Observation of a high degree of stopping for laser-accelerated intense proton beams in dense ionized matter

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Intense particle beams generated from the interaction of ultrahigh intensity lasers with sample foils provide options in radiography, high-yield neutron sources, high-energy-density-matter generation, and ion fast ignition. An accurate understanding of beam transportation behavior in dense matter is crucial for all these applications. Here we report the experimental evidence on one order of magnitude enhancement of intense laser-accelerated proton beam stopping in dense ionized matter, in comparison with the current-widely used models describing individual ion stopping in matter. Supported by particle-in-cell (PIC) simulations, we attribute the enhancement to the strong decelerating electric field approaching 1 GV/m that can be created by the beam-driven return current. This collective effect plays the dominant role in the stopping of laser-accelerated intense proton beams in dense ionized matter. This finding is essential for the optimum design of ion driven fast ignition and inertial confinement fusion.
Alpha-particle stopping in dense ionized matter is essential to achieve ignition in inertial confinement fusion. Fast ignition (FI) relies even more on a detailed understanding of ultrahigh-current ion stopping in matter, which is therefore considered as a fundamental process of utmost importance to nuclear fusion. In the fast ignition scheme, a short and intense pulse of energetic charged particles—electrons, protons, or heavy ions—generated by an ultra-high-intensity laser, is directed toward the pre-compressed fusion pellet. The charged-particle beam requirements to achieve ignition have been discussed and studied in detail previously based on single-particle stopping theory. However, the collective effects induced by high-current charged-particle beams could alter significantly the projected range, the magnitude of energy deposition, and therefore change the requirements for ignition correspondingly. Besides, in the cases of ion beam-driven inertial confinement fusion and high-energy density science, which require ultrahigh beam intensity from accelerators, no collective effects on ion stopping processes due to high beam intensity are considered nor—to the best of our knowledge—were they reported in any previous experiments.

Since the discovery of alpha decay and the availability of energetic fission fragments, it became interesting to study fast particle stopping processes in matter. In past decades, numerous theoretical models, some of which can be considered to be further developments of the early work of Bethe and Bloch, are built to describe individual charged particle stopping in dense ionized matter. Only recently experiments with sufficient precision were carried out with dense ionized matter to distinguish between different models. In these experiments, incident particles are generated from laser-induced nuclear reactions, or from traditional accelerators. Hence the beam intensity was low, and the individual ion stopping theories can be discriminated. Ultra-high-intensity lasers have opened up perspectives in many fields of research and application. By irradiating a thin foil with ultra-high-intensity lasers, an ultrahigh accelerating field can be formed and multi-MeV ions with high intensity (10^10 A/cm^2) in short timescale (ps) are produced. Such beams provide experimental opportunities to investigate the beam-driven complex collective phenomena. The stopping power for these intense beam could be orders of magnitude higher than that for individual particles if the beam intensity is high enough. In our previous experiment, we sent the laser-accelerated ion beams directly into the plasma target, and observed that the energy spectra of the ions were significantly downshifted after passing though the dense plasma. This energy downshift was far beyond the Bethe–Bloch predictions (see Supplementary Figs. 8 and 9 for details). However, the large energy spread of the incident beam makes it difficult to correctly interpret the results.

In this article, we improve the precision of the measurement by using a magnetic dipole to trim out a quasi-monoenergetic proton beam. The dense ionized target is produced by irradiating a tri-cellolace acetate (TCA) foam sample with soft X-rays from a laser-heated hohlraum. Thus the temperature and density are homogeneous across the ionized target. This state can be maintained for a period of more than 10 ns. This period is two to three orders of magnitude longer than the beam duration and the beam-plasma interaction timescale. Therefore, the target can be considered to be quasi-static. This kind of experimental scenario allows for precise measurement of intense proton beam stopping in dense ionized matter. We observed that the energy loss is enhanced by one order of magnitude in comparison to the predictions from individual-proton stopping theories, Bethe–Bloch, Li–Petrasso (LP), and standard stopping model (SSM). Through PIC simulation, we attribute the high degree of enhancement to a strong deaccelerating electric field induced by the intense proton beam. This collective effect is the primary cause for the enhanced stopping, and it is likely to have a major impact on nuclear fusion scenarios like fast ignition, alpha-particle self-heating, as well as ion driven inertial confinement fusion.

Results
The experiment was carried out at the XG-III laser facility of Laser Fusion Research Center in Mianyang. The experimental layout is displayed in Fig. 1. Here a short and intense laser beam of 800 fs duration, 20 μm focal spot, and 150 J total energy irradiates a CH-coated tungsten foil (15-μm thick) to generate a charged-particle beam. The beam consists of a mixture of protons (H_1^+) and carbon ions with different charge states (C_1^+, C_2^+, and C_3^+). They originate at the backside of the target by means of the target normal sheath acceleration (TNSA). The predominant particle species is H_1^+, because the charge-to-mass ratio is maximum for this species, and is, therefore, more efficiently accelerated than the lower charge-to-mass ratio species of carbon ions. The TNSA mechanism results in a broad range of particle energies, which is not favorable for quantitative analysis of the particle energy loss. A magnetic dipole, with entrance and exit slits, was used to generate a monoenergetic beam. The ions, spatially collimated by the 500 μm entrance slit, are dispersed laterally by the magnetic dipole according to their specific p/q value, where p and q are the particle momentum and charge, respectively. A second 500 μm exit slit, selects the quasi-monoenergetic ion pulses. The selected ions consist of different particle species, with similar p/q value, they have, however, different velocities and therefore arrive at the target pulse by pulse with different time delay. In the current case, the C_2^+ and C_3^+ ions lag behind proton pulse by about 30 ns at the plasma target, and C_1^+ and C_2^+ are delayed more, therefore the laser-accelerated carbon ions have no influence on the proton beam stopping measurement.

A gold hohlraum converter was used to generate soft X-rays by interaction of a ns laser pulse (150 J), with the hohlraum walls. The X-rays subsequently irradiated and heated the foam target. The hydrodynamic response of the heated foam target under this kind of scheme has been very well-investigated and the state has been well characterized. Once heated by soft X-rays from hohlraum radiation, the material expansion occurs inside the target between the sponge-like structures. This micro expansion leads to target homogenization, while the volume and density of the entire target stay constant for more than 10 ns. Therefore, homogeneous, ns-long-living, and quasi-static ionized matter is generated. Unlike producing ionized matter through direct heating by high-power lasers—in which case strong electromagnetic fields are generated in the target and will greatly influence the proton transportation behavior—here the electromagnetic fields resulted from the heating process can be neglected.

In order to determine plasma parameters, the emission spectra of the gold hohlraum and target matter were measured. The gold hohlraum radiation spectrum is well-represented by a 20 eV black body radiation spectrum, while the temperature of the plasma target is 17 eV. This value was obtained from a Boltzmann slope analysis of the He-like carbon lines. Given a temperature of 17 eV, and mass density of 2 mg/cm^3, the number density of free electrons is determined to be 4 x 10^20 cm^3 based on the FLYCHK code.

A Thomson parabola spectrometer (TPS) in conjunction with a plastic track detector CR39 was used to obtain the energy spectrum of the charged particles. The energy resolution of the
The energy loss of intense ion beam in ionized matter is composed of two terms as 
\[\frac{dE}{dx} = \left(\frac{dE}{dx}\right)_{\text{collision}} + \left(\frac{dE}{dx}\right)_{\text{collective}}.\]
The first term \(\left(\frac{dE}{dx}\right)_{\text{collision}}\) describes the collisional stopping induced by binary interaction of the individual projectiles with the individual particles in the plasma. The second term \(\left(\frac{dE}{dx}\right)_{\text{collective}}\) describes the collective stopping induced by the beam-driven electric fields. \(\left(\frac{dE}{dx}\right)_{\text{collision}}\) consists of contributions from free electrons and plasma ions. The ionic contributions for partially ionized plasma include two parts, bound electrons and nuclei. In the current regime, where the protons are much faster than the thermal electrons, the contribution of the nuclei to \(\left(\frac{dE}{dx}\right)_{\text{collision}}\) can be neglected\(^7\). Here in this article the nuclear stopping is excluded.

In Fig. 3, the measured energy loss is compared to theoretical models, e.g., Bethe–Bloch model, Li–Petrasso (LP) theory, and SSM by Deutsch. These theories are based on binary collisions with free electrons, bound electrons, and/or plasmons. They all underestimate the measured stopping power by as much as one order of magnitude, even when considering an error of about 15% from the uncertainty of plasma electron density. We attribute this unusual high degree of stopping to collective electromagnetic effects induced by high-current ion beams.

In order to understand this enhanced stopping, both collective electromagnetic effects and close particle–particle interactions need to be taken into account. The most appropriate tool to simulate the conditions of the experiment is the particle-in-cell method (PIC), which in recent years has established itself as a state-of-the-art method for solving problems of kinetic plasma physics\(^5,79-79\).

We used the recently developed PIC code LAPINS\(^79,80\), which is able to simulate intense beam-plasma interaction in a self-consistent way, which contains both close collisions and collective electromagnetic fields (see details in “Methods”). The simulation assumes, the incident proton beam to have Gaussian distribution in space and time, with a beam duration of 1 ps and a transverse extension of 1 mm. The energy spectrum is also assumed to be Gaussian, with the peak of the energy distribution at 3.36 MeV and the full width at half maximum (FWHM) is about 0.10 MeV. After passing through the plasma target, the central energy is downshifted to 2.98 MeV and the FWHM increased to about 0.25 MeV.

**Discussion**

The energy loss of intense ion beam in ionized matter is composed of two terms as 
\[\frac{dE}{dx} = \left(\frac{dE}{dx}\right)_{\text{collision}} + \left(\frac{dE}{dx}\right)_{\text{collective}}.\]

TPS achieves \(E/\delta E \sim 34\) for protons at energy \(E = 3.36\) MeV (see section I of the Supplementary information for details), where \(\delta E\) is the energy range covered by the incident beam spot on the detector. In Fig. 2a, tracks recorded on CR39 film are displayed for ions passing through the system with/without target. When the plasma target is inserted, only protons are observed in the TPS. The deflection distances of protons without/with target are converted to energies in Fig. 2b and c, respectively. The energy distribution of the incident, unperturbed protons without target centers at 3.36 MeV, and the full width at half maximum (FWHM) is about 0.10 MeV. After passing through the plasma target, the central energy is downshifted to 2.98 MeV and the FWHM increased to about 0.25 MeV.

**Fig. 1 Layout of the experiment.** a A ps laser is focused onto a tungsten foil, generating intense short-pulse ion beams with different species. A magnetic dipole with slits at the entrance and exit serve as p/q analyser to select monoenergetic ion beams. Such ions interact with the laser-generated plasma target and emerge from the target with a lower energy due to the incurred energy loss. The final-state energy is measured by a Thomson parabola in conjunction with CR39 film. b Parabola spectra of laser-accelerated ions without dipole measured by Thomson parabola in conjunction with Fuji image plate. c The target consists of a gold hohlraum converter to produce the soft X-rays that irradiate the TCA foam to generate a dense ionized sample. d The insert shows the simulation result of an intense proton beam moving along the z direction, inducing a strong longitudinal electric field, which is counter-directional to the proton beam propagation, causing the unusual high degree of stopping.
These ion species with various energies. The solid curves represent the theoretical tracks of ions recorded on TPS CR39 passing through null target and the converted energies of protons. The spatial size of this decelerating field is comparable to the size of the proton bunch. This is different from the plasma wakefield case, where the spatial structure of the electric field is determined by the plasma density. Here the plasma wakefield wavelength is much smaller than the beam length, therefore the wakefield-induced collective acceleration and deceleration cancel out. The central energy of proton spectrum is downshifted by 0.36 MeV after passing through the plasma. As shown in Fig. 3, this energy shift (blue triangle) agrees with experimental data in magnitude. We carried out additional simulations for different beam densities at $8 \times 10^{11}$ cm$^{-3}$ and $8 \times 10^{15}$ cm$^{-3}$, which are defined as low- and intermediate-current cases, respectively. For the low-current case, the beam-induced longitudinal electric field is excited under such conditions. After passing through the plasma, the energy spectrum is downshifted by only 0.03 MeV as shown in Fig. 4c. No collective decelerating field is excited under such conditions. As for the intermediate case, the stopping due to the collective effects is comparable to that caused by binary collisions, giving rise to an energy loss of 0.06 MeV as shown in Fig. 4c.

In all, the energy loss of laser-accelerated intense proton beam in dense ionized matter consists of $(dE/dx)_{\text{collision}}$ and $(dE/dx)_{\text{collective}}$. The LP, SSM, and Li-Petrasso models, and PIC simulation for low-current case give similar predictions for $(dE/dx)_{\text{collision}}$, which is one order of magnitude lower than the experimental data. PIC simulation for high-current cases shows that when sending a very dense ion bunch into the plasma, strong electric fields can be induced, and the ion bunch is imbedded in the deceleration field. This leads to a significant enhancement of the energy loss, which fairly well explains our observation.

In summary, the laser-accelerated intense proton beam stopping in a dense ionized matter has been measured. Benefitting from the fact that we have a quasi-monoenergetic proton beam and long-living well-characterized dense ionized target, accurate stopping power data were obtained. The measured stopping power exceeds the classical theory predictions in binary collision scheme by about one order of magnitude. The phenomenon can be very well explained by our PIC simulation combined with a Monte Carlo binary collision model and a reduced model taking account of the collective electromagnetic effects. The stopping power is

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**Fig. 2** TPS CR39 tracks of quasi-monoenergetic ions passing through the system with/without target and the converted energies of protons. 

**Fig. 3** Measured (exp.-after plasma), numerical (PIC), and analytical predictions (Bethe–Bloch, SSM, and Li-Petrasso) of the proton beam energy spectra downshift after passing through the dense plasma target in relative to the central energy $E_0$ of incident proton beam. The symbols represent the central energies and the bars represent the FWHMs of the respective spectra. For comparison, the data for the incident proton beam (no target) are shown as well.
A beam density of $8 \times 10^{11}$ cm$^{-3}$ will be important for the optimum design of ion-driven inertial confinement fusion and fast ignition scenarios.

**Methods**

The collisional model in the current PIC code is based on Monte Carlo binary collisions, which has the advantage of calculating the beam stopping in a natural manner. The model includes binary collisions among electron-electron, electron-ion, and ion-ion, taking into account contributions from both free and bound electrons. Compared with other existing models, physical quantities, such as angular scattering, momentum transferring, and temperature variation, can be taken into account quite readily in the approach.

In the calculations, three steps are made iteratively: (i) pair of particles are selected randomly in the cell, i.e., either electron-electron, electron-ion, or ion-ion pairs; (ii) for these pair of particles, the binary collisions are associated with changes in the velocity of the particles within the time interval $\Delta t$, which are calculated; (iii) and then the velocity of each particle is replaced by the newly calculated one.

In order to contain both bound and free electrons’ contribution into the binary collision model, we here take the collision frequency between ions and electrons, in the above (ii) step, as,

$$\nu_{\text{e-i}} = \frac{8\sqrt{2}n_i e^2 Z_n^2}{3m_i^3 \beta^3} \ln (\lambda_{fi}) + \frac{A - Z_{fi} \ln (\lambda_{fi})}{Z_{fi} \ln (\lambda_{fi})},$$

where

$$\ln (\lambda_{fi}) = \ln \left[ \frac{2\pi^2 m_e b^2}{I_{fi}(Z)} \right] - \beta^2 - C_{\text{fi}} / A - \delta / 2,$$

and

$$\ln (\lambda_{fi}) \equiv \ln (\lambda_{fi} / b).$$

At the low-temperature limit, when all electrons are bound at the nucleus, the calculated stopping powers converge to the NIST ones with the average ionization degree approaching zero as the stopping powers of cold materials can be well calculated by Bethe–Bloch formula. With the increase of temperature, more and more bound electrons are ionized, giving rise to an increased stopping power to cold matter. When the temperature is further increased, with ionizations reaching the maximum, lowered stopping power is observed, which is due to the suppression of collision frequency between projected proton beam and hot plasmas in the target.

**Data availability**

The datasets generated and analyzed during the current study are available from the corresponding authors upon reasonable request. The simulation details are available from the corresponding author on reasonable request.

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**References**

1. Hurricane, O. A. et al. Inertially confined fusion plasmas dominated by alpha-particle self-heating. *Nat. Phys.* 12, 800 (2016).
69. Borghesi, M. et al. Multi-MeV proton source investigations in ultraintense laser-foil interactions. Phys. Rev. Lett. 92, 055003 (2004).

70. Sarri, G. et al. Dynamics of self-generated, large amplitude magnetic fields following high-intensity laser matter interaction. Phys. Rev. Lett. 109, 205002 (2012).

71. Chung, H.-K., Chen, M. H., Morgan, W. L., Ralchenko, Y. & Lee, R. W. FLYCHK: generalized population kinetics and spectral model for rapid spectroscopic analysis for all elements. High. Energy Density Phys. 1, 3–12 (2005).

72. Zhang, Y. et al. An angular-resolved multi-channel Thomson parabola spectrometer for laser-driven ion measurement. Rev. Sci. Instrum. 89, 093302 (2018).

73. Jung, D. et al. Development of a high resolution and high dispersion Thomson parabola. Rev. Sci. Instrum. 82, 013306 (2011).

74. Rajeev, R., Rishad, K. P. M., MadhuTrivikram, T., Narayanan, V. & Krishnamurthy, M. A Thomson parabola ion imaging spectrometer designed to probe relativistic intensity ionization dynamics of nanoclusters. Rev. Sci. Instrum. 82, 083303 (2011).

75. Peter, T. & Meyer-ter-Vehn, J. Energy loss of heavy ions in dense plasma. I. Linear and nonlinear Vlasov theory for the stopping power. Phys. Rev. A 43, 1998–2014 (1991).

76. Gericke, D. O. & Schlanges, M. Energy deposition of heavy ions in the regime of strong beam-plasma correlations. Phys. Rev. E 67, 037401 (2003).

77. Cayzac, W. et al. Predictions for the energy loss of light ions in laser-generated plasmas at low and medium velocities. Phys. Rev. E 92, 053109 (2015).

78. Chen, B. Z., Wu, D., Ren, J. R., Hoffmann, D. H. H. & Zhao, Y. T. Transport of intense particle beams in large-scale plasmas. Phys. Rev. E 101, 051203 (2020).

79. Wu, D., Yu, W., Fritzsche, S. & He, X. T. High-order implicit particle-in-cell method for plasma simulations at solid densities. Phys. Rev. E 100, 013207 (2019).

81. Huang, C. et al. Hosing instability in the blow-out regime for plasma-wakefield acceleration. Phys. Rev. Lett. 99, 255001 (2007).

82. Adli, E. et al. Acceleration of electrons in the plasma wakefield of a proton bunch. Nature 561, 363–367 (2018).

83. Fano, U. Penetration of protons, alpha particles, and mesons. Annu. Rev. Nucl. Sci. 13, 1–66 (1963).

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Author contributions

Yongtao Zhao conceived this work, organized the experiments and simulations with Wenyin Zhou and Dong Wu, respectively. Jieru Ren, Zhigang Deng, and Yongtao Zhao carried out the experiment together with the high power laser team (Zongqiang Zhao, Wemin Zhou, and Yuqiu Gu), the plasma diagnostics team (Shaoyi Wang, Quanping Fan, Bubu Ma, Bo Cui, Xing Wang, Zhurong Cao, and Leifeng Cao), ion beam characterization team (Wei Qi, Shuai Yin, Shukai He, Wei Liu, Rui Cheng, Xianming Zhou, Jianhua Feng, Yihang Zhang, and Zhe Zhang). Jieru Ren, Zhigang Deng, Shuai Yin, Wei Qi, Shaoyi Wang, and Quanping Fan analyzed the main part of the experimental data. Benzheng Chen, Jieru Ren, Yongtao Zhao, and Dong Wu performed the simulations and related analysis. Shaoping Zhu, Zhongfeng Xu, Guangqiu Xiao, Hongwei Zhao, Yutong Li, Yuqiu Gu, and Leifeng Cao contribute in the physical discussion. Jieru Ren, Yongtao Zhao, Dong Wu, and Dieter H.H. Hoffmann wrote the paper.

Competing interests

The authors declare no competing interests.

Additional information

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