Summary of Working Group 2: Ion beams from plasmas

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Summary of Working Group 2: Ion beams from plasmas

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1. Introduction

The investigation of ion acceleration with high power lasers has been a very active field of research internationally [1] since the first observations of multi-MeV proton beams from laser-matter interactions were reported 15 years ago. The most established and robust acceleration mechanism is the so-called Target Normal Sheath Acceleration (TNSA), where ions are accelerated in the sheath field set by laser-energised MeV electrons at the target surfaces. TNSA beams are already used in applications, which exploit their advantageous properties such as short burst duration and ultralow emittance. A number of alternative acceleration mechanisms have emerged which promise higher efficiency, and, in some cases, enhanced spectral profiles, and are attracting an increasingly significant experimental attention. The ongoing improvement of laser parameters (pulse energy and contrast) and diagnostics tools, jointly with technological innovation in target manufacturing are all key factors currently contributing to a fervid international activity, of which the WG2 presentations provided a comprehensive snapshot. As a brief reminder of the state-of-the-art in the field, a summary of published data on proton acceleration is presented in Fig. 1 illustrating the continuous increase in maximum energy with laser performance

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and highlighting (stars) the potential for a variety of advanced target concepts, including (for ps-class pulses and ultra thin foils) the onset of volumetric interaction in the relativistic transparency regime. We are aware that reports of significantly higher proton energies have entered the scientific discussion over the last few years, but we note that these results remain as yet unpublished and their validity unconfirmed.

2. Enhanced TNSA and Coulomb explosion

As shown in Fig. 1, spatial confinement and potential recirculation of the hot electron distribution responsible for the energy transfer in TNSA has been demonstrated to increase maximum proton energies [12, 13], yet at the expense of strong influences from supporting structures. The realization of an idealized situation of a finite size target completely isolated in space was presented by T. Ostermayr (LMU Munich) who used spherical targets of varying radius levitating with active motion control in a large aperture rf quadrupole Paul trap. While experiments performed at the Texas PW for larger (up to 20 μm) radius can be explained in the framework of enhanced TNSA from curved surfaces, a second campaign at the Phelix laser for sub focal spot scale plastic spheres lead to energetic and spectrally peaked proton beams predominantly emitted in laser forward direction. Here, a directed Coulomb explosion could be the dominant mechanism and is currently investigated by 3D PIConGPU simulations. A similar scenario of nano-droplets exposed to few cycle laser pulses was theoretically investigated and presented by L. di Lucchio (FZ Jülich, DESY) [14]. M. Kaluza (IOQ Jena and HIJ) on the other hand reported quasi-monoenergetic proton spectra at few MeV energy from shots on liquid water droplets of 22 μm diameter where a strong correlation was found experimentally with the length of the ASE pedestal and thus preplasma gradient. Coulomb explosion of CO2 clusters was demonstrated by Y. Fukuda (JAEA) to efficiently transfer energy to surrounding protons when the clusters are mixed with hydrogen gas. A surprisingly high increase in proton energies was reported by A. Zigler (Hebrew University

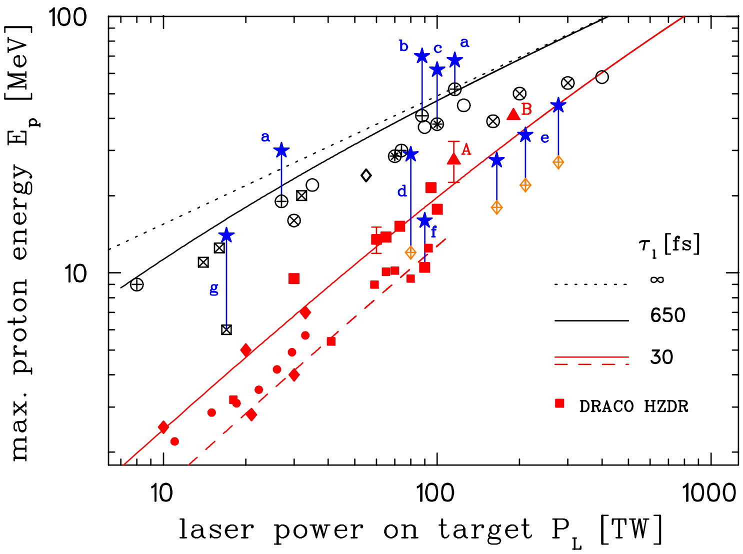

Figure 1: Overview of maximum proton energies achieved with linear polarization as a function of laser power P_L on target based on Fig. 4 of Ref. [2] (note that for the comparison of different laser systems P_L may suffer from systematic differences in quoting such values). The plot is updated with recently published peer-reviewed work and emphasizes energy enhancing mechanisms (blue stars connected to individual TNSA references). Open black symbols as in [2] represent data from single-shot glass laser systems where record energies were reached with a) hollow cone targets [3] and b,c) in regimes where relativistic transparency sets in [4, 5]. Filled symbols depict results obtained with state-of-the-art Ti:Sapphire laser ultra-short pulse systems (again as in [2]), squares representing Draco (HZDR) data [2, 6], circles UHI100 (CEA Saclay) data [7] and A) and B) highlighting recent TNSA improvements [8, 9] on the multi 100 TW laser scale. Energies, though still at a lower level than for ps-class laser pulses, could be further increased by using e) ultra-thin targets (selection restricted to linear polarization, comparison between thinnest and thickest targets still assumed to be dominated by TNSA) [10], d) carbon nanotube foam coated thin targets [11], or f,g) flat targets of finite size (reduced mass targets) [12, 13]. Promising enhancement factors for protons are typically observed to reach values between 1.5 and 2.5.

Jerusalem) in a series of experimental campaigns [15] where the laser was focused on H2O nano tube (*snow*) coated glass plates (front side acceleration) and justified on the basis of local field enhancements at the snow tips.

Pure proton targets were realized with few micron diameter jets of frozen hydrogen and similar results presented independently (with different source technology) from Polaris (M. Kaluza) and Draco (M. Rehwald, HZDR Dresden). While similar energies were observed as from reference foils, pure proton pulses, high conversion efficiency and high repetition rate (up to 1 Hz) could be demonstrated and the use of pure noble gases seems realistic in near future.

3. Beam Transport, Manipulation and Applications

Three conceptually different approaches were discussed for the energy selective capture, transport and potential phase-space manipulations of laser accelerated proton bunches, motivated by the provision of controlled beam parameters for further use in medical, plasma, or accelerator research.

First, the use of a small coil-shaped wire, directly attached to the rear-side of an otherwise isolated target was demonstrated by S. Kar (Queens University Belfast). Powered by the charge neutralizing current inherently linked to the particle acceleration process itself, a positively charged area on the wire is tuned to co-propagate with the ion bunch and not only leads to a focusing of the proton pulse with high energy acceptance but simultaneously boosts the maximum energy by a factor of almost two.

Second, V. Bagnoud (GSI, LIGHT collaboration) reported in a plenary talk on the efficient phase space rotation of proton bunches, energy selected around 10 MeV and collimated by a pulsed solenoid field. This first combination of plasma, pulsed field, and conventional radio-frequency technology allowed for either an energy compression to 2.5% energy spread or a temporal focus of below 450 ps pulse duration [16].

Third, the ELIMED collaboration is currently engaged in delivering ion beam transport based on established technology and bespoke dosimetry for an ion beamline (ELIMAIA) [17] on the ELI Beamlines research infrastructure [18]. The ELIMED concept and status, including preliminary test of detector response to conventional and laser-accelerated ion beams, were presented by F. Romano and G. Milluzzo (LNS-INFN). This topic was complemented by a series of talks, given by C. Altana, A. Gizzi, A. Muoio, and S. Sinigardi dealing with the L3IA initiative at ILIL (Pisa and representing groups from Bologna, Catania, Florence, Frascati, Milan, and Naples) for the implementation of an optimized TNSA-based proton beamline, including preplasma and target optimization, diagnostics development, and dedicated simulation support.

While most of the talks focused on development and characterization of acceleration processes, a small number were devoted to prospective applications of the ion beams. P. Antici (INRS) presented a novel approach to the creation of nanoparticles by irradiation of a silicon substrate with a laser accelerated proton beam. The short pulse nature of the substrate heating is key to the formation of regular structures with 10s of nm diameter. A novel approach for the metrology of picosecond ion bursts and for the study of time-resolved ion induced damage in bulk material was introduced by B. Dromey (Queens University Belfast). Transverse time resolved optical probing (chirped probe) of the opacity resulting from ion induced damage, where the penetration depth is used as a measure of the ion energy, confirmed the ps duration of the energetic ion distribution. S. Ter-Avetysian (IBS-GIST) discussed experiments showing the conversion of positive, laser accelerated ions into beams of energetic negative ions and neutral atoms, through charge exchange processes taking place in a water spray [19], which provide novel and unique capabilities for laser-driven sources.

A strong motivation for the field of laser-driven ion acceleration is the prospective of future application to cancer therapy [20], and the potential advantages of laser-accelerated ions were reviewed in the talk by C. Obcemea (Memorial Sloan Kettering Cancer Center, New York).

4. Ion acceleration from ultrathin foils

Experiments employing ultrathin foils (with thickness down to a few nm) are very actively pursued by many research groups, and the WG2 program reflected this interest. The interaction of intense laser pulses with ultrathin targets allows access to volumetric acceleration regimes, where the bulk species in the target can be efficiently accelerated. Provided the opacity of the target to radiation can be maintained during the irradiation, Radiation Pressure Acceleration, through the so-called Light Sail process [21, 22], can become the dominant acceleration process. On the other hand, target decompression during the interaction leads to regimes of relativistic transparency [23, 24], which are also of interest in view of an enhanced energy coupling into the target, and enhanced acceleration (observed so far only for $\sim$ ps pulses [4, 25, 5]). A broad overview of the processes taking place during these interactions was presented by P. McKenna (Strathclyde) in a plenary talk. C. Scullion (Queens University Belfast) presented results obtained on the GEMINI laser at the Rutherford Appleton laboratory (UK), showing a strong dependence of ion energy from target thickness and polarization, with the highest ion energies (35 MeV protons and 300 MeV Carbon ions) observed using 10 nm thick carbon targets and circular polarization. These shots were characterized by a very distinctive beam profile, in a scenario highly suggestive of the onset of Light Sail acceleration, as confirmed by Particle in Cell simulations also discussed in the plenary talk by A. Sgattoni (Pisa University). A thickness and polarization dependence of ion energy was also reported by G.A. Becker (Jena University), in measurements obtained using the Polaris laser system, operating in the second harmonic: the trend for very thin target (around 10 nm) was broadly consistent with Light Sail acceleration, while TNSA processes dominated for thicker targets (100-800 nm). M. Zepf (Queens University) and W. Ma (LMU) reported on recent efforts to enhance ion acceleration by using a Carbon Nanotube Foam (CNF) layer deposited onto nm-scale DLC foils. Ionization of the CNF layer by the laser pulse leads to the interaction with a relativistically underdense plasma. The laser pulse undergoes strong self-focusing and pulse shortening, and the enhanced intensity on the nm foil is reflected in an increased acceleration efficiency. A three-fold enhancement of Carbon energies (compared to a bare foil) for an optimal CNF thickness and circular polarization (consistent with Radiation Pressure Acceleration) was observed in a GEMINI experiment [11], with similar results obtained on the PULSAR system at IBS, GIST. A. Alejo (QUB), presenting results from a VULCAN experiment, discussed how ion bunching during Light Sail drive of thin CD foils is reflected in a highly enhanced neutron production through D-D fusion in the accelerated ion layer (which is strongly reduced for transparent targets). N. Dover (Imperial College) reported how the energy of protons in these longer pulse ($\sim$ ps) VULCAN interactions is maximized for target thicknesses allowing transparency to occur at the peak of the laser pulse. R. Prasad (HHUD) reported on exploratory investigations on the ARCTURUS laser of acceleration under target irradiation by two consecutive 30 fs pulses. This revealed an unexpected enhancement of ion energy with a 50 ps delay between the two pulses, which may be related to the interaction of the second pulse with an optimal, preconfigured density profile.

5. Collisionless shock acceleration

Ion acceleration through reflection from collisionless, electrostatic shocks [26] is another acceleration process, which is attracting significant experimental attention. Recent theoretical work has highlighted the promise of employing shaped density profile for enhancing this acceleration process [27]. Work also reported by N. Dover (IC) described how tailoring the profile of a gas jet, by using laser-driven blast waves, can be used to control the energy and spectral profile of the shock-accelerated accelerated ions [28] . This experiment employed the CO2 laser system at the Accelerator Test Facility at BNL.

6. Conclusion

The talks presented within WG2 confirmed the high level of activity in the field, displayed a significant progress in the understanding of the ion acceleration mechanisms, and highlighted important technological innovation. While there is still scope for optimising TNSA sources by applying advanced targetry concepts, and for developing innovative applications, acceleration dominantly due to radiation pressure or reflection from collisionless shocks, or enhanced by relativistic transparency effects can now be accessed by selecting particular interaction conditions and target parameters. This level of control and understanding is highly promising in view of further development with upcoming, next generation laser sources, providing higher laser power and/or repetition rate.

References

[1] A. Macchi, M. Borghesi, M. Passoni, Ion acceleration by superintense laser-plasma interaction, New Journal of Physics 85 (2013) 751.

[2] K. Zeil, S. D. Kraft, S. Bock, M. Bussmann, T. Cowan, T. Kluge, J. Metzkes, T. Richter, R. Sauerbrey, U. Schramm, Scaling of proton energies in ultra-short pulse laser plasma acceleration, New Journal of Physics 12 (2010) 045015.

[3] T. Kluge, S. A. Gaillard, K. A. Flippo, T. Burris-Mog, W. Enghardt, B. Gall, M. Geissel, A. Helm, S. D. Kraft, T. Lockard, J. Metzkes, D. T. Offermann, M. Schollmeier, U. Schramm, K. Zeil, M. Bussmann, T. E. Cowan, High proton energies from cone targets: electron acceleration mechanisms, New Journal of Physics 14 (2) (2012) 023038.
URL `http://stacks.iop.org/1367-2630/14/i=2/a=023038`

[4] D. Jung, B. J. Albright, L. Yin, D. C. Gautier, R. Shah, S. Palaniyappan, S. Letzring, B. Dromey, H.-C. Wu, T. Shimada, R. P. Johnson, M. Roth,

J. C. Fernandez, D. Habs, B. M. Hegelich, Beam profiles of proton and carbon ions in the relativistic transparency regime, New Journal of Physics 15 (12) (2013) 123035.
URL http://stacks.iop.org/1367-2630/15/i=12/a=123035

[5] F. Wagner, S. Bedacht, V. Bagnoud, O. Deppert, S. Geschwind, R. Jaeger, A. Ortner, A. Tebartz, B. Zielbauer, D. H. H. Hoffmann, M. Roth, Simultaneous observation of angularly separated laser-driven proton beams accelerated via two different mechanisms, Physics of Plasmas 22 (6) (2015) –. doi:http://dx.doi.org/10.1063/1.4922661.
URL http://scitation.aip.org/content/aip/journal/pop/22/6/10.1063/1.4922661

[6] J. Metzkes, T. Kluge, K. Zeil, M. Bussmann, S. D. Kraft, T. E. Cowan, U. Schramm, Experimental observation of transverse modulations in laser-driven proton beams, New Journal of Physics 16 (2) (2014) 023008.
URL http://stacks.iop.org/1367-2630/16/i=2/a=023008

[7] M. Passoni, L. Bertagna, T. Ceccotti, P. Martin, Proton maximum energy cutoff scaling laws for bulk targets, AIP Conference Proceedings 1153 (1).

[8] J. S. Green, A. P. L. Robinson, N. Booth, D. C. Carroll, R. J. Dance, R. J. Gray, D. A. MacLellan, P. McKenna, C. D. Murphy, D. Rusby, L. Wilson, High efficiency proton beam generation through target thickness control in femtosecond laser-plasma interactions, Applied Physics Letters 104 (21) (2014) –. doi:http://dx.doi.org/10.1063/1.4879641.
URL http://scitation.aip.org/content/aip/journal/apl/104/21/10.1063/1.4879641

[9] K. Ogura, M. Nishiuchi, A. S. Pirozhkov, T. Tanimoto, A. Sagisaka, T. Z. Esirkepov, M. Kando, T. Shizuma, T. Hayakawa, H. Kiriyama, T. Shimomura, S. Kondo, S. Kanazawa, Y. Nakai, H. Sasao, F. Sasao, Y. Fukuda, H. Sakaki, M. Kanasaki, A. Yogo, S. V. Bulanov, P. R. Bolton, K. Kondo, Proton acceleration to 40 mev using a high intensity, high contrast

optical parametric chirped-pulse amplification/ti:sapphire hybrid laser system, Opt. Lett. 37 (14) (2012) 2868–2870. doi:10.1364/OL.37.002868.
URL http://ol.osa.org/abstract.cfm?URI=ol-37-14-2868

[10] I. J. Kim, K. H. Pae, C. M. Kim, H. T. Kim, J. H. Sung, S. K. Lee, T. J. Yu, I. W. Choi, C.-L. Lee, K. H. Nam, P. V. Nickles, T. M. Jeong, J. Lee, Transition of proton energy scaling using an ultrathin target irradiated by linearly polarized femtosecond laser pulses, Phys. Rev. Lett. 111 (2013) 165003. doi:10.1103/PhysRevLett.111.165003.
URL http://link.aps.org/doi/10.1103/PhysRevLett.111.165003

[11] J. H. Bin, W. J. Ma, H. Y. Wang, M. J. V. Streeter, C. Kreuzer, D. Kiefer, M. Yeung, S. Cousens, P. S. Foster, B. Dromey, X. Q. Yan, R. Ramis, J. Meyer-ter Vehn, M. Zepf, J. Schreiber, Ion acceleration using relativistic pulse shaping in near-critical-density plasmas, Phys. Rev. Lett. 115 (2015) 064801. doi:10.1103/PhysRevLett.115.064801.
URL http://link.aps.org/doi/10.1103/PhysRevLett.115.064801

[12] S. Buffechoux, J. Psikal, M. Nakatsutsumi, L. Romagnani, A. Andreev, K. Zeil, M. Amin, P. Antici, T. Burris-Mog, A. Compant-La-Fontaine, E. d'Humières, S. Fourmaux, S. Gaillard, F. Gobet, F. Hannachi, S. Kraft, A. Mancic, C. Plaisir, G. Sarri, M. Tarisien, T. Toncian, U. Schramm, M. Tampo, P. Audebert, O. Willi, T. E. Cowan, H. Pépin, V. Tikhonchuk, M. Borghesi, J. Fuchs, Hot electrons transverse refluxing in ultraintense laser-solid interactions, Phys. Rev. Lett. 105 (2010) 015005. doi:10.1103/PhysRevLett.105.015005.
URL http://link.aps.org/doi/10.1103/PhysRevLett.105.015005

[13] K. Zeil, J. Metzkes, T. Kluge, M. Bussmann, T. E. Cowan, S. D. Kraft, R. Sauerbrey, B. Schmidt, M. Zier, U. Schramm, Robust energy enhancement of ultrashort pulse laser accelerated protons from reduced mass targets, Plasma Physics and Controlled Fusion 56 (8) (2014) 084004.
URL http://stacks.iop.org/0741-3335/56/i=8/a=084004

[14] L. Di Lucchio, A. A. Andreev, P. Gibbon, Ion acceleration by intense, few-cycle laser pulses with nanodroplets, Physics of Plasmas 22 (5). doi:http://dx.doi.org/10.1063/1.4921667.
URL http://scitation.aip.org/content/aip/journal/pop/22/5/10.1063/1.4921667

[15] A. Zigler, S. Eisenman, M. Botton, E. Nahum, E. Schleifer, A. Baspaly, I. Pomerantz, F. Abicht, J. Branzel, G. Priebe, S. Steinke, A. Andreev, M. Schnuerer, W. Sandner, D. Gordon, P. Sprangle, K. Ledingham, Enhanced proton acceleration by an ultrashort laser interaction with structured dynamic plasma targets , Physical Review Letters 110 (2013) 215004.

[16] S. Busold, D. Schumacher, C. Brabetz, D. Jahn, F. Kroll, O. Deppert, U. Schramm, T. E. Cowan, A. Blazevic, V. Bagnoud, M. Roth, Towards highest peak intensities for ultra-short mev-range ion bunches, Scientific Reports 5 (2015) 12459. doi:10.1038/srep12459.

[17] G. Cirrone, F. Romano, V. Scuderi, A. Amato, G. Candiano, G. Cuttone, D. Giove, G. Korn, J. Krasa, R. Leanza, R. Manna, M. Maggiore, V. Marchese, D. Margarone, G. Milluzzo, G. Petringa, M. Sabini, F. Schillaci, A. Tramontana, L. Valastro, A. Velyhan, Transport and dosimetric solutions for the {ELIMED} laser-driven beam line, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 796 (2015) 99 – 103, proceedings of the 10th International Conference on Radiation Effects on Semiconductor Materials Detectors and Devices. doi:http://dx.doi.org/10.1016/j.nima.2015.02.019.
URL http://www.sciencedirect.com/science/article/pii/S0168900215002004

[18] B. Le Garrec, S. Sebban, D. Margarone, M. Precek, S. Weber, O. Klimo, G. Korn, B. Rus, Eli-beamlines: extreme light infrastructure science and

technology with ultra-intense lasers (2014). doi:10.1117/12.2039165.
URL http://dx.doi.org/10.1117/12.2039165

[19] M. Schnürer, F. Abicht, R. Prasad, M. Borghesi, G. Priebe, J. Bränzel, A. Andreev, P. Nickles, S. Jequier, V. Tikhonchuk, S. Ter-Avetisyan., Charge steering of laser plasma accelerated fast ions in a liquid spray - creation of mev negative ion and neutral atom beam, Physics of Plasmas 20 (2013) 113105. doi:10.1063/1.4829005.

[20] K. W. D. Ledingham, P. R. Bolton, N. Shikazono, C.-M. C. Ma, Towards laser driven hadron cancer radiotherapy: A review of progress, Applied Sciences 4 (3) (2014) 402. doi:10.3390/app4030402.
URL http://www.mdpi.com/2076-3417/4/3/402

[21] A. P. L. Robinson, M. Zepf, S. Kar, R. G. Evans, C. Bellei, Radiation pressure acceleration of thin foils with circularly polarized laser pulses, New Journal of Physics 10 (1) (2008) 013021.
URL http://stacks.iop.org/1367-2630/10/i=1/a=013021

[22] A. Macchi, S. Veghini, F. Pegoraro, "light sail" acceleration reexamined, Phys. Rev. Lett. 103 (2009) 085003. doi:10.1103/PhysRevLett.103.085003.
URL http://link.aps.org/doi/10.1103/PhysRevLett.103.085003

[23] R. J. Gray, D. A. MacLellan, B. Gonzalez-Izquierdo, H. W. Powell, D. C. Carroll, C. D. Murphy, L. C. Stockhausen, D. R. Rusby, G. G. Scott, R. Wilson, N. Booth, D. R. Symes, S. J. Hawkes, R. Torres, M. Borghesi, D. Neely, P. McKenna, Azimuthal asymmetry in collective electron dynamics in relativistically transparent laserfoil interactions, New Journal of Physics 16 (9) (2014) 093027.
URL http://stacks.iop.org/1367-2630/16/i=9/a=093027

[24] S. Palaniyappan, B. Hegelich, H. Wu, D. Jung, D. Gautier, L. Yin, B. Albright, R. Johnson, T. Shimada, S. Letzring, D. Offermann, J. Ren,

C. Huang, R. Hörlein, B. Dromey, J. Fernandez, R. Shah, Dynamics of relativistic transparency and optical shuttering in expanding overdense plasmas, Nature Physics 8 (2012) 763. doi:10.1038/nphys2390.

[25] D. Jung, L. Yin, B. J. Albright, D. C. Gautier, S. Letzring, B. Dromey, M. Yeung, R. Hrlein, R. Shah, S. Palaniyappan, K. Allinger, J. Schreiber, K. J. Bowers, H.-C. Wu, J. C. Fernandez, D. Habs, B. M. Hegelich, Efficient carbon ion beam generation from laser-driven volume acceleration, New Journal of Physics 15 (2) (2013) 023007.
URL http://stacks.iop.org/1367-2630/15/i=2/a=023007

[26] L. O. Silva, M. Marti, J. R. Davies, R. A. Fonseca, C. Ren, F. S. Tsung, W. B. Mori, Proton shock acceleration in laser-plasma interactions, Phys. Rev. Lett. 92 (2004) 015002. doi:10.1103/PhysRevLett.92.015002.
URL http://link.aps.org/doi/10.1103/PhysRevLett.92.015002

[27] F. Fiuza, A. Stockem, E. Boella, R. A. Fonseca, L. O. Silva, D. Haberberger, S. Tochitsky, C. Gong, W. B. Mori, C. Joshi, Laser-driven shock acceleration of monoenergetic ion beams, Phys. Rev. Lett. 109 (2012) 215001. doi:10.1103/PhysRevLett.109.215001.
URL http://link.aps.org/doi/10.1103/PhysRevLett.109.215001

[28] O. Tresca, N. P. Dover, N. Cook, C. Maharjan, M. N. Polyanskiy, Z. Najmudin, P. Shkolnikov, I. Pogorelsky, Spectral modification of shock accelerated ions using a hydrodynamically shaped gas target, Phys. Rev. Lett. 115 (2015) 094802. doi:10.1103/PhysRevLett.115.094802.
URL http://link.aps.org/doi/10.1103/PhysRevLett.115.094802