Matter and Radiation at Extremes | EDITORIAL | scitation.org/journal/mre

Recent progress in matter in extreme states created by laser

Cite as: Matter Radiat. Extremes 7, 013001 (2022); doi: 10.1063/5.0078895
Submitted: 8 October 2021 • Accepted: 12 November 2021 •
Published Online: 14 December 2021

View Online Export Citation CrossMark

K. Batani,[1,a)] D. Batani,[2,3] X. T. He,[4,5] and K. Shigemori[6]

AFFILIATIONS

[1]Institute of Plasma Physics and Laser Micro Fusion, Warsaw, Poland
[2]University of Bordeaux, CEA, CNRS, UMR 5107, 33405 Talence, France
[3]Plasma Physics Department, National Research Nuclear University MEPhI, Moscow, Russia
[4]Center for Applied Physics and Technology, Peking University, Beijing, China
[5]Institute of Applied Physics and Computational Mathematics, Beijing, China
[6]Institute of Laser Engineering, Osaka University, Osaka, Japan

Note: This paper is part of the Special Issue on Matter in Extreme States Created by Laser.
[a)]**Author to whom correspondence should be addressed:** katarzyna.batani@ifpilm.pl

I. INTRODUCTION

Strong interest in the modeling of planetary interiors, dwarf stars, and the physical conditions necessary to achieve inertial confinement fusion (ICF) have driven attention to the properties of matter at high density, temperature, and pressure (beyond the megabar limit). Extreme states of matter have been studied using gas guns, explosives, and Z-pinches, among other methods (see, e.g., Refs. 1–4). However in recent years, lasers have become the most reliable standard tool for creating extreme states of matter. Indeed, laser experiments enable very high pressures to be reached with relative ease and with relatively high repetition rates, and in addition the apparatus required is simpler than that associated with other methods. The first measurements of the equation of state (EOS) in the multi-megabar pressure range using laser-driven shocks were performed at the Laboratoire pour l'Utilisation des Lasers Intenses (LULI) in 1995 by the group of Koenig *et al.*[5] These were soon followed by the well-known measurements of the hydrogen EOS performed at the Lawrence Livermore National Laboratory (LLNL) using the NOVA laser.[6] Since then, laser-driven shocks have been used to measure EOS and other physical properties of a variety of materials. Using lasers, it has been possible to obtain a completely new set of experimental data that are important for several fields of physics: modeling of planetary interiors and dwarf stars,[7–10] inertial confinement fusion (ICF),[11–13] and materials science. They have allowed the generation of multi-megabar shock waves to bring matter to extreme conditions of high energy density. Recent experiments in converging geometry have studied matter in the gigabar pressure regime.[14] This experimental renaissance has been accompanied by new developments in theoretical models of matter under extreme conditions,[15–18] which are becoming able to describe matter at densities above those of the solid state and at high temperatures, as well as technological developments with regard to target design,[19,20] novel diagnostic techniques,[21–24] and a deeper understanding of the behavior of consolidated diagnostics.[25–27]

Beyond the acquisition of EOS data points, there have been extensive studies of phase transitions and the transport properties of materials in recent years. There have also been a considerable number of studies focusing on the optical properties of materials of relevance to planetary science, such as water and carbon (diamond), these being among the main constituents of giant planets like Uranus and Neptune, as well as of many recently discovered extrasolar planets. In the case of water, these have included detailed studies of reflectivity[7] and refractive index.[28]

Three papers in this "Matter in extreme states created by laser" special issue are directly related to these aspects of matter under extreme conditions.[9,12,15]

Wang *et al.*[12] analyze the behavior of the shock Hugoniot curve of polycrystalline diamond at pressures relevant to ICF, for which polycrystalline diamond (also referred as high-density carbon, HDC) is a promising ablator candidate. The authors of the paper examine the deviation of the EOS of HDC from that of single-crystal diamond and confirm its stiffer compressibility due to its smaller grain size and lower initial density. Their paper also addresses the use of porous models, which represents an important open problem in high-pressure physics. Changing the initial density of a sample enables the exploration of a wider range of parameters of the EOS of the material (i.e., it allows data to be obtained away from the main Hugoniot curve); however, the influence of porosity on the data thus obtained is still not well understood.

Liu *et al.*[15] combine density functional theory (DFT) with the use of deep potentials (DPs) to systematically study the electronic thermal conductivity of warm dense aluminum at the nominal solid-state density and at temperatures ranging from 0.5 to 5.0 eV. Furthermore, they use the Green–Kubo method in conjunction with DP molecular dynamics simulations to obtain the ionic thermal conductivity.

Finally, Chen *et al.*[9] study the electrical conductivity of water under extreme temperatures and densities. Apart from its relevance to the modeling of planetary magnetic fields, this work is important because high-energy-density water is created using a free-electron laser (FEL) operating at 13.6 nm. This is emerging as a new tool in the study of matter under extreme conditions (see also Ref. 29), alongside femtosecond optical lasers, which in the work of Chen *et al.* are used to probe the created states (together with the FEL itself) and measure the transient reflection and transmission of an ultrathin water sheet sample. When the energy density in the water sample is increased, the thermally excited free-carrier density increases beyond that of the electron carriers produced by direct photoionization, leading to significant specular reflection due to the critical electron density shielding of electromagnetic waves.

The study of the properties of materials like carbon and water under extreme conditions is of direct relevance to planetary science, and, as such, it is an important area of laboratory astrophysics. The paper by Terasaki *et al.*[30] addresses another key problem in laboratory astrophysics, namely, Rayleigh–Taylor (RT) instability. As is well known, RT instability occurs when a heavy fluid overlies a light fluid in a gravitational field. This turns out to be an important scenario for planetary core formation, in particular for our own planet the Earth. Here, the instability may develop between the layer of liquid Fe and Fe–Si alloys beneath the planetary magma ocean. This process has been discussed based on numerical simulations and experiments using analog materials. However, experiments on the RT instability using the core-forming melt have not been performed at high pressures. In the work of Terasaki *et al.*, the development of RT instability at the interface between liquid Fe and an Fe–Si alloy is studied *in situ* at the high pressures produced using a high-power laser-shock technique. The perturbation of the Fe–Si surface is observed to develop exponentially with time and to increase with increasing Si content.

The other papers in this special issue address important aspects of the study of matter under extreme conditions related to the development of diagnostics and experimental methods, including better modeling techniques and a deeper understanding of how consolidated diagnostics work [e.g., velocity interferometer for any reflector (VISAR)].

II. DEVELOPING AND UNDERSTANDING OPTICAL DIAGNOSTICS

Diagnostics are of course a key element in all experiments, and optical diagnostics often play a central role. Therefore, developing novel approaches while also gaining deeper understanding of how consolidated diagnostics works is essential to advancing the field of study of matter in extreme conditions.

A velocity interferometer for any reflector (VISAR)[31] is a standard diagnostic used in practically all laser-driven shock experiments nowadays either for measurements of the free surface velocity of laser-shocked opaque materials or for direct measurements of the shock velocity in transparent materials. These velocities are then used to define the basic parameters (pressure, temperature, and density) of the compressed material.

In this context, the paper by Yan *et al.*[26] uses nonequilibrium molecular dynamics simulations to provide an atomic-scale picture of the dynamics of particles near the surface of a medium under ultra-strong shocks. It is shown that the measured free surface velocity under ultra-strong shocks is actually the velocity of the critical surface at which the incident probe light is reflected. They show that the doubling rule commonly used in the case of relatively weak shocks to determine particle velocity behind the shock front is generally not valid under ultra-strong shocks. Also, the free surface velocity has a single-peaked structure: after a short period of acceleration, it exhibits a long slowly decaying tail, which is not sensitive to the atomic mass of the medium. A scaling law for the free surface velocity is also proposed, which may be used to improve measurements of particle velocity in future laser-driven shock experiments.

A diagnostic complementary to VISAR is photonic Doppler velocimetry (PDV). In general, this is employed in experiments where shock waves are created by guns or explosives. In their paper, Nissim *et al.*[25] introduce a novel system design for PDV adapted to laser-driven shock wave experiments and present some first experimental results obtained at the Israel National Laser Facility at the Soreq Nuclear Research Center using Au foils of different thicknesses (10, 15, 20, 30, and 40 μm). They measured the free surface velocity of gold 2 ns after shock breakout. The result (7.3 km/s, with an error of 1.5%) corresponds to a pressure of 7 Mbar. Nissim *et al.* expect that it will be possible to extend their measurements to higher pressures by increasing the beat frequency.

III. RADIATION AND PARTICLE SOURCES AS NOVEL DIAGNOSTIC TOOLS

Short-pulse high-intensity lasers can drive very intense and short pulses of x-rays and particles that can be used to probe matter under extreme conditions. In recent years, such secondary radiation has begun to be used extensively in conjunction with laser-driven experiments.[32,33]

In this context, Rosmej *et al.*[22] discuss the generation of betatron radiation from direct laser-accelerated electrons in a plasma of density close to the critical electron density. They show how this approach allows the development of ultrabright x-ray sources. Experimental data, obtained on the PHELIX facility using 20 J of focused laser energy, point to the generation of betatron radiation with an ultrahigh photon number of 7×10^{11} per shot in the 1–30 keV range. These results are confirmed by 3D particle-in-cell simulations.

In their paper, Martynenko *et al.*[23] deal instead with the optimization of more conventional laser-driven x-ray sources for probing matter under extreme conditions by means of x-ray absorption spectroscopy. They have used solid targets of different materials and several laser configurations to optimize plasma-based x-ray emission. In particular, they present experimental results on the spectrally resolved emission of aluminum and silicon, and they show that the maximum laser-to-x-rays conversion efficiency is obtained by using high contrast, high intensity, and short duration, pulses, and by using targets of thickness about 10 μm. They also find that the use of a plastic coating on the target additionally increases the integrated emissivity by suppressing the expansion of the emission layer due to the laser prepulse.

Laser-driven protons also have been used to probe matter under extreme conditions. In this context, the paper by Raffestin *et al.*[21] describes experimental results on proton acceleration obtained using the high-energy petawatt PETAL laser system. Despite a moderately relativistic (<10^{19} W/cm^2) laser intensity, proton energies as high as 51 MeV have been measured, significantly above those expected from preliminary numerical simulations using idealized interaction conditions. Improved hydrodynamic and kinetic simulations, taking into account the actual laser parameters, show the importance of hot-electron production in the extended, low-density preplasma created by the laser pedestal. Two effects contribute to boost the electron acceleration: (i) stimulated backscattering of the incoming laser light, triggering stochastic electron heating in the counter-propagating laser beam, and (ii) laser filamentation, leading to local intensifications of the laser field and plasma channeling. Moreover, owing to the large (~100 μm) waist and picosecond duration of the PETAL beam, the hot electrons can sustain a high electrostatic field at the target rear side for a long time, thus enabling efficient target normal sheath acceleration (TNSA) of the rear-side protons.

IV. TARGET OPTIMIZATION

Deeper understanding of how diagnostics work and the consequent enhancement of their performance go hand in hand with improvements in target manufacture. The paper by Calestani *et al.*[19] addresses the question of target optimization for enhancement of laser absorption coupling to allow the creation of extreme conditions of matter. Creation of warm dense matter requires efficient coupling of ultra-intense ultrashort laser pulse, since the compression of a flat target is usually very low owing to reflection of the laser light at the plasma critical density. Coupling can be improved in two ways: either by ensuring that laser light impinges on the target before arrival of the main laser pulse, creating a micrometer-scale plasma, or by using targets with nano- or microstructured surfaces.

Structuring the surface of the target with micro- or nano-patterning can enhance coupling, and, depending on the laser features and target geometry, the conditions can be met that allow the generation of hot dense matter, high-brightness radiation sources, or even high-energy particle beams. Calestani *et al.*[19] have used ZnO nanowires in this context to produce micro- and nano-structuring on a thin-foil target.

Their choice of a thin-foil substrate was dictated by the need to achieve proton acceleration via TNSA at the rear side. The parameters of the chemical process used for fabrication of the nanowires were studied in depth to enable control over the nanowire size, shape, and distribution. Moreover, the manufacturing process was optimized to provide accurate reproducibility of key parameters in the widest possible range, as well as good homogeneity over the whole foil area.

V. CONCLUSION

The study of matter under extreme conditions is a blooming area of research, as can be seen, for instance, from other special issues of *Matter and Radiation at Extremes* ("Magnetized plasmas in HEDP" and "Progress in matter and radiation at extremes in China"), and lasers have clearly become a standard research tool in this field. At the same time, new tools are emerging (e.g., the use of x-ray free-electron lasers), and progress is being made in theoretical understanding, in developing new diagnostics, and in designing new types of experiments. Applications range from ICF to planetary science and astrophysics. The interesting research articles included in this special issue on "Matter in extreme states created by laser" give a taste of the current status of research and a good overview of recent trends in this branch of science.

REFERENCES

[1] L. V. Al'tshuler, S. B. Kormer, A. A. Bakanova *et al.*, Sov. Phys. JETP **11**, 573 (1960).

[2] K. K. Krupnikov, A. A. Bakanova, M. I. Brazhnik *et al.*, Sov. Phys. Dokl. **8**, 205 (1963).

[3] L. V. Al'tshuler, K. K. Krupnikov, B. N. Ledenev *et al.*, Sov. Phys. JETP **7**, 606 (1958).

[4] R. F. Trunin, M. A. Podurets, L. V. Popov *et al.*, Sov. Phys. JETP **75**, 777 (1992).

[5] M. Koenig, B. Faral, J. M. Boudenne, D. Batani, A. Benuzzi, S. Bossi, C. Rémond, J. P. Perrine, M. Temporal, and S. Atzeni, "Relative consistency of equation of state by laser driven shock waves," Phys. Rev. Lett. **74**, 2260 (1995).

[6] G. W. Collins, P. Celliers, L. B. Da Silva, R. Cauble, D. Gold, M. Foord, K. S. Budil, R. Stewart, N. C. Holmes, M. Ross, B. A. Hammel, J. D. Kilkenny, R. J. Wallace, and A. Ng, "Equation of state measurements of hydrogen isotopes on Nova," Phys. Plasmas **5**, 1864 (1998).

[7] P. M. Celliers, G. W. Collins, D. G. Hicks, M. Koenig, E. Henry, A. Benuzzi-Mounaix, D. Batani, D. K. Bradley, L. B. Da Silva, R. J. Wallace, S. J. Moon, J. H. Eggert, K. K. M. Lee, L. R. Benedetti, R. Jeanloz, I. Masclet, N. Dague, B. Marchet, M. Rabec Le Gloahec, Ch. Reverdin, J. Pasley, O. Willi, D. Neely, and C. Danson, "Electronic conduction in shock-compressed water," Phys. Plasmas **11**, L41 (2004).

[8] D. Batani, F. Strati, H. Stabile, M. Tomasini, G. Lucchini, A. Ravasio, M. Koenig, A. Benuzzi-Mounaix, H. Nishimura, Y. Ochi, J. Ullschmied, J. Skala, B. Kralikova, M. Pfeifer, Ch. Kadlec, T. Mocek, A. Präg, T. Hall, P. Milani, E. Barborini, and P. Piseri, "Hugoniot data for carbon at megabar pressures," Phys. Rev. Lett. **92**, 065503 (2004).

[9] Z. Chen, X. Na, C. B. Curry, S. Liang, M. French, A. Descamps, D. P. DePonte, J. D. Koralek, J. B. Kim, S. Lebovitz, M. Nakatsutsumi, B. K. Ofori-Okai, R. Redmer, C. Roedel, M. Schörner, S. Skruszewicz, P. Sperling, S. Toleikis, M. Z. Mo, and S. H. Glenzer, "Observation of a highly conductive warm dense state of water with ultrafast pump–probe free-electron-laser measurements," Matter Radiat. Extremes **6**, 054401 (2021).

[10] K. Shigemori, D. Ichinose, T. Irifune, K. Otani, T. Shiota, T. Sakaiya, and H. Azechi, "Measurements of sound velocity of laser-irradiated iron foils relevant to Earth core condition," Eur. Phys. J. D **44**, 301–305 (2007).

[11] M. Koenig, A. Benuzzi, B. Faral, J. Krishnan, J. M. Boudenne, T. Jalinaud, C. Rémond, A. Decoster, D. Batani, D. Beretta, and T. A. Hall, "Brominated plastic equation of state measurement using laser driven shocks," Appl. Phys. Lett. **72**, 1033 (1998).

[12] P. Wang, C. Zhang, S. Jiang, X. Duan, H. Zhang, L. Li, W. Yang, Y. Liu, Y. Li, L. Sun, H. Liu, and Z. Wang, "Density-dependent shock Hugoniot of polycrystalline diamond at pressures relevant to ICF," Matter Radiat. Extremes **6**, 035902 (2021).

[13] J. A. Gaffney, S. X. Hu, P. Arnault, A. Becker, L. X. Benedict, T. R. Boehly, P. M. Celliers, D. M. Ceperley, O. Čertík, J. Clérouin, G. W. Collins, L. A. Collins, J.-F. Danel, N. Desbiens, M. W. C. Dharma-wardana, Y. H. Ding, A. Fernandez-Pañella, M. C. Gregor, P. E. Grabowski, S. Hamel, S. B. Hansen, L. Harbour, X. T. He, D. D. Johnson, W. Kang, V. V. Karasiev, L. Kazandjian, M. D. Knudson, T. Ogitsu, C. Pierleoni, R. Piron, R. Redmer, G. Robert, D. Saumon, A. Shamp, T. Sjostrom, A. V. Smirnov, C. E. Starrett, P. A. Sterne, A. Wardlow, H. D. Whitley, B. Wilson, P. Zhang, and E. Zurek, "A review of equation-of-state models for inertial confinement fusion materials," High Energy Density Phys. **28**, 7 (2018).

[14] A. L. Kritcher, D. C. Swift, T. Döppner, B. Bachmann, L. X. Benedict, G. W. Collins, J. L. DuBois, F. Elsner, G. Fontaine, J. A. Gaffney, S. Hamel, A. Lazicki, W. R.

Johnson, N. Kostinski, D. Kraus, M. J. MacDonald, B. Maddox, M. E. Martin, P. Neumayer, A. Nikroo, J. Nilsen, B. A. Remington, D. Saumon, P. A. Sterne, W. Sweet, A. A. Correa, H. D. Whitley, R. W. Falcone, and S. H. Glenzer, "A measurement of the equation of state of carbon envelopes of white dwarfs," Nature **584**, 51–54 (2020).

[15] Q. Liu, J. Li, and M. Chen, "Thermal transport by electrons and ions in warm dense aluminum: A combined density functional theory and deep potential study," Matter Radiat. Extremes **6**, 026902 (2021).

[16] K. Jakubowska, D. Batani, J. Clerouin, and B. Siberchicot, "Theoretical and experimental refraction index of shock compressed and pre-compressed water in the megabar pressure range," Europhys. Lett. **126**, 56001 (2019).

[17] S. Zhang, H. Wang, W. Kang, P. Zhang, and X. T. He, "Extended application of Kohn-Sham first-principles molecular dynamics method with plane wave approximation at high energy—From cold materials to hot dense plasmas," Phys. Plasmas **23**, 042707 (2016).

[18] X. Liu, X. Zhang, C. Gao, S. Zhang, C. Wang, D. Li, P. Zhang, W. Kang, W. Zhang, and X. T. He, "Equations of state of poly-α-methylstyrene and polystyrene: First-principles calculation versus precision measurements," Phys. Rev. B **103**, 174111 (2021).

[19] D. Calestani, M. Villani, G. Cristoforetti, F. Brandi, P. Koester, L. Labate, and L. A. Gizzi, "Fabrication of ZnO-nanowires coated thin-foil targets for ultra-high intensity laser interaction experiments," Matter Radiat. Extremes **6**, 046903 (2021).

[20] S. Paleari, D. Batani, T. Vinci, R. Benocci, K. Shigemori, Y. Hironaka, T. Kadono, A. Shiroshita, P. Piseri, S. Bellucci, A. Mangione, and A. Aliverdiev, "A new target design for laser shock-compression studies of carbon reflectivity in the megabar regime," Eur. Phys. J. D **67**, 136 (2013).

[21] D. Raffestin, L. Lecherbourg, I. Lantuéjoul, B. Vauzour, P. E. Masson-Laborde, X. Davoine, N. Blanchot, J. L. Dubois, X. Vaisseau, E. d'Humières, L. Gremillet, A. Duval, Ch. Reverdin, B. Rosse, G. Boutoux, J. E. Ducret, Ch. Rousseaux, V. Tikhonchuk, and D. Batani, "Enhanced ion acceleration using the high-energy petawatt PETAL laser," Matter Radiat. Extremes **6**, 056901 (2021).

[22] O. N. Rosmej, X. F. Shen, A. Pukhov, L. Antonelli, F. Barbato, M. Gyrdymov, M. M. Günther, S. Zähter, V. S. Popov, N. G. Borisenko, and N. E. Andreev, "Ultra-bright betatron radiation based on direct laser acceleration of electrons in plasma of near critical density," Matter Radiat. Extremes **6**, 048401 (2021).

[23] A. S. Martynenko, S. A. Pikuz, I. Yu. Skobelev, S. N. Ryazantsev, C. D. Baird, N. Booth, L. N. K. Döhl, P. Durey, A. Ya. Faenov, D. Farley, R. Kodama, K. Lancaster, P. McKenna, C. D. Murphy, C. Spindloe, T. A. Pikuz, and N. Woolsey, "Optimization of a laser plasma-based x-ray source according to WDM absorption spectroscopy requirements," Matter Radiat. Extremes **6**, 014405 (2021).

[24] K. Shigemori, T. Sakaiya, Y. Asakura, T. Kondo, K. Shimizu, T. Kadono, Y. Hironaka, and H. Azechi, "Sound velocity measurements by x-ray shadowgraph technique for melting phenomena at ultrahigh-pressure regime," Rev. Sci. Instrum. **83**, 10E529 (2012).

[25] N. Nissim, E. Greenberg, M. Werdiger, Y. Horowitz, L. Bakshi, Y. Ferber, B. Glam, A. Fedotov-Gefen, L. Perelmutter, and S. Eliezer, "Free surface velocity measurements of opaque materials in laser-driven shock-wave experiments using photonic Doppler velocimetry," Matter Radiat. Extremes **6**, 046902 (2021).

[26] Z. Yan, H. Liu, X. Zhang, G. Ren, J. Liu, W. Kang, W. Zhang, and X. He, "Dynamics of particles near the surface of a medium under ultra-strong shocks," Matter Radiat. Extremes **6**, 026903 (2021).

[27] C. Mo, Z. Fu, W. Kang, P. Zhang, and X. T. He, "First-principles estimation of electronic temperature from x-ray Thomson scattering spectrum of isochorically heated warm dense matter," Phys. Rev. Lett. **120**, 205002 (2018).

[28] D. Batani, K. Jakubowska, A. Benuzzi-Mounaix, C. Cavazzoni, C. Danson, T. Hall, M. Kimpel, D. Neely, J. Pasley, M. Rabec Le Gloahec, and B. Telaro, "Refraction index of shock compressed water in the megabar pressure range," Europhys. Lett. **112**, 49901 (2015).

[29] Y. Maeda, Y. Hironaka, T. Iwasaki, K. Kawasaki, Y. Sakawa, T. Izumi, M. Ota, S. Egashira, Y. Nakagawa, N. Higashi, Y. Sentoku, R. Kodama, N. Ozaki, T. Matsuoka, T. Somekawa, T. Yabuuchi, Y. Inubushi, T. Togashi, A. Kon, K. Sueda, K. Miyanishi, S. Shingubara, T. Shimizu, A. Okumura, and K. Shigemori, "Observation of ultrahigh energy density state with x-ray free electron laser SACLA," High Energy Density Phys. **36**, 100813 (2020).

[30] H. Terasaki, T. Sakaiya, K. Shigemori, K. Akimoto, H. Kato, Y. Hironaka, and T. Kondo, "*In situ* observation of the Rayleigh–Taylor instability of liquid Fe and Fe–Si alloys under extreme conditions: Implications for planetary core formation," Matter Radiat. Extremes **6**, 054403 (2021).

[31] P. M. Celliers, G. W. Collins, L. B. Da Silva, D. M. Gold, and R. Cauble, "Accurate measurement of laser-driven shock trajectories with velocity interferometry," Appl. Phys. Lett. **73**, 1320 (1998).

[32] A. Ravasio, M. Koenig, S. Le Pape, A. Benuzzi-Mounaix, H. S. Park, C. Cecchetti, P. Patel, A. Schiavi, N. Ozaki, A. Mackinnon, B. Loupias, D. Batani, T. Boehly, M. Borghesi, R. Dezulian, E. Henry, M. Notley, S. Bandyopadhyay, R. Clarke, and T. Vinci, "Hard x-ray radiography for density measurement in shock compressed matter," Phys. Plasmas **15**, 060701 (2008).

[33] A. Ravasio, L. Romagnani, S. Le Pape, A. Benuzzi-Mounaix, C. Cecchetti, D. Batani, T. Boehly, M. Borghesi, R. Dezulian, L. Gremillet, E. Henry, D. Hicks, B. Loupias, A. MacKinnon, N. Ozaki, H. S. Park, P. Patel, A. Schiavi, T. Vinci, R. Clarke, M. Notley, S. Bandyopadhyay, and M. Koenig, "Proton radiography of a shock compressed target," Phys. Rev. E **82**, 016407 (2010).