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

Preamble

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

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Utilizing the laser-driven Z-pinch effect, we propose an approach to generate an ultra-short, intense MeV neutron source with femtosecond pulse duration. The self-generated magnetic field driven 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 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} cm^{-2}s^{-1}. Such laser-driven neutron sources are beyond the capability of existing approaches and pave the way for groundbreaking applications in r-process nucleosynthesis studies and high-precision Time-of-Flight neutron data measurement.

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

Introduction

Conventional neutron sources, spanning isotope, accelerator, and reactor types, have played a pivotal role in advancing diverse scientific and technological domains, including materials science and nuclear physics [**?**]. Spallation neutron sources, representing the forefront of this evolution, are distinguished as a novel generation of high-intensity, pulsed neutron sources. They achieve neutron flux levels near 10^{17} cm$^{-2}\cdot$s^{-1} with brief pulse widths. These attributes significantly enhance precision in Time-of-Flight (TOF) measurements, a cornerstone in nuclear reactor design and nuclear astrophysics [**?**, **?**].

Despite these advancements, the replication of high neutron flux conditions, which is crucial for understanding r-process nucleosynthesis [**?**], remains a formidable challenge. Integral to the cosmic formation of heavy elements, neutron star mergers are the primary site for this process [**?**], while the possibility of contribution from supernovae explosions is still under debate [**?**]. These astrophysical events require conditions including intensive neutron flux ranging from 10^{22} to 10^{28} cm$^{-2}\cdot$s^{-1}, a range still elusive in laboratory settings. This gap not only hinders our comprehensive understanding of these astrophysical phenomena but also limits advancements in related fields such as nuclear physics and astrophysics. The urgency to develop new methodologies capable of achieving these extreme conditions in a controlled environment is therefore paramount.

The recent development of laser-driven high-intensity neutron sources shows the potential to fill this gap due to their exceptional temporal resolution and ability to achieve highly localized neutron beams (spatial resolution) [**?**, **?**]. These sources employ various methodologies, including photoneutron production [**?**, **?**] (10^{21} cm$^{-2}\cdot$s^{-1}), target normal sheath acceleration (TNSA) [**?**, **?**] (10^{24} cm$^{-2}\cdot$s^{-1}), and target compression via spherical shells (NIF) [**?**] (10^{30} cm$^{-2}\cdot$s^{-1}). While these methods offer advancements, the neutron flux from the laser-driven Z-pinch shows the potential to surpass current capabilities.

Z-pinch is a phenomenon where an axial current flowing through a plasma generates a magnetic field. The interaction between this magnetic field and the current creates a radial Lorentz force, which compresses the plasma radially to a small volume [?]. Fusion and x-ray research are exploring the potential of Z-pinch devices [?]. Recent strides have pivoted around the augmentation of laser-driven Z-pinch mechanics from nanowire arrays [?], presenting notable intrigue. These nanowire arrays efficiently absorb energy from a femtosecond petawatt laser, resulting in a high degree of ionization and intense x-ray generation [?, ?]. Additionally, ions in the array are accelerated, triggering micro-scale fusion reactions [?].

Therefore, we carried out PIC simulations and found that a femtosecond petawatt laser can pinch a single nanowire to over 120 times its original density. This ultra-high density achieved through the pinch is referred to as a micro-pinch due to its tiny spatial scale and short duration. Simulations suggest that such micro-pinches can facilitate nuclear fusion reactions, leading to an intense, short-lived neutron pulse with an unprecedented flux level of 10^{27} $cm^{-2}s^{-1}$.

II. Simulation Setting

To investigate the neutron generation process in a Z-pinch setup, we employ full-dimensional kinetic simulations to reveal the ultra-short pinch process and the generation of neutrons using the Particle-in-Cell (PIC) code Smilei [?]. The original nuclear reaction scheme [?, ?] has been introduced in Smilei. Specifically, the cross section for the reaction D + D → n + ^{3}He has been integrated into the debugging version of Smilei. We have improved this debugging version, corrected and checked the nuclear reaction cross sections, using a periodic boundary condition in a box [?]. In addition, we have also added the nuclear reaction D + T → n + ^{4}He (data from [?]) in this paper to explore the potential for an even more intensive neutron source.

In our simulation, the nanowire where the Z-pinch is triggered is composed of deuterated polyethylene (CD_2). The particle number density of deuterium is set to $= 7.8 \times 10^{22}$ cm^{-3}. Diameters of 300 nm and 500 nm have been considered with varying wire length. The initial temperature of the particles is set at 300 Kelvin. The nanowire target is irradiated by 400 nm wavelength circularly-polarized (CP) laser pulses of 30 fs or 60 fs FWHM duration. The dimensionless amplitude of the laser field ranges from a_0 = 10–40 ($a_0 = eE/m\,c\omega$), 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, respectively. The focal spot size of the laser should be large enough to cover the entire single nanowire. A typical focal spot size is about 5 μm, reaching a peak intensity of 5×10^{21} W/cm^2 (a_0 = 17). To avoid numerical heating, the size and number of cells are adjusted dynamically according to the volume of the nanowires. One typical cell size is set as 7.5 nm × 5 nm × 5 nm, with 27 macro-particles per cell. There are 640 × 192 × 192 cells for the small-sized nanowire, corresponding to a cube of 4.8

μm × 0.96 μm × 0.96 μm, which is large enough to contain the entire nanowire. The simulation boundaries are set to open conditions for both the fields and the particles. Since field ionization is the dominating ionization process compared with that from Coulomb collisions between particles, collisional ionization is switched off to save simulation time. Binary collisions between deuterium (and tritium) are enabled, allowing nuclear reactions to occur.

III. Simulation Results

When irradiated by ultrashort, high-intensity laser pulses, the atoms inside the wire undergo field ionization. This ionization process leads to a considerable potential difference on the surface of the nanowire. This potential disparity is balanced by a significant return current flowing across the nanowire’ s surface, maintaining quasi-neutrality. For a rough estimation, 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 represents the FWHM duration of the laser, set at 60 fs. This estimated current of 2.2×10^5 A provides a starting point for further analysis of the Z-pinch dynamics.

We perform 3D simulations to illustrate this laser-induced Z-pinch process. Fig. 1 [Figure 1: see original paper] shows that electrons are pulled out by a CP laser in void (negative current represented in blue), while the positive current density represents the return current of electrons flowing in the opposite direction (positive current represented 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 estimation. Due to the extremely high current density, the induced magnetic field around the nanowire is also significant. The 2D image in Fig. 1 illustrates the transverse magnetic field distribution in the simulation. The maximum field reaches 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 current (electrons) of the nanowire. The current on the inner surface of the nanowire is subjected to a force radially inward due to the generated magnetic field, whereas the forces on the outer electrons of the nanowire are opposite in direction. Hence, the nanowire is compressed inward, while electrons extracted from the nanowire are pushed outward.

When the return electrons are pinched radially inward by the Lorentz force, they induce an electric field due to charge separation. Deuterium ions are then drawn and pinched symmetrically inward from the surface by this electric field, resulting in strong radial symmetry for the kinetic energy distribution of deuterium particles within the nanowire. In our subsequent discussion, we estimate that the temperature of deuterium in the Z-pinch is 190 keV by comparing the ratios of nuclear reaction rates. Those electrons extracted from the nanowire (which are being pushed outward) will also induce an electric field, drawing the surface deuterium outward and accelerating them. If it is an array target, collisions between them are also significant for nuclear reactions because of their higher energy. Eventually, the pinched-inward ions are compressed near the center, creating a high-density zone (Fig. 2 [Figure 2: see original paper]). The corresponding maximum energy density can reach the order of 1×10^{24} MeV/cm^3 (1×10^{12} J/cm^3) around 54 fs, which is two orders of magnitude higher than in our previous work [**?**].

As shown in Fig. 2, the compression occurs within approximately t_c = 10 fs, and the most compressed diameter is around D = 30 nm. The maximum density of deuterium can exceed _m = 1×10^{25} cm^{-3}, which is 120 times higher than the initial ion density. The ion (proton or deuterium) radial flux reaches approximately 1.0×10^{34} cm$^{-2} \cdot$ s^{-1} (_mπD/t_c). Hence, nanowires can also serve as sources for other nuclear reactions, such as p + ^{11}B $\rightarrow 3\alpha$. These ions concentrate within an extremely small volume of approximately 30×30 nm^2, causing intense nuclear reactions, including neutron production. For lasers with $a_0 > 40$, the maximum density in the nanowires shows a slight increase. For example, with $a_0 = 150$, there will be a maximum density of 1.8×10^{25} cm^{-3} at the front of the wire, due to intense axial particle acceleration and the combined effect of nanowire micro-pinch, which occurs long before the peak of the laser pulse. When the laser intensity increases, both the magnitude of the return current density and the maximum ion density rise, but not indefinitely in our simulation. This would limit the number of nuclear reactions during the Z-pinch (Fig. 4(a)). It may be caused by instabilities [**?**], such as sausage or kink instabilities in the Z-pinch effect.

Figure 3 [Figure 3: see original paper] demonstrates the number and density of nuclear reactions (D + D $\rightarrow$ n + ^{3}He) generated by the Z-pinch. Here, the propagation of the produced neutrons is not considered; it is the moment when energetic ions are colliding with each other at the densest vicinity. Due to the extremely high particle number density, nuclear reactions primarily take place around the axis of the nanowire, as shown in Fig. 3(a). The neutron density resulting from D-D nuclear reactions is approximately on the order of 10^{18} cm^{-3}. The extremely short compression leads to a burst of reactions within femtoseconds, where the reaction rate exceeds 100/fs at such a small time scale, as shown in Fig. 3(b).

If suitable nuclear reactions are available, the induced reaction shows an ultra-high peak flux and ultra-short pulse duration. From the simulations, we obtain neutrons with a narrow pulse width (30 fs) and a small source surface area ($\pi \times 30$ nm $\times$ 3000 nm = 2.8×10^5 nm^2). The corresponding neutron (particle) flux may reach 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, circularly polarized and linearly polarized) and the number of nuclear reactions generated by the Z-pinch. Additionally, increasing the length is efficient in enhancing the number of nuclear reactions during the pinch phase. Diameters of nanowires also have an impact on the substance of material; the efficiency of nuclear reaction generation is highest in the 500 nm diameter wire, followed by 300 nm. Both of these efficiencies are higher than those observed in 200 nm and 800 nm wires.

When the D-T system is considered, the fusion yield is found to be more than that of D-D by over 10 times. Comparing their yield in the same system, the equivalent temperature [?] at which nuclear reactions occur in this nanowire is around 190 keV. The neutron flux could reach 10^{27} $\mathrm{cm}^{-2} \cdot \mathrm{s}^{-1}$ in the D-T reaction system. For the nanowire with 500 nm diameter, lengths of 6 µm, 8 µm, and 10 µm can generate 3.4×10^5, 4.7×10^5, and 5.9×10^5 neutrons, respectively. It is noteworthy that this growth is almost linear with length (due to the pulse width of the laser, the length needs to be long enough). More than 10^6 neutrons could be generated within a single pulse if the length of the nanowire is increased to 20 µm, 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 a study on the interaction between lasers and nanowires, with a particular focus on the Z-pinch effect. Notably, the deuterium density within the nanowire could exceed the initial density by over a hundred times. We analyze the pinch density and current under different laser and nanowire parameters. This also indicates the potential existence of stable regions in the Z-pinch effect induced by lasers. The Z-pinch effect makes laser-driven nanowires a short-time-scale and high spatial-density environment for nuclear reactions to occur. It is suitable for use as a neutron source, which also possesses the advantages of a small spatial scale (30 nm × 30 nm) and short pulse width (30 fs). This compression leads to an extremely intense and short neutron pulse. Its peak neutron flux reaches 10^{27} $\mathrm{cm}^{-2} \cdot \mathrm{s}^{-1}$. The high-flux nuclear reaction (neutron) sources can be utilized for research in laboratory nuclear astrophysics r-process [?]. The laser can not only pinch deuterium ions but also other particles as sources in nanowires. One typical example is the proton source. With a radial flux around 1.0×10^{34} $\mathrm{cm}^{-2} \cdot \mathrm{s}^{-1}$, the proton source will provide a unique way for the two-proton capture reaction during the rp-process [?].

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