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

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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} cm^{-2}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.

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

I. 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[1]. 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} $\mathrm{cm}^{-2} \cdot \mathrm{s}^{-1}$ with brief pulse widths. These attributes significantly enhance precision in Time-of-Flight (TOF) measurements, a cornerstone in nuclear reactor design and nuclear astrophysics [2, 3].

Despite these advancements, the replication of high neutron flux conditions, which is crucial for understanding r-process nucleosynthesis[4], remains a formidable challenge. Integral to the cosmic formation of heavy elements, neutron star mergers is the primary site for this process[5], while the possibility of the contribution from supernovae explosions is still under debate[6]. These astrophysical events require conditions, including the intensive neutron flux ranging from 10^{22} to 10^{28} $\mathrm{cm}^{-2} \cdot \mathrm{s}^{-1}$, 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 show the potential to fill this gap due to their exceptional temporal resolution and ability to achieve highly localized neutron beams (spatial resolution) [7, 8]. These sources employ various methodologies, including photoneutron production[9, 10] (10^{21} $\mathrm{cm}^{-2} \cdot \mathrm{s}^{-1}$), target normal sheath acceleration (TNSA) [11, 12] (10^{24} $\mathrm{cm}^{-2} \cdot \mathrm{s}^{-1}$), target compression via spherical shells (NIF)[13] (10^{30} $\mathrm{cm}^{-2} \cdot \mathrm{s}^{-1}$). While these methods offer advancements, the neutron flux from the laser-driven Z-pinch shows the potential to surpass the 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[14]. Fusion and x-ray researches are exploring the potential of Z-pinch devices[15-18]. Recent strides have pivoted around the augmentation of laser-driven Z-pinch mechanics from nanowire arrays[19-21], presenting notable intrigue. These nanowire arrays efficiently absorb the energy from a femtosecond petawatt laser, resulting in a high degree of ionization and intense x-ray generation[22, 23]. Additionally, ions in the array are accelerated, triggering micro-scale fusion reactions[24].

Therefore, we carried out a PIC simulation then find that a fs 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 a unprecedented flux level, 10^{27} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$.

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II. SIMULATION SETTING

To investigate the neutron-generation process in a Z-pinch setup, we employ full-dimensional kinetic simulations to reveal the ultrashort pinch process and neutron generation using the Particle-in-Cell (PIC) code Smilei [25]. The original nuclear-reaction scheme [26, 27] has been introduced in Smilei. Specifically, the cross section for the reaction $D + D \rightarrow n + {}^3He$ has been integrated into the debugging version of Smilei. We have improved the debugging version, corrected and checked the nuclear-reaction cross sections, using periodic boundary conditions in a box [28]. In addition, in this paper we have also added the nuclear reaction $D + T \rightarrow n + {}^4He$ (data from [29]) to assess the potential for a higher-intensity neutron source.

In our simulation, the nanowire in which the Z-pinch is triggered is composed of deuterated polyethylene (CD_2). The particle number density of deuterium is set to $\rho = 7.8 \times 10^{22}$ cm^{-3}. Diameters of 300 nm and 500 nm are considered with varying wire lengths. The initial temperature of the particles is set at 300 Kelvin. The nanowire target is irradiated by circularly polarized (CP) laser pulses with a wavelength of 400 nm and an FWHM duration of 30 fs or 60 fs. The dimensionless amplitude of the laser field ranges from $a_0 = 10$ to 40 ($a_0 = eE/m_e c\omega$), where e and m_e 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 $\sim 5 \times 10^{21}$ 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 macroparticles per cell. There are 640 × 192 × 192 cells for a small-sized nanowire, corresponding to a cube of 4.8 μm × 0.96 μm × 0.96 μm, which is large enough to contain the whole nanowire. The simulation boundaries are set to open conditions for both the fields and the particles. Since field ionization is the dominant ionization process compared with ionization from Coulomb collisions between particles, collisional ionization is switched off to save simulation time. Binary collisions between deuterium and tritium are included, and nuclear reactions may occur.

III. SIMULATION RESULT

When irradiated by ultrashort, high-intensity laser pulses, the atoms inside the wire undergo field ionization. The 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 surface, maintaining quasi-neutrality. For a rough estimate, we assume that electrons ionized from atoms within the nanowire are mostly driven 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 the 3D simulation to illustrate this laser-induced Z-pinch process. Fig. 1 shows that electrons are pulled out by a CP laser into the void (negative current represented in blue), while the positive current density is 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 (a cross section of 30×30 nm^2, $I_{\text{max}} \sim 1.4 \times 10^5$ A), consistent with the estimate. 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 $B_y = 1.0 \times 10^6$ T, exceeding the incident laser field ($a_0 = 17,\ B_y = 4.6 \times 10^5$ T). This quasi-static magnetic field exerts a $J \times B$ force on both the inner and outer currents (electrons) of the nanowire. The current on the inner surface of the nanowire is subjected to a radially inward force 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.

Fig. 1. The 3D current density and 2D magnetic fields during the pinch simulation. In the 3D image, the red color represents positive current (max $J_x = 1.4 \times 10^{16}$ A/cm^2), while the blue color represents negative current. The 2D image illustrates the magnetic field (max $B_y = 1.0 \times 10^6$ T). The x-positive direction aligns with the laser propagation and the axial direction of the nanowire, whereas the y and z directions correspond to the radial directions of the nanowire.

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 in the kinetic-energy distribution of deuterium particles within the nanowire. In the following discussion, we estimate that the temperature of deuterium in the Z-pinch is 190 keV by comparing the ratios of nuclear-reaction rates. The momentum distribution on the surface is continuous, like a 2D shock wave. The mo-

Fig. 2. Spatial and temporal profile of deuterium density. The time-dependent variation of N_{max} is plotted along the curve in (a), specifically at the section marked by the red line. Subfigure (a)(2) shows the particle number density after compression, reaching approximately 10^{25} cm^{-3}.

Visible labels: "At 54 fs" ; "Number density (cm^{-3})" ; "Time (fs)" ; "Deuterium" ; $\times 10^{24}$; (1), (2), (3).

···mentum is between ± 50 MeV/c when the deuterium is accelerated toward the axis center. The electrons extracted from the nanowire and pushed outward also induce an electric field, drawing the surface deuterium outward and accelerating it. If the target is an array, collisions among these ions 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). The corresponding maximum energy density can reach the order of 1×10^{24} MeV/cm^3 (1×10^{12} J/cm^3) at 54 fs, two orders of magnitude higher than in our previous work [30].

As shown in Fig. 2, the compression occurs within approximately $t_c = 10$ fs, and the minimum compressed diameter is about $D = 30$ nm. The maximum density of deuterium can exceed $\rho_m = 1 \times 10^{25}$ cm^{-3}, which is 120 times higher than the initial ion density. The radial ion flux of protons or deuterons reaches approximately 1.0×10^{34} $\text{cm}^{-2} \cdot \text{s}^{-1}$, $(\rho_m \pi D)/t_c$. Thus, nanowires can also serve as sources for other nuclear reactions, such as $p + {}^{11}B \to 3\alpha$. These ions are concentrated 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 increases slightly. For example, with $a_0 = 150$, the maximum density at the front of the wire reaches 1.8×10^{25} cm^{-3}, owing to intense axial particle acceleration and the combined effect of the 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 simulations. This limits the number of nuclear reactions during the Z-pinch (Fig. 4(a)), possibly because of stability.

Fig. 3. (a) Longitudinal cross section of accumulated neutron number density; the blue curve shows the neutron distribution along the Z-axis, indicating the spatial distribution where D-D nuclear reactions occur. In (b), the blue curve represents the number of nuclear reactions produced per femtosecond, while the red curve depicts the temporal evolution of the maximum deuterium density. The data in the figure have been normalized. The nanowire has a diameter of 300 nm and a length of 3.6 μm.

Visible labels: (a) “Number density of neutron (cm^{-3})” ; x (μm); z (μm); $\times10^{18}$. (b) “Neutron_timesteps” ; “Deuterium_timesteps” ; “Neutron yield” ; “Max deuterium density (cm^{-3})” ; “Time (fs)” ; 1e25.

Figure 3 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. This is the moment when energetic ions collide with one another in the densest region. Owing to the extremely high particle number density, nuclear reactions are seen to occur primarily 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, with a reaction rate exceeding 100/fs at this short time scale, as shown in Fig. 3(b). If suitable nuclear reactions are available, the induced reaction exhibits an ultrahigh peak flux and an ultrashort pulse duration. From the simulations, we obtain neutrons with a narrow pulse width of 30 fs and a small source size ($\pi\,30$ nm $\times$ 3000 nm $= 2.8\times10^5$ nm^2). The corresponding neutron (particle) flux may reach 10^{26} cm$^{-2}\cdot$s^{-1}.

Figure 4(a) illustrates the relationship between laser parameters—30 fs and 60 fs, circular polarization and linear polarization—and the number of nuclear reactions generated by the Z-pinch. Additionally, increasing the length is efficient in

(a) *Reaction within 300 nm diameter wire*
Axes: neutron yield vs. a_0.
Legend: circle 60 fs; circle 30 fs; linear 30 fs; 1/10 D–T.

(b)
Axes: 500 nm D–T nuclear yield vs. nanowire length (μm); 300 nm D–D nuclear yield.
Legend: D–T 500 nm; D–D 300 nm.

Fig. 4. (a) Relationship between the number of reactions in a nanowire with a diameter of 300 nm and a length of 3.6 μm under several laser intensities. The blue circles represent a circularly polarized laser with a 60 fs pulse width, while the orange and green markers represent circularly and linearly polarized lasers with a 30 fs pulse width, respectively. The yellow band indicates the approximate range of nuclear reactions that we estimate can be generated by existing Z-pinch devices under the same material conditions. The red star corresponds to one-tenth of the D–T reaction counts. (b) Number of fusion reactions for different nanowire lengths. The red circles represent D–T fusion, with the yield shown on the left axis. The blue squares represent D–D fusion, with the yield shown on the right axis.

enhancing the number of nuclear reactions during the pinch phase. Nanowire diameter also affects the reaction rates. Under the same conditions, when normalized to the amount of material, the generation efficiency of nuclear reactions is highest for a wire with a diameter of 500 nm, followed by 300 nm. Both efficiencies are higher than those observed in the 200 nm and 800 nm wires.

When the D–T system is considered, the fusion yield is found to exceed that of D–D by more than a factor of 10. Comparing their yields in the same system, the equivalent temperature [31] 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 a nanowire with a diameter of 500 nm, 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 because, due to the laser pulse width, the nanowire must be sufficiently long. More than 10^6 neutrons could be generated within a single pulse if the nanowire length were increased to 20 μm, as shown in Fig. 4(b). Cascaded D–D and D–T reactions also occur within the system.

IV. CONCLUSION

In summary, we first studied the interaction between lasers and nanowires, with particular focus on the Z-pinch effect. Notably, the deuterium density within the nanowire can exceed the initial density by more than two orders of magnitude. We analyzed the pinch density and current under different laser and nanowire parameters. The results also indicate the possible existence of stable regions in the laser-induced Z-pinch effect. The Z-pinch effect makes laser-driven nanowires a short-timescale, high-spatial-density environment for nuclear reactions. This makes them suitable for use as a neutron source, with the additional advantages of a small spatial scale (30 nm × 30 nm) and a short pulse width of 30 fs. This compression produces an extremely intense and short neutron pulse. Its peak neutron flux reaches 10^{27} $\mathrm{cm}^{-2} \cdot \mathrm{s}^{-1}$. Such high-flux nuclear-reaction (neutron) sources can be used for research on the r-process in laboratory nuclear astrophysics [32]. The laser can pinch not only deuterium ions but also other particle sources in nanowires. One typical example is a proton source. With a radial flux of around 1.0×10^{34} $\mathrm{cm}^{-2} \cdot \mathrm{s}^{-1}$, the proton source will provide a unique pathway for the two-proton capture reaction during the rp-process [33].

[1] I. S. Anderson, C. Andreani, J. M. Carpenter, G. Festa, G. Gorini, C.-K. Loong, and R. Senesi, *Physics Reports* **654**, 1 (2016), publisher: Elsevier.

[2] J. Wei, H. Chen, Y. Chen, Y. Chen, Y. Chi, C. Deng, H. Dong, L. Dong, S. Fang, J. Feng, S. Fu, L. He, W. He, Y. Heng, K. Huang, X. Jia, W. Kang, X. Kong, J. Li, T. Liang, G. Lin, Z. Liu, H. Ouyang, Q. Qin, H. Qu, C. Shi, H. Sun, J. Tang, J. Tao, C. Wang, F. Wang, D. Wang, Q. Wang, S. Wang, T. Wei, J. Xi, T. Xu, Z. Xu, W. Yin, X. Yin, J. Zhang, Z. Zhang, Z. Zhang, M. Zhou, and T. Zhu, *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **600**, 10 (2009).

[3] R. Garoby, A. Vergara, H. Danared, I. Alonso, E. Bargallo, B. Cheymol, C. Darve, M. Eshraqi, H. Hassanzadegan, A. Jansson, I. Kittelmann, Y. Levinsen, M. Lindroos, C. Martins, Midttun, R. Miyamoto, S. Molloy, D. Phan, A. Ponton, E. Sargsyan, T. Shea, A. Sunesson, L. Tchelidze, C. Thomas,

M. Jensen, W. Hees, P. Arnold, M. Juni-Ferreira, F. Jensen, A. Lundmark, D. McGinnis, N. Gazis, J. W. Il, M. Anthony, E. Pitcher, L. Coney, M. Gohran, J. Haines, R. Linander, D. Lyngh, U. Oden, H. Carling, R. Andersson, S. Birch, J. Cereijo, T. Friedrich, T. Korhonen, E. Laface, M. Mansouri-Sharifabad, A. Monera-Martinez, A. Nordt, D. Paulic, D. Piso, S. Regnell, M. Zaera-Sanz, M. Aberg, K. Breimer, K. Batkov, Y. Lee, L. Zanini, M. Kickulies, Y. Bessler, J. Ringnér, J. Jurns, A. Sadeghzadeh, P. Nilsson, M. Olsson, J.-E. Presteng, H. Carlsson, A. Polato, J. Harborn, K. Sjögreen, G. Muhrer, and F. Sordo, Physica Scripta 93, 014001 (2017).

[4] J. J. Cowan, C. Sneden, J. E. Lawler, A. Aprahamian, M. Wiescher, K. Langanke, G. Martínez-Pinedo, and F.-K. Thielemann, Rev. Mod. Phys. 93, 015002 (2021).

[5] F.-K. Thielemann, A. Arcones, R. Käppeli, M. Liebendörfer, T. Rauscher, C. Winteler, C. Fröhlich, I. Dillmann, T. Fischer, G. Martinez-Pinedo, K. Langanke, K. Farouqi, K.-L. Kratz, I. Panov, and I. Korneev, Progress in Particle and Nuclear Physics 66, 346 (2011), particle and Nuclear Astrophysics.

[6] E. Pian, P. D' Avanzo, S. Benetti, M. Branchesi, E. Brocato, S. Campana, E. Cappellaro, S. Covino, V. D' Elia, J. P. U. Fynbo, F. Getman, G. Ghirlanda, G. Ghisellini, A. Grado, G. Greco, J. Hjorth, C. Kouveliotou, A. Levan, L. Limatola, D. Malesani, P. A. Mazzali, A. Melandri, P. Møller, L. Nicastro, E. Palazzi, S. Piranomonte, A. Rossi, O. S. Salafia, J. Selsing, G. Stratta, M. Tanaka, N. R. Tanvir, L. Tomasella, D. Watson, S. Yang, L. Amati, L. A. Antonelli, S. Ascenzi, M. G. Bernardini, M. Boër, F. Bufano, A. Bulgarelli, M. Capaccioli, P. Casella, A. J. Castro-Tirado, E. Chassande-Mottin, R. Ciolfi, C. M. Copperwheat, M. Dadina, G. De Cesare, A. Di Paola, Y. Z. Fan, B. Gendre, G. Giuffrida, A. Giunta, L. K. Hunt, G. L. Israel, Z.-P. Jin, M. M. Kasliwal, S. Klose, M. Lisi, F. Longo, E. Maiorano, M. Mapelli, N. Masetti, L. Nava, B. Patricelli, D. Perley, A. Pescalli, T. Piran, A. Possenti, L. Pulone, M. Razzano, R. Salvaterra, P. Schipani, M. Spera, A. Stamerra, L. Stella, G. Tagliaferri, V. Testa, E. Troja, M. Turatto, S. D. Vergani, and D. Vergani, Nature 551, 67 (2017).

[7] J. Alvarez, J. Fernández-Tobias, K. Mima, S. Nakai, S. Kar, Y. Kato, and J. Perlado, Physics Procedia 60, 29 (2014), 3rd International Meeting of the Union for Compact Accelerator-driven Neutron Sources, UCANS III, 31 July–3 August 2012, Bilbao, Spain the 4th International Meeting of the Union for Compact Accelerator-driven Neutron Sources, UCANS IV, 23–27 September 2013, Sapporo, Hokkaido, Japan.

[8] A. Taylor, M. Dunne, S. Bennington, S. Ansell, I. Gardner, P. Norreys, T. Broome, D. Findlay, and R. Nelmes, Science 315, 1092 (2007), https://www.science.org/doi/pdf/10.1126/science.1127185.

[9] X. Jiao, J. Shaw, T. Wang, X. Wang, H. Tsai, P. Poth, I. Pomerantz, L. Labun, T. Toncian, M. Downer, and B. Hegelich, Matter and Radiation at Extremes 2, 296 (2017).

[10] K. W. D. Ledingham, I. Spencer, T. McCanny, R. P. Singhal, M. I. K. Santala, E. Clark, I. Watts, F. N. Beg, M. Zepf, K. Krushelnick, M. Tatarakis, A. E. Dangor, P. A. Norreys, R. Allott, D. Neely, R. J. Clark, A. C. Machacek, J. S. Wark, A. J. Cresswell, D. C. W. Sanderson, and J. Magill, Phys. Rev. Lett. 84, 899 (2000).

[11] M. Roth, D. Jung, K. Falk, N. Guler, O. Deppert, M. Devlin, A. Favalli, J. Fernandez, D. Gautier, M. Geissel, R. Haight, C. E. Hamilton, B. M. Hegelich, R. P. Johnson, F. Merrill, G. Schaumann, K. Schoenberg, M. Schollmeier, T. Shimada, T. Taddeucci, J. L. Tybo, F. Wagner, S. A. Wender, C. H. Wilde, and G. A. Wurden, Phys. Rev. Lett. 110, 044802 (2013).

[12] M. Günther, O. Rosmej, P. Tavana, M. Gyrdymov, A. Skobliakov, A. Kantsyrev, S. Zähter, N. Borisenko, A. Pukhov, and N. Andreev, Nature Communications 13, 170 (2022).

[13] A. L. Kritcher, C. V. Young, H. F. Robey, C. R. Weber, A. B. Zylstra, O. A. Hurricane, D. A. Callahan, J. E. Ralph, *et al.*, Nature Physics 18, 251.

[14] W. H. Bennett, Phys. Rev. 45, 890 (1934).

[15] M. G. Haines, S. V. Lebedev, J. P. Chittenden, F. N. Beg, S. N. Bland, and A. E. Dangor, Physics of Plasmas 7, 1672 (2000).

[16] M. G. Haines, Plasma Physics and Controlled Fusion 53, 093001 (2011).

[17] V. Kantsyrev, A. Safronova, A. Esaulov, K. Williamson, I. Shrestha, F. Yilmaz, G. Osborne, M. Weller, N. Ouart, V. Shlyaptseva, L. Rudakov, A. Chuvatin, and A. Velikovich, High Energy Density Physics 5, 115 (2009).

[18] D. D. Ryutov, M. S. Derzon, and M. K. Matzen, Rev. Mod. Phys. 72, 167 (2000).

[19] K. K. Ostrikov, F. Beg, and A. Ng, Reviews of Modern Physics 88, 011001 (2016), publisher: American Physical Society.

[20] V. Kaymak, A. Pukhov, V. N. Shlyaptsev, and J. J. Rocca, Phys. Rev. Lett. 117, 035004 (2016).

[21] J. J. Rocca, M. G. Capeluto, R. C. Hollinger, S. Wang, Y. Wang, G. R. Kumar, A. D. Lad, A. Pukhov, and V. N. Shlyaptsev, Optica 11, 437 (2024).

[22] C. Bargsten, R. Hollinger, M. G. Capeluto, V. Kaymak, A. Pukhov, S. Wang, A. Rockwood, Y. Wang, D. Keiss, R. Tommasini, R. London, J. Park, M. Busquet, M. Klapisch, V. N. Shlyaptsev, and J. J. Rocca, Science Advances 3, e1601558 (2017).

[23] Y. Shou, D. Kong, P. Wang, Z. Mei, Z. Cao, Z. Pan, Y. Li, S. Xu, G. Qi, S. Chen, J. Zhao, Y. Zhao, C. Fu, W. Luo, G. Zhang, X. Yan, and W. Ma, Optics Express 29, 5427 (2021), publisher: Optica Publishing Group.

[24] A. Curtis, C. Calvi, J. Tinsley, R. Hollinger, V. Kaymak, A. Pukhov, S. Wang, A. Rockwood, Y. Wang, V. N. Shlyaptsev, *et al.*, Nature Communications

Figure 3

Figure 1: Figure 3

9, 1077 (2018).

[25] J. Derouillat, A. Beck, F. Pérez, T. Vinci, M. Chiaramello, A. Grassi, M. Flé, G. Bouchard, I. Plotnikov, N. Aunai, J. Dargent, C. Riconda, and M. Grech, Computer Physics Communications 222, 351 (2018).

[26] D. P. Higginson, A. Link, and A. Schmidt, Journal of Computational Physics 388, 439 (2019).

[27] D. P. Higginson, I. Holod, and A. Link, Journal of Computational Physics 413, 109450 (2020).

[28] Z. Zhu, J. Xu, and G.-Q. Zhang, Physical Review C 106, 034604 (2022).

[29] https://www.nndc.bnl.gov/ (National Nuclear Data Center).

[30] D. Kong, G. Zhang, Y. Shou, S. Xu, Z. Mei, Z. Cao, Z. Pan, P. Wang, G. Qi, Y. Lou, Z. Ma, H. Lan, W. Wang, Y. Li, P. Rubovic, M. Veselsky, A. Bonasera, J. Zhao, Y. Geng, Y. Zhao, C. Fu, W. Luo, Y. Ma, X. Yan, and W. Ma, Matter and Radiation at Extremes 7, 064403 (2022).

[31] W. Bang, M. Barbui, A. Bonasera, G. Dyer, H. J. Quevedo, K. Hagel, K. Schmidt, F. Consoli, R. De Angelis, P. Andreoli, E. Gaul, A. C. Bernstein, M. Donovan, M. Barbarino, S. Kimura, M. Mazzocco, J. Sura, J. B. Natowitz, and T. Ditmire, Phys. Rev. Lett. 111, 055002 (2013).

[32] J. J. Cowan, C. Sneden, J. E. Lawler, A. Aprahamian, M. Wiescher, K. Langanke, G. Martínez-Pinedo, and F.-K. Thielemann, Rev. Mod. Phys. 93, 015002 (2021).

[33] H. Schatz, A. Aprahamian, J. Görres, M. Wiescher, T. Rauscher, J. Rembges, F.-K. Thielemann, B. Pfeiffer, P. Möller, K.-L. Kratz, H. Herndl, B. Brown, and H. Rebel,

388 Physics Reports **294**, 167 (1998).

Figures