nanowire to over 120 times its initial density, achieving an unprecedented particle number density of 10^{25} cm^{-3}. Through full-dimensional kinetic simulations that include nuclear reactions, we demonstrate that these Z-pinches can generate neutron pulses of exceptional intensity and brevity, with peak fluxes reaching 10^{27} cm^{-2}s^{-1}. Such laser-driven neutron sources transcend the capabilities of existing methods and open pathways for groundbreaking applications in r-process nucleosynthesis studies and high-precision Time-of-Flight neutron measurements.

Keywords: nanowire target, Z-pinch, D-D fusion reaction, laser-plasma interaction, neutron source

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INTRODUCTION

Conventional neutron sources—including isotopic, accelerator-based, and reactor-based systems—have been instrumental in advancing diverse scientific and technological fields, particularly materials science and nuclear physics [1]. Spallation neutron sources represent the current frontier, delivering neutron fluxes approaching 10^{17} cm$^{-2}\cdot$s^{-1} with brief pulse durations. These characteristics significantly enhance the precision of Time-of-Flight (TOF) measurements, which are fundamental to nuclear reactor design and nuclear astrophysics [2–5].

Despite these advances, reproducing the extreme neutron flux conditions essential for understanding r-process nucleosynthesis [6] remains a formidable challenge. Neutron star mergers serve as the primary astrophysical site for this process, which is integral to the cosmic formation of heavy elements, though the potential contribution from supernova explosions remains under debate [7, 8]. These events require neutron fluxes ranging from 10^{22} to 10^{28} cm$^{-2}\cdot$s^{-1}—a regime still inaccessible in laboratory settings. This gap not only impedes our comprehensive understanding of these astrophysical phenomena but also constrains progress in related fields such as nuclear physics and astrophysics. The urgent need for new methodologies capable of achieving such extreme conditions in controlled environments is therefore paramount.

Recent developments in laser-driven high-intensity neutron sources show promise for bridging this gap, offering exceptional temporal resolution and highly localized neutron beams [9, 10]. Various approaches have been employed, including photoneutron production [11, 12] (10^{21} cm$^{-2}\cdot$s^{-1}), Target Normal Sheath Acceleration (TNSA) [13, 14] (10^{24} cm$^{-2}\cdot$s^{-1}), and target compression via spherical shells (NIF) [15] (10^{30} cm$^{-2}\cdot$s^{-1}). While these methods represent significant progress, the neutron flux achievable through laser-driven Z-pinch has the potential to surpass current capabilities.

The Z-pinch phenomenon occurs when an axial current flowing through plasma generates a magnetic field whose interaction with the current creates a radial Lorentz force, compressing the plasma to a small volume [16]. Fusion and X-ray research have long explored Z-pinch devices [17–20]. Recent advances have focused on enhancing laser-driven Z-pinch dynamics using nanowire arrays [21–23], which efficiently absorb energy from femtosecond petawatt lasers, producing high degrees of ionization and intense X-ray emission [24, 25]. Additionally, accelerated ions in these arrays trigger micro-scale fusion reactions [26].

Building on this foundation, we performed Particle-in-Cell (PIC) simulations and discovered that a femtosecond petawatt laser can pinch a single nanowire to over 120 times its original density. This ultra-high density state, achieved through the pinch, is termed a "micro-pinch" due to its tiny spatial scale and short duration. Our simulations indicate that such micro-pinches can facilitate nuclear fusion reactions, producing an intense, short-lived neutron pulse with an unprecedented flux level of 10^{27} $cm^{-2} \cdot s^{-1}$.

Putong Wang and Xuesong Geng contributed equally to this work.

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II. SIMULATION SETUP

To investigate neutron generation in a Z-pinch configuration, we employ full-dimensional kinetic simulations using the Particle-in-Cell (PIC) code Smilei [27] to reveal the ultra-short pinch process and neutron production. The original nuclear reaction scheme [28, 29] has been implemented in Smilei, with the cross section for the D + D → n + ^{3}He reaction integrated into the debugging version. We have improved this version, corrected and verified the nuclear reaction cross sections using periodic boundary conditions in a simulation box [30]. Additionally, we have incorporated the D + T → n + ^{4}He reaction [31] in this study to explore the potential for even more intense neutron sources.

In our simulations, the nanowire where the Z-pinch is triggered consists of deuterated polyethylene (CD_2). The deuterium particle number density is set to $= 7.8 \times 10^{22}$ cm^{-3}. We have considered nanowire diameters of 300 nm and 500 nm with varying lengths. The initial particle temperature is set at 300 Kelvin. The nanowire target is irradiated by 400 nm wavelength circularly-polarized (CP) laser pulses with 30 fs or 60 fs FWHM duration. The dimensionless laser field amplitude ranges from $a_0 = 10$ to 40 ($a_0 = eE/m c\omega$), where e and m are the electron charge and mass, E is the laser electric field, ω is the laser frequency, and c is the speed of light in vacuum. The focal spot size is sufficiently large to cover the entire single nanowire, with a typical spot size of about 5 μm, reaching a peak intensity of ~5×10^{21} W/cm^2 ($a_0 = 17$). To avoid numerical heating, cell size and number are adjusted dynamically according to the nanowire volume. A typical cell size is 7.5 nm × 5 nm × 5 nm with 27 macro-particles per cell. For the small-sized nanowire, the simulation domain contains 640 × 192 × 192 cells, corresponding to a cube of 4.8 μm × 0.96 μm × 0.96 μm—large enough to contain the entire nanowire. Simulation boundaries employ open conditions for both fields and particles. Since field ionization dominates over collisional ionization, the latter is disabled to save computational time. Binary collisions between deuterium (and tritium) ions are enabled, allowing nuclear reactions to occur.

III. SIMULATION RESULTS

When irradiated by ultrashort, high-intensity laser pulses, atoms within the nanowire undergo field ionization, creating a substantial potential difference across the nanowire surface. This potential disparity is balanced by a significant return current flowing across the surface, maintaining quasi-neutrality. For a rough estimate, we assume electrons ionized from atoms within the nanowire are mostly extracted by the laser, corresponding to a total charge of $Q = 1.3 \times 10^{-8}$ C. The current can be calculated as I = Q/t, where t is the laser FWHM duration (60 fs), yielding an estimated current of 2.2×10^5 A that provides a baseline for analyzing Z-pinch dynamics.

Our 3D simulations illustrate this laser-induced Z-pinch process. Figure 1 [Figure 1: see original paper] shows electrons being pulled out by the CP laser (negative current in blue), while the positive current density represents return electrons flowing in the opposite direction (positive current in red). The return current density reaches $J = 10^{15}$-10^{16} A/cm^2 (across a cross-section of 30 × 30 nm^2, I_{max} ~ 1.4×10^5 A), consistent with our estimate. This extremely high current density induces a significant magnetic field around the nanowire. The 2D image in Fig. 1 illustrates the transverse magnetic field distribution, with a maximum field reaching B_y = 1.0×10^6 T—exceeding the incident laser field ($a_0 = 17$, B_y = 4.6×10^5 T). This quasi-static magnetic field exerts a J × B force on both inner and outer currents (electrons) of the nanowire. The current on the inner surface experiences a radially inward force, while forces on outer electrons are directed outward, compressing the nanowire inward while pushing extracted electrons outward.

As return electrons are pinched radially inward by the Lorentz force, they induce an electric field due to charge separation. Deuterium ions are then drawn symmetrically inward from the surface by this electric field, creating strong radial symmetry in the kinetic energy distribution of deuterium particles within the nanowire. In subsequent analysis, we estimate the deuterium temperature in the Z-pinch to be 190 keV by comparing nuclear reaction rate ratios. Electrons extracted from the nanowire (pushed outward) also induce an electric field that draws surface deuterium outward and accelerates it. For array targets, collisions between these outward-accelerated ions become significant for nuclear reactions due to their higher energies. Eventually, the pinched-inward ions compress near the center, forming a high-density zone (Fig. 2 [Figure 2: see original paper]). The corresponding maximum energy density can reach ~1 × 10^{24} MeV/cm^3 (1 × 10^{12} J/cm^3) around 54 fs—two orders of magnitude higher than in our previous work [32].

As shown in Fig. 2, compression occurs within approximately t_c = 10 fs, with the most compressed diameter around D = 30 nm. The maximum deuterium density can exceed _m = 1 × 10^{25} cm^{-3}, which is 120 times higher than the initial ion density. The ion radial flux (proton or deuterium) reaches ~1.0 × 10^{34} $cm^{-2} \cdot s^{-1}$ (_mπD/t_c), representing an intense source of interest for laboratory nuclear astrophysics research [33-35]. Thus, nanowires can serve as platforms for other nuclear reactions, such as p + ^{11}B → 3α.

These ions concentrate within an extremely small volume of approximately 30 × 30 nm^2, driving intense nuclear reactions and neutron production. For lasers with $a_0 > 40$, the maximum density shows only slight increases. For example, at $a_0 = 150$, a maximum density of 1.8 × 10^{25} cm^{-3} appears at the front of the wire due to intense axial particle acceleration combined with the micro-pinch effect, occurring well before the laser pulse peak. As laser intensity increases, both return current density and maximum ion density rise, though not indefinitely in our simulations, which would limit nuclear reactions during the Z-pinch (Fig. 4(a) [Figure 4: see original paper]). This limitation may arise from instabilities [36] such as sausage or kink modes in the Z-pinch.

Figure 3 [Figure 3: see original paper] demonstrates the number and density of nuclear reactions (D + D → n + ^{3}He) generated by the Z-pinch. Neutron propagation is not considered; the data represent the moment when energetic ions collide in the densest region. Due to the extremely high particle density, nuclear reactions occur primarily around the nanowire axis, as shown in Fig. 3(a). The neutron density from D-D reactions is approximately 10^{18} cm^{-3}. The ultra-short compression produces a burst of reactions within femtoseconds, with reaction rates exceeding 100/fs at these timescales (Fig. 3(b)).

When suitable nuclear reactions are available, the system produces ultra-high peak flux with ultra-short pulse duration. Our simulations yield neutrons with narrow pulse widths (30 fs) and small source areas (π × 30 nm × 3000 nm = 2.8 × 10^5 nm^2), corresponding to neutron fluxes potentially reaching 10^{26} $cm^{-2} \cdot s^{-1}$.

Figure 4 Figure 4: see original paper illustrates the relationship between laser parameters (30 fs and 60 fs, circular and linear polarization) and the number of nuclear reactions generated by the Z-pinch. Increasing nanowire length efficiently enhances reaction yield. The highest nuclear reaction efficiency occurs for 500 nm diameter wires, followed by 300 nm wires—both significantly outperforming 200 nm and 800 nm wires. For the D-T system, fusion yield exceeds D-D by more than tenfold. Comparing yields in the same system, the equivalent temperature for nuclear reactions in the nanowire is ~190 keV [37]. The neutron flux could reach 10^{27} $cm^{-2} \cdot s^{-1}$ in the D-T reaction system. For a 500 nm diameter nanowire, lengths of 6 μm, 8 μm, and 10 μm generate 3.4×10^5, 4.7×10^5, and 5.9×10^5 neutrons, respectively. This growth is nearly linear with length (the nanowire must be sufficiently long relative to the laser pulse width). Over 10^6 neutrons could be generated within a single pulse for a 20 μm long nanowire, as shown in Fig. 4(b). Cascade reactions of D-D and D-T also occur within the system.

IV. CONCLUSION

In summary, we have conducted the first study of laser-nanowire interactions focusing on the Z-pinch effect, demonstrating that deuterium density within the nanowire can exceed its initial value by over a hundredfold. We have analyzed the pinch density and current under various laser and nanowire parameters, revealing potential stable regimes in laser-induced Z-pinch effects. The Z-pinch creates a short-timescale, high-spatial-density environment for nuclear reactions in laser-driven nanowires, making them suitable as neutron sources with advantages of small spatial scale (30 nm × 30 nm) and short pulse duration (30 fs). This compression produces extremely intense, short neutron pulses with peak flux reaching 10^{27} $cm^{-2} \cdot s^{-1}$. Such high-flux neutron sources can enable research in r-process nucleosynthesis [38]. The laser can pinch not only deuterium ions but also other particles in nanowires, such as protons. With radial flux around 1.0×10^{34} $cm^{-2} \cdot s^{-1}$, the proton source offers a unique platform for two-proton capture reactions during the rp-process [39]. Future studies could employ targets with different compositions to further advance laboratory nuclear astrophysics research [40, 41], providing potential high-intensity solutions.

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