Spinoff Technologies from the Development of Short Pulse Lasers for Fast Ignition IFE

G. J. Williams[1], E.S. Grace[1,2], C. Haefner[3], M. Hill[4], A. Kemp[1], S Kerr[1], E. Liang[5], S. Libby[1], T. Ma[1], D Mariscal[1], D. Rusby[1], G Scott[1], R. Simpson[1,6], F. Treffert[7,8], S. Wilks[1], G. Zeraouli[9]

[1] Lawrence Livermore National Laboratory, Livermore CA USA
[2] School of Physics, The Georgia Institute of Technology, Atlanta, GA, USA
[3] Fraunhofer Institute of Laser Technology, Aachen, Germany
[4] AWE Plc, Aldermaston RG7 4PR, United Kingdom
[5] Department of Space Physics and Astronomy, Rice University, Houston, TX, USA
[6] Department of Nuclear Science and Engineering, Massachusetts Institute of Technology, Cambridge USA
[7] SLAC National Accelerator Laboratory, Menlo Park, CA, USA
[8] Institut für Kernphysik, Technische Universität Darmstadt, Darmstadt, Germany
[9] Department of Electrical Computer Engineering, Colorado State University, Fort Collins, Colorado, USA

1. Executive Summary

A wide range of laser-based inertial fusion energy schemes have been put forward as a path to high gain including fast ignitor platforms [1-5]. In this, short pulse (10-20 ps), high power (multi-petawatt) lasers provide the spark to quickly heat pre-compressed fuel by delivering 10s of kJ of kinetic energy through beams of either electrons, protons, or ions. These particles are driven by lasers with energy in the 100s of kJ range, well above the current 4 kJ laser energy capabilities of today [6]. Realizing fast ignition concepts requires multiple coordinated research programs addressing its individual components: increasing on-target laser energy by >20x from state-of-the-art (laser architectures), optimizing short pulse driven secondary particle mechanisms (laser-target interaction), and particle transport in ignition-relevant target environments (beam-hot spot interaction). Development in these areas can also play a role in IFE or MFE research such as first-wall material studies, in-situ diagnostics, MFE heating schemes, and ion stopping experiments. In addition, short pulse lasers are poised to be transformational tools in a diverse range of applications when high repetition rate, picosecond, 100 kJ-class lasers are available. In this whitepaper, we propose to leverage such lasers for advanced photon, neutron, and other secondary particle sources for spinoff applications. This includes x-ray and particle radiography, medical radiotherapy, medical isotope production, and transmutation of nuclear waste, all of which are application goals that have been promised for more than three decades. We argue that the development of fast ignitor schemes and laser technology will directly impact high-value spinoff technologies that compete with conventional accelerator- or reactor-based secondary sources.

2. Introduction

Laser-based indirect drive is a successful inertial confinement fusion (ICF) scheme, as demonstrated by the recent ignition-threshold experiments at the National Ignition Facility at Lawrence Livermore National Laboratory. However, the platform does not currently scale to the high gains (>100) necessary for an inertial fusion energy (IFE) power plant. Decoupling the compression from the heating phase using the fast-ignitor (FI) scheme is a top candidate to reach high gains with reasonable constraints on the facility and driver size. In the fast-ignitor approach, nanosecond, megajoule-class long pulse lasers first compress a fuel capsule, through either direct- or indirect-drive mechanisms. The dense fuel core is quickly heated through energy transfer from laser-accelerated charged particles from a picosecond, petawatt-class short pulse laser.

Fast ignitor designs require particle beams to collisionally deposit 10-50 kJ of energy in the compressed fusion fuel [1-3]. Depending on the particle type, electrons or ions, the interaction of the beam with the compressed fuel is governed by different phenomena. State of the art high-intensity short pulse lasers achieve coupling efficiencies of laser light to primarily target electrons of 30-80% via the ponderomotive force [7]. The quasistatic electric field formed by relativistic electrons recirculating in a free-standing target accelerates protons and light ions to MeV energies and can reach laser-to-ion conversion efficiencies of up to 10% [8]. Electrons have a high conversion efficiency but scatter easily and energy deposition is not localized. Protons and heavy ions are more ballistic, focusable, and stop quickly at a distinct Bragg peak, but typically only have a few percent conversion efficiency. In any of these cases, the requisite laser energy is on the order of 100 kJ in picosecond durations, more than 20x the currently operating highest-energy short pulse laser, NIF-ARC. A research program to develop these laser-based fast ignition schemes would focus on the following topics: (1) development of a 100 kJ short pulse laser, (2) identification of short pulse laser parameters for efficient electron or ion acceleration, (3) charged particle transport, (4) experimental demonstration of source production and control.

These objectives share a significant overlap with the goals of a diverse set of fundamental research fields that currently exist and rely on secondary sources from ultraintense short pulse lasers, including creating extreme states of matter, laboratory astrophysics, and nuclear science at high energy density conditions. While these fields will undoubtedly benefit from a fast ignition IFE program, an arguably more impactful outcome will be realizing three decades of promises to revolutionize industrial, medical, and environmental application. We have selected a few to highlight the potential quantum leap spinoff technologies would gain by using a 100 kJ, high-repetition rate laser.

Evaluating the potential commercialization of each of these applications remains extremely uncertain as the cost basis of each 100-kJ laser is unknown. At present, high energy short pulse lasers are approximately \$10,000 per laser joule. Even with a 100x cost reduction, an FI-IFE laser is \$10M without facility infrastructure. As well, the market volume may not support such cost efficiencies and could immediately eliminate some applications from being competitive with a laser driver. Similarly, if the market is already saturated, the profit margins may be too small to justify an additional source. Once a single, first-of-its-kind FI-IFE laser is completed, spinoff applications into industry is conceivable and the central commercialization questions can be posed:

- Is there an existing market or will the market have to be developed?
- What is the size of the market?
- What is the unique selling point?
- What are the costs, price acceptance, and profit margins?

3. Applications

Hadron Radiotherapy

Contrary to X-ray based treatment, the energy loss of a proton or heavier ion in a material following the Bragg curve enables precise energy deposition into cancerous cells while leaving the surrounding healthy tissue largely unaffected. For use in a clinical setting, ion beams require both high energy (200+ MeV/u) and narrow bandwidth (<1%) [9], well beyond demonstrated maximum laser-based proton energies (E_m) of ~100 MeV [10]. The well-established TNSA scaling predicts E_m to scale with the square root of laser intensity, suggesting a required focused intensity of $>10^{23}$ W/cm^2 to reach relevant proton energies. Recent results from the NIF-ARC laser, however, suggest a more efficient process for multi-picosecond, large focal spot laser pulses [11-12]. Using this modified scaling for picosecond lasers, the necessary intensity to reach 200 MeV proton energies drops to only 10^{20} W/cm^2, equivalent to the ARC laser upgraded to ~100 kJ of total energy. With a high repetition rate FI-IFE laser, we estimate that 10^{14} protons/s at 200 MeV are produced, equivalent to an instantaneous dose rate of 10^{12} Gy/s and an average dose rate of 10^5 Gy/s. These extremely high dose rates are unique to laser-driven protons and dovetail into the promising FLASH delivery method of proton therapy [13, 14].

Medical Isotope Production

The decay product of molybdenum-99 (Mo-99), technetium-99m (Tc-99m), is used in about two-thirds of all diagnostic medical isotope procedures in the United States [15]. Until recently, all domestic sources of Mo-99 used research reactors to make this isotope via neutron irradiation of fissile U-235 in highly enriched uranium (HEU). In the past decade, significant investments have been made to establish a reliable domestic supply of Mo-99 produced without HEU. Currently several companies use compact particle accelerators to drive the necessary nuclear reactions through electron bombardment of a Mo-100 target or an ion-driven neutron source irradiating a Mo-98 target. The three companies currently contracted with NNSA to produce Mo-99 have an annual revenue of around $200M per year [16].

Approximately 40,000 doses of Mo-99 are used daily for medical procedures in the US with each dose containing ~0.02 Ci. An 100 kJ, 10 ps, 10 Hz IFE laser would be capable of producing a neutron flux of $>10^{15}$ n/cm^2/s using a pitcher-catcher target configuration and a Li(p,n) reaction. This neutron flux could potentially meeting the demand of the entire country by producing 10,000-100,000 doses/day, depending on the Mo-98 target configuration, which represents a more than 100x increase compared to estimates for existing laser architectures. Additionally, such a neutron source could simultaneously used in a radiography or survivability configuration in a different line of sight.

Transmutation of Nuclear Waste

Current management of high-level nuclear waste relies largely on either dry cask storage or deep geological storage in waste repositories such as the proposed and controversial Yucca Mountain Nuclear Waste Repository. Transmutation of nuclear waste would provide an attractive alternative since this avoids many of the resource management and cost issues associated with cask or repository storage. Transmutation involves using neutrons or other particles to bombard nuclear waste thereby transmuting in through nuclear reactions from long-lived radioactive isotopes into short-lived or even stable material. For example, plutonium-240 has a half-live of ~20000 years, but fission of plutonium-240 via neutrons produces Cesium-137 (half-life of 2 years) and Ruthenium-104 (stable).

Photon and particle-driven nuclear reactions have been proposed as a solution for waste transmutation using accelerators [17] but with the advent of high-energy, high-repetition rate lasers, the inherent benefits of a laser-driven approach may be advantageous. This includes the high particle flux exceeding what is possible with accelerators due to space charge limits for multiple-particle-absorption events, multiple particle species (photons, ions, neutrons) possible in a single-shot exposure, and now, repetition rates up to 10 kHz with new laser architectures.

MeV X-ray Radiography

X-ray radiography has utility within medical, industry, national security, and stockpile stewardship applications where MeV-class x-rays are required for high areal density objects. Current premiere sources use linear accelerators to generate up to ~500 rads of x-rays in ~50 ns and are limited to one or two lines of sight [18].

Laser-based bremsstrahlung x-ray sources have key advantages such as a 10 ps frame duration, ability to optically realign the laser to support multiple lines of sight, and arbitrary temporal spacing. X-ray production efficiency for lasers is dependent on exceeding intensities of $\sim 10^{18}$ W/cm^2 and maximizing energy on target, where a near-linear scaling relation is expected with energy. Recent experiments at Omega EP [19] and NIF-ARC [20] have shown up to 4 rads of X-rays per kilojoule of laser energy are produced, which is approaching the required dose for some low-Z or moderate areal density applications. At 100 kJ incident laser energy, a significantly higher instantaneous dose rates (40,000 rad/ns vs 10 rad/ns at a linear accelerator) can be achieved, while matching total delivered doses. For dynamic imaging, this translates to better images at faster frame rates and eliminates any motion blur. The laser energy could also be split to support single-shot tomography.

Proton Radiography

As with proton-based fast ignition, radiography using protons offers advantages as it is sensitive to electric and magnetic fields, have localized energy deposition, high detection efficiencies, and small-scattered backgrounds. At energies >200 MeV, the proton propagation length approaches macroscopic solid density objects and would start to be comparable to existing linear-accelerator-based proton radiography facilities such as LANSCE, while the instantaneous flux rates would be up to 10^4 higher.

Neutron Radiography

The ability of MeV neutrons to penetrate very high areal density objects while, contrary to X-rays, maintaining a high sensitivity to hydrogen-containing compounds is essential to many industrial and security applications. Laser-driven neutrons beams are unique probes due to their spectrum tunability, flexibility in imaging geometry, and the ability to significantly reduce environmental activation compared to other neutron sources. These neutrons are robustly and efficiently produced in a pitcher-catcher scheme where ions are accelerated from a primary 'pitcher' target and impinge on a secondary 'catcher' target where nuclear reactions produce neutrons. Two reactions, Li(p,n) and Be(d,n*) have demonstrated $10^{10\text{-}11}$ n/sr in a single shot from ~100 J lasers [21]. Conservatively scaling the neutron yield linearly with laser energy, to 10^{14} n/sr/shot, would result in a peak flux of 10^{23} n/sr/s and an average flux of 10^{15} n/sr/s, which is nine and three orders of magnitude above other existing neutron sources, respectively. Currently, only megajoule-yield ICF implosions approach these peak fluxes. Neutron radiography requirements for static and dynamic imaging have a nominal average and peak flux of $>1\times10^{11}$ n/sr/second and $>1\times10^{13}$ n/sr/shot, respectively. An IFE-relevant short pulse laser would easily reach these requirements and, using these high yields, advanced techniques like neutron resonance spectroscopy could be employed to provide 2D flash radiographs with elemental discrimination in a single frame.

Neutron damage

A neutron source with 10^{15} n/sr/shot and the ability to provide broadband, DD, or DT neutrons is ideally suited to study transient atomic dynamics of radiation-induced damage cascades and void formation related to fusion reactor first-wall materials. Neutron-induced displacement in a lattice structure or helium bubble growth at grain boundaries compromises the integrity of the first wall and is well understood for prompt-event-irradiation. The development of a laser-driven neutron source capable of reaching the relevant average flux regimes will enable testing of components to empirically determine longevity of fusion reactors. Key question to answer for first-wall materials is how does their behavior change at high flux, high repetition irradiation, including the possibility of annealing/healing through repetitive irradiation. Lasers may be ideally suited as a research test bed and proving ground.

4. Summary

Short pulse laser technology has key roles to play on the path to inertial fusion energy. If a fast ignition scheme is pursued and a 100-kJ-class petawatt laser is developed, it will usher in new era of HED research and achieve application goals that have been promised for more than three decades. Many of the application examples show promise but could not compete with existing sources due to low flux, either average or peak. A high repetition rate, high energy lasers have the potential of exceeding competitors by orders of magnitude in some cases. The greatest risk to realizing the discussed applications is the driver and facility costs, which will come down with economies of scale.

5. Acknowledgements

This work was performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344 and funded by the LLNL LDRD program under tracking code 22-ERD-022.

6. References

1. Max Tabak, James Hammer, Michael E. Glinsky, William L. Kruer, Scott C. Wilks, John Woodworth, E. Michael Campbell, and Michael D. Perry, and Rodney J. Mason "Ignition and high gain with ultrapowerful lasers", Physics of Plasmas **1**, 1626 (1994)
2. M. Roth, et al., "Fast Ignition by Intense Laser-Accelerated Proton Beams", Phys. Rev. Lett. **86**, 436 (2001)
3. Medin, S., et al., (2002). Evaluation of a power plant concept for fast ignition heavy ion fusion. *Laser and Particle Beams, 20*(3), 419-422. doi:10.1017/S0263034602203109
4. S. Wilks, et al., "Short Pulse laser based ion fast ignition for IFE", whitepaper for this workshop. (2022)
5. A. Kemp, et al., "Electron-driven fast-ignition approach to IFE", whitepaper for this workshop. (2022)
6. Di Nicola, J. M., et al., Proc. SPIE 9345, 934501 (2015).
7. M. C. Levy, S. C. Wilks, M. Tabak, S. B. Libby, and M. G. Baring. Petawatt laser absorption bounded. Nature Communications, 5:4149 EP –, 06 2014.
8. G. J. Williams, et al., In preparation.
9. M. Goitein, T. Lomax, and E. Pedroni, Physics Today **55**, 9, 45 (2002); https://doi.org/10.1063/1.1522215
10. A. Higginson, et al. Near-100 mev protons via a laser- driven transparency-enhanced hybrid acceleration scheme. Nature Communications, 9(1):724, 2018.
11. D. Mariscal, T. Ma, S. C. Wilks, et al., "First demonstration of arc-accelerated proton beams at the national ignition facility," Phys. Plasmas **26**(4), 043110 (2019).
12. R. A. Simpson, et al. Demonstration of TNSA proton radiography on the national ignition facility advanced radiographic capability (NIF-ARC) laser. Plasma Physics and Controlled Fusion, 63(12):124006, nov 2021.
13. Vozenin, M. C., Hendry, J. H. & Limoli, C. L. Biological benefits of ultra-high dose rate FLASH radiotherapy: Sleeping beauty awoken. Clin. Oncol. (R. Coll. Radiol.) 31, 407–415. https://doi.org/10.1016/j.clon.2019.04.001 (2019)
14. J. Bin, L. Obst-Huebl, et al., A new platform for ultra-high dose rate radiobiological research using the bella pw laser proton beamline. Scientific Reports, 12(1):1484, 2022.
15. National Academies of Sciences, Engineering, and Medicine. *Molybdenum-99 for medical imaging*. National Academies Press, 2016.
16. NNSA. n.d. "NNSA's Molybdenum-99 Program: Establishing a Reliable Domestic Supply of Mo-99 Produced Without Highly Enriched Uranium." Accessed September 26, 2021. https://www.energy.gov/nnsa/nnsas-molybdenum-99-program-establishing-reliable-domestic-supply-mo-99-produced-without
17. F. Venneri, C. Bowman, and R. Jameson. Accelerators address nuclear waste problems. Physics World, 6(8):40–46, aug 1993.
18. Burns, M. J., et al. "DAHRT accelerators update and plans for initial operation." *Proceedings of the 1999 Particle Accelerator Conference (Cat. No. 99CH36366)*. Vol. 1. IEEE, 1999.
19. A. Compant La Fontaine, C. Courtois, and E. Lefebvre. Production of multi-mev bremsstrahlung x-ray sources by petawatt laser pulses on various targets. Physics of Plasmas, 19(2):023104, 2012.
20. Kerr, Shaun, et al. "MeV x-ray sources from dual compound parabolic concentrator targets." *Bulletin of the American Physical Society* 66 (2021).
21. Petrov G. et al., *Phys. Plasmas, 19,* p. 093106, 2012.