CLAIMS

1. A method to excite shock waves in a sample, the method comprising:
   (a) splitting a pulsed laser beam into a plurality of pulsed laser beams;
   (b) spatially shaping the plurality of pulsed laser beams into a set of concentric pulsed laser rings of different predetermined diameters; and
   (c) controlling time intervals between ring-shaped laser pulses so as to match a propagation time in the sample of ring-shaped laser shock waves from one ring to the next.

2. The method of claim 1 wherein the laser pulse is a high-energy laser pulse.

3. The method of claim 1 wherein controlling time intervals between laser pulses in different rings so as to match a propagation time of ring-shaped laser shock waves from one ring to the next is done in order to fulfill the acoustic phase matching conditions for coherent excitation and build-up of a primary ring-shaped shock wave travelling in a sample toward the center of the rings where shock focusing takes place.

4. The method of claim 1 wherein the shock waves are generated in a sample and shock propagation will be within the plane of the sample, converging toward a focal region.

5. The method of claim 4 wherein the sample is less than 1 mm thick.

6. The method of claim 4 wherein the sample is less than 0.1 mm thick.

7. A method to excite shock waves in a sample, the method comprising:
   (a) splitting a laser pulse into a plurality of pulsed laser beams;
   (b) spatially shaping the plurality of pulsed laser beams into spatially separated parallel pulsed laser lines; and
   (c) controlling time intervals between line-shaped laser pulses in predetermined locations so as to match a propagation time in the sample of line-shaped laser shock waves from one line to the next.

8. The method of claim 7 wherein the laser pulse is a high-energy laser pulse.

9. The method of claim 8 wherein controlling time intervals between pulses in different lines so as to match a propagation time of laser shock waves from one line to the next is done in order to fulfill the acoustic phase matching conditions for coherent excitation and build-up of a primary shock wave converging toward a focal region after passing through an acoustically focusing element.

10. The method of claim 8 wherein the shock waves are generated in a sample and shock propagation will be within the plane of the sample, converging toward a focal region after passing through an acoustically focusing element.

11. The method of claim 10 wherein the sample is less than 1 mm thick.

12. The method of claim 11 wherein the sample is less than 0.1 mm thick.

Executive summary

The aim of the project is the experimental investigation of microscale shock focusing in the Nelson's group at MIT. The tabletop experimental setup at MIT produces a high energy laser pulse shaped as a ring onto the sample surface. Two ring shock waves get laser excited. One ring shock wave propagates outwards, while the other one propagates inwards. The inward propagating shock converges, accelerates, and increases in amplitude as it concentrates towards the center of the ring, where unique conditions of transient high temperatures and high pressures can be achieved. In the frame of this project, we plan to investigate further time-resolved shock diagnostics to calibrate accurately the pressure inferred by shock focusing. A new laser shock excitation technique of multiple rings of different sizes will be optically designed in the frame of this project to boost the shock focusing conditions. This new methodology may find applications in medical therapies or laboratory simulations of astrophysics, while its potential contribution to the fundamental research lies in the understanding of matter under extreme conditions of pressure and temperature.

Context

Shock wave is a pressure wave with supersonic velocity. Shock waves appear in processes at extreme conditions e.g. supersonic flow, explosion, cavitation collapse, electrical discharge making shock waves of interest in a wide variety of disciplines.
Considering the dimension, the current state of the research field may be distinguished into "large scale" and "small scale". In the scope of "large scale" science, shock waves continue to be investigated in the fields of astrophysics [1, 2], aerospace technology [3, 4], high energy density physics [5] including inertial confinement fusion [6], etc. In the scope of "small scale" science, shock waves have been down scaled to miniature and microscopic dimensions in the recent decades. Besides the fundamental research topics such as [7–16], shock waves at smaller scale have found application in the fields of artificial insemination [17], drug delivery [18], micro gas turbine [19], material testing [20], etc. We must ask these fundamental questions: 1. What difference do macro and micro shock waves make? 2. How do micro shocks interact with other fluid-mechanical phenomena? Although there are numerous reports on the large-scale shock waves, the micro-scale shock waves are rather new to the scientific community and have been emerging in the last two decades. Since many aspects of the micro shock waves are not well understood, there is a strong need of experiments on micro shocks, and this project shall provide relevant experimental results.

Previous works of Nelson's group in the area of microscale shock focusing [20–25] will be the starting point for this project. In addition, the applicant has carried out related works [16, 26–30] on laser-plasma induced micro shock waves, cavitation bubbles and the corresponding development in optical metrology, thus providing a solid scientific framework for the project. The working principle of the standing setup in Nelson's group is

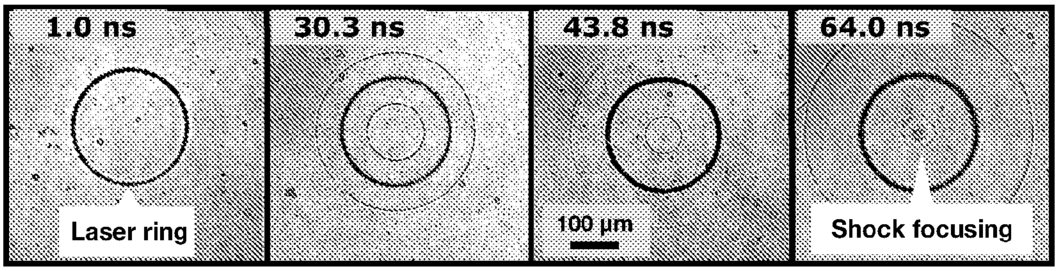

Fig. 1: Snapshot images of the ring shock waves taken at increasing time delays. The laser ring of 0.05 mJ energy excites two propagating ring shock waves. After about 64 ns the inner ring shock wave undergo acoustic focusing at the center.

illustrated in Fig. 1(A), where the inward propagating shock is responsible for generating extreme conditions of dynamic high pressure at the center of the ring.

OBJECTIVES OF THE PROPOSAL

The key research questions can be briefly summarized as follows: 1. How do focusing shock waves and cavitation bubbles interact at microscale in real time? 2. How can we create extreme pressure and temperature conditions within a small confined geometry in a tabletop experiment? 3. What new applications to focusing shock waves can be investigated?

One objective of the project is to answer the aforementioned questions, and ask new scientific questions along the way. Unexpected effects are actually expected to occur, because this research area is, as mentioned before, quite new to the scientific community.

Furthermore, we plan to make a 'multi-shots' experiment illustrated in Fig. 1(B). The objective is to boost the shock wave excitation by applying synchronous laser excitation from multiple laser rings spatially and temporally following the shock propagation, to maximize the laser excitation of the shock waves, prior to the injection into the plasma created by the bubble. The advantage of this new technique of multi-beam synchronous laser shock excitation is that the laser energy is spread over a large area and we can efficiently apply lasers of large energies, while avoiding saturation of the laser-induced excitation efficiency. The target of the combination is to substantially increase the pressure-temperature conditions at the shock focus and create unprecedented plasma conditions.

Scientific and technical program

This proposal is an experimental work based on the original setup [21] in Nelson's group for 2D focusing of laser-generated shock waves, which is accessible for optical diagnostics enabling the direct visualization of shock waves with corresponding pressures close to TPa.

The research program is scheduled for the first half of 2020 and its contents are presented in the following.

1. Compensate the optical aberration in the system. This can be done by modelling the system by ray tracing software (Zemax, Code V or OSLO) and analyzing the corresponding Seidel diagram. Because the standing setup doesn't focus the laser beam as an ideal ring with homogeneous intensity, there is a complex geometrical shape with different tensile sites for nucleation. Better lens combination shall be designed, and applied in the experimental setup. Consequently, overall imaging quality may be improved. This will benefit not only the imaging (probe process) but also the shock creation (pump process).
2. Bring the "multi-shots" setup from concept to reality. One of the preliminary setups is sketched in Fig. 2. Multiple ring-shape laser foci shall be produced to generate multiple inward propagating shock waves with defined time delay in order to amplify the shock wave. In this figure, a simple modified version of the standing setup is sketched. In a further step, a much more sophisticated optical cavity assembly in combination with a phase disk for beam transformation from Gaussian to donut-shaped ring will be designed, in order to replace the axicons to achieve better results by homogenizing the beam profile. The novel setups require advanced optical modelling prior to the experiments. The modelling will help to determine the arrangement of the optical components responsible for the spatial and temporal coordinates of the synchronous laser pulses. Subsequently, additional optical components will be purchased, and the experiment will be performed. Furthermore, stray light such as ghost reflections shall be analyzed through modelling and then experimentally reduced, because it may be an error source for the detection of sonoluminescence.
3. Improve the data analysis (optional). The raw data delivered from the experiment are in the form of images, which are subsequently evaluated by Matlab. The size of the cavitation bubbles, which is important information for this project, is determined from the images. Pattern recognition algorithm can be applied to further automatize the data analysis and evaluate all the bubbles instead of sampling just a few of them.
4. Simulate the microscale focusing shock wave (optional). Codes based on Navier-Stokes equations instead of Euler equations may be applied to generate theoretical expectations, which will be compared with experimental results. Because the dissipative effects of shocks in a small confined geometry (such as in a thin disk or tube) may become non-negligible, Navier-Stokes simulation may provide more insights

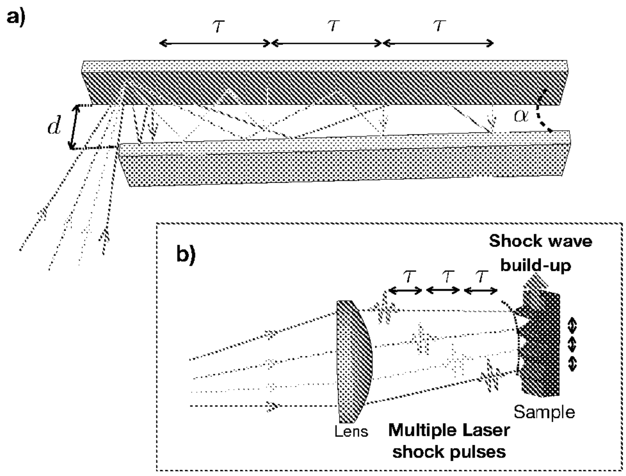

Fig. 2: **(a)** A tilted optical cavity produces different optical delays for beams of different direction / angle. [3] **(b)** Each of these beams can be focused on the sample surface at different times τ, that can be modified by tuning the cavity spacing d, and at different locations controlled with the tilt angle α. A scan of the delay time τ can be performed to track the shock build-up - i.e. the synchronous laser excitation of multiple shock waves.

in, e.g. shock attenuation due to boundary layer development. Since shock focusing and attenuation are competing processes, the inward propagating shock may eventually have constant velocity if certain conditions such as hydraulic dimensions are met. The constant shock velocity may lead to constant post-shock temperature and pressure, which are also interesting factors for chemical studies.

The anticipated difficulties will occur mainly in point 2. Although the experiments are carefully concepted, it is still a challenge to detect sonoluminescence. Owing to the fact that the mechanism of sonoluminescence remains uncertain, it is not easy to create the best experimental conditions. The mechanisms can be dielectric breakdown of the gas, fracture-induced light emission, bremsstrahlung, collision-induced emission, Casimir effect, etc. [31]. However, the other points of the research program are straightforward, so that we are optimistic for at least a partial success. If the sonoluminescence phenomenon is successful generated in this setup, it will be a great plus to the aforementioned goals of the project.

Conclusion

A novel "multi shots" experiment for shock focusing has recently been concepted by Nelson's group at the Massachusetts Institute of Technology. The applicant, who has relevant experience and some new original ideas, intends to carry out a 6-months postdoctoral research and realize this concept. Since the project has multiple steps, there can be short-term and long-term goals which are realistic for this postdoctoral stay and beyond. If the "multi shots" experiment for shock focusing is successful, it may become a practical methodology for creating extreme pressure and temperature conditions within a microscale confined geometry. This has straightforward potential application in materials science, specifically, in discerning and differentiating the molecular attributes that are critical to the mechanophore transformations during shock loading, where shock-induced stress and strain-rates would be coupled.

This project may also deepen the cooperation with research partners back in Germany and other European countries, who have been working with the applicant on related topics and published papers such as [16, 26–30, 32] for the last five years.

References

1. P Moore and GE Hunt. Atlas of the solar system. *Chicago: Rand McNally, 1983.*, 1983.

2. AH Sulaiman, A Masters, MK Dougherty, D Burgess, M Fujimoto, and GB Hospodarsky. Quasiperpendicular high mach number shocks. *Physical review letters*, 115 (12):125001, 2015.

3. A Wagner, M Schramm, JP Hickey, and K Hannemann. Hypersonic shock wave boundary layer interaction studies on a flat plate at elevated surface temperature. *Proc. ISIS21 Glasgow*, 2016.

4. A Russell, H Zare-Behtash, and K Kontis. Joule heating flow control methods for high-speed flows. *Journal of Electrostatics*, 80:34–68, 2016.

5. EG Gamaly, L Rapp, V Roppo, S Juodkazis, and AV Rode. Generation of high energy density by fs-laser-induced confined microexplosion. *New Journal of Physics*, 15(2): 025018, 2013.

6. J Lindl. Development of the indirect-drive approach to inertial confinement fusion and the target physics basis for ignition and gain. *Physics of plasmas*, 2(11): 3933–4024, 1995.

7. M Sun, T Ogawa, and K Takayama. Shock propagation in narrow channels.

ISSW23, Fort Worth, TX, 2001.

8. M Brouillette. Shock waves at microscales. *Shock waves*, 13(1):3–12, 2003.

9. G Mirshekari and M Brouillette. One-dimensional model for microscale shock tube flow. *Shock Waves*, 19(1):25–38, 2009.

10. G Mirshekari and M Brouillette. Microscale shock tube. *Journal of Microelectromechanical Systems*, 21(3):739–748, 2012.

11. G Mirshekari, Martin Brouillette, Jerome Giordano, C Hébert, J-D Parisse, and Pierre Perrier. Shock waves in microchannels. *Journal of Fluid Mechanics*, 724: 259–283, 2013.

12. DE Zeitoun and Y Burtschell. Navier–stokes computations in micro shock tubes. *Shock Waves*, 15(3-4):241–246, 2006.

13. DE Zeitoun. Correlations of shock mach number attenuation in small size diameter tubes. *Physics of Fluids*, 27(1):011701, 2015.

14. JM Austin and DJ Bodony. Wave propagation in gaseous small-scale channel flows. *Shock Waves*, 21(6):547, 2011.

15. A Deshpande and B Puranik. A numerical investigation of shock propagation in three-dimensional microducts. *Shock Waves*, 27(4):565–582, 2017.

16. U Teubner, Y Kai, T Schlegel, DE Zeitoun, and W Garen. Laser-plasma induced shock waves in micro shock tubes. *New Journal of Physics*, 19(10):103016, 2017.

17. KPJ Reddy and N Sharath. The motion of a 2 mm tantalum block induced by underwater explosion. *Current Science*, 104(2):172–176, 2013.

18. G Jagadeesh, GD Prakash, SG Rakesh, US Allam, MG Krishna, SM Eswarappa, and D Chakravortty. Needleless vaccine delivery using micro-shock waves. *Clinical and Vaccine Immunology*, 18(4):539–545, 2011.

19. G Vézina, H Fortier-Topping, F Bolduc-Teasdale, D Rancourt, M Picard, JB Plante, M Brouillette, and L Fréchette. Design and experimental validation of a supersonic concentric micro gas turbine. *Journal of Turbomachinery*, 138(2): 021007, 2016.

20. D Veysset, SE Kooi, R Haferssas, M Hassani-Gangaraj, M Islam, AA Maznev, Y Chernukha, XG Zhao, K Nakagawa, D Martynowych, X Zhang, AM Lomonosov, CA

Schuh, R Radovitzky, T Pezeril, and KA Nelson. Glass fracture by focusing of laser-generated nanosecond surface acoustic waves. *Scripta Materialia*, 158:42–45, 2019.

21. T Pezeril, G Saini, D Veysset, S Kooi, P Fidkowski, R Radovitzky, and KA Nelson. Direct visualization of laser-driven focusing shock waves. *Physical review letters*, 106(21):214503, 2011.

22. D Veysset, T Pezeril, S Kooi, A Bulou, and KA Nelson. Laser-induced versus shock wave induced transformation of highly ordered pyrolytic graphite. *Applied Physics Letters*, 106(16):161902, 2015.

23. D Veysset, AA Maznev, T Pezeril, S Kooi, and KA Nelson. Interferometric analysis of laser-driven cylindrically focusing shock waves in a thin liquid layer. *Scientific reports*, 6(1):24, 2016.

24. D Veysset, AA Maznev, István A Veres, T Pezeril, SE Kooi, AM Lomonosov, and KA Nelson. Acoustical breakdown of materials by focusing of laser-generated rayleigh surface waves. *Applied Physics Letters*, 111(3):031901, 2017.

25. D Veysset, U Gutiérrez-Hernández, L Dresselhaus-Cooper, F De Colle, S Kooi, KA Nelson, PA Quinto-Su, and T Pezeril. Single-bubble and multibubble cavitation in water triggered by laser-driven focusing shock waves. *Physical Review E*, 97(5): 053112, 2018.

26. W Garen, F Hegedűs, Y Kai, S Koch, B Meyerer, W Neu, and U Teubner. Shock wave emission during the collapse of cavitation bubbles. *Shock Waves*, pages 1–10, 2016.

27. Y Kai, B Meyerer, W Garen, and U Teubner. Experimental investigation of laser generated shock waves and the onset of evaporation in a mini-shock glass tube filled with water. *Proc. ISIS20 Riga*, 2014.

28. Y Kai, W Garen, and U Teubner. Experimental investigations on microshock waves and contact surfaces. *Physical review letters*, 120(6):064501, 2018.

29. Y Kai, W Garen, T Schlegel, and U Teubner. A novel shock tube with a laser–plasma driver. *Laser and Particle Beams*, 35(4):610–618, 2017. doi: 10.1017/S0263034617000635.

30. Y Kai, W Garen, DE Zeitoun, and U Teubner. Formation and hot flow duration of micro shock flows. *Physics of Fluids*, 30(7):072001, 2018.

31. MP Brenner, S Hilgenfeldt, and D Lohse. Single-bubble sonoluminescence. *Reviews of modern physics*, 74(2):425, 2002.

32. F Tavella, H Höppner, V Tkachenko, N Medvedev, F Capotondi, T Golz, Y Kai, M Manfredda, E Pedersoli, MJ Prandolini, et al. Soft x-ray induced femtosecond solid-to-solid phase transition. *IIigh Energy Density Physics*, 24:22–27, 2017.

Recent advancements in the production and characterization of laser driven shock waves at the microscale has enabled the study of micro-samples and allows for many shock experiments to be performed in a single day. In general, shock waves are generated via the absorption of laser energy by a planar metallic transducer or other absorbing material which then launches a single shock wave into the surrounding sample of interest.

In this new initiative, we propose an innovative approach, building on our well-established expertise on laser driven shock waves [1], to apply the concept of a multi-beam laser shock excitation technique utilizing the rather simple optical cavity device sketched in Fig.1. We will use this new generation technique to investigate the behavior of synchronous build-up of shock waves during propagation along the sample surface of selected **mechanophore** compounds.

The proposed tasks include excitation of **multiple laser shock waves** on sample surfaces, at speci cally chosen locations and at controlled delay times. The optical cavity of Fig.1 can output multiple laser beams that have controlled spatiotemporal spread, that can be ne-tuned to match the shock propagation on the sample surface, to maximize the laser excitation of the shock front. Motivated by the advantages that mechanophores [2] provide, materials that undergo chemical and optical changes in response to mechanical impulses, we will focus on the development of a new methodology to activate and characterize mechanophore transformations at a solid interface under shock conditions. Speci cally, we intend to discern and differentiate the molecular attributes that are critical to the mechanophore transformations during shock loading, where shock-induced stress and strain-rates would be coupled.

These experimental results will help build an understanding of the ultrafast physical processes involved during shock loading of mechanophore samples, in conjunction with providing a tool to study the fundamental aspects of synchronous laser-shock energy build-up.

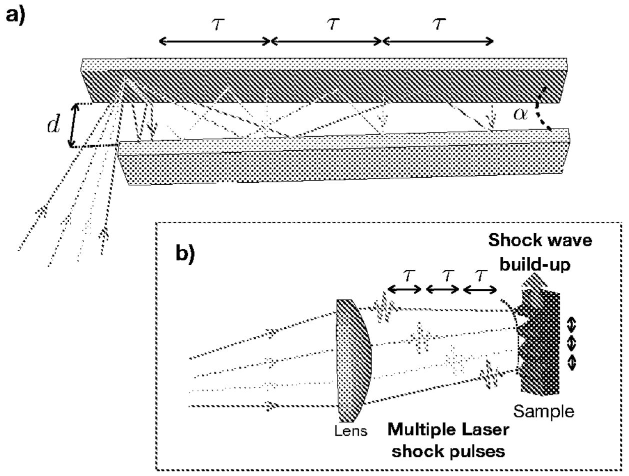

Fig. 1: **(a)** A tilted optical cavity produces different optical delays for beams of different direction / angle. [3] **(b)** Each of these beams can be focused on the sample surface at different times τ, that can be modi ed by tuning the cavity spacing d, and at different locations controlled with the tilt angle α. A scan of the delay time τ can be performed to track the shock build-up - i.e. the synchronous laser excitation of multiple shock waves.

[1] Our recent publications on laser shock waves. D. Veysset, S. E. Kooi, R. Haferssas, M. Hassani-Gangaraj, M. Islam, A. Maznev, Y. Chernukha, X. Zhao, K. Nakagawa, D. Martynowich, X. Zhang, A. Lomonosov, C. Schuh, R. Radovitzky, T. Pezeril, Keith A. Nelson, *Scr. Mater.* 158, 42 (2019). // D. Veysset, U. Gutiérez-Hernandez, L. Dresselhaus-Cooper, F. De Colle, S. Kooi, K. A. Nelson, P. A. Quinto-Su, T. Pezeril, *Phys. Rev. E* 97, 053112 (2018). // D. Veysset, A. Maznev, István A. Veres, T. Pezeril, S. Kooi, Alexey M. Lomonosov, Keith A. Nelson, *Appl. Phys. Lett.* 111, 031901 (2017). // D. Veysset, A. Maznev, T. Pezeril, S. Kooi, Keith A. Nelson, Scienti c Reports 6, 24 (2016). // D. Veysset, T. Pezeril, S. Kooi, A. Bulou, Keith A. Nelson, Appl. Phys. Lett. 106, 161902 (2015). // C. Klieber, V. Gusev, T. Pezeril, Keith A. Nelson, Phys. Rev. Lett. 114, 065701 (2015). // J.-H. Lee, D. Veysset, J. P. Singer, M. Retsch, G. Saini, T. Pezeril, K. A. Nelson, E. L. Thomas, *Nature Communications* 3, 1164 (2012). // T. Pezeril, G. Saini, D. Veysset, S. Kooi, P. Fidkowski, R. Radovitzky, Keith A. Nelson, *Phys. Rev. Lett.* 106, 214503 (2011).

[2] J. Sung, M. Robb, S. White, J. Moore, N. Sottos, *J. Am. Chem. Soc.* 140, 5000 (2018).

[3] J.-L. Wu et al., *Light: Science & Applications* 6, 16196 (2017).

Optically Engineered Additive High Pressure Laser Driven Shock

SUMMARY

Recent advancements in the production and characterization of laser driven shock waves at the microscale has enabled both the study of samples of limited quantity and provided experimental methods to perform many shock experiments in a single day. In general, shock waves are generated via the absorption of laser energy by a planar metallic transducer, or other absorbing material, which then launches a single shock wave into the surrounding sample of interest.

In this new initiative, we propose an innovative approach, building on our well-established expertise on laser driven shock waves [1], to apply the concept of a multi-beam laser shock excitation technique utilizing the optical cavity design detailed in Fig.1. While this method could be used to probe any materials system, we will apply this next generation technique to investigate the behavior of synchronous build-up of multi-shock waves during propagation along the surface of selected **mechanophore** compounds as well as in **nano-alloys**.

The proposed tasks include excitation of **multiple laser shock waves** on sample surfaces, at speci cally chosen locations and at controlled delay times. The optical cavity of Fig.1 can output multiple laser beams that have controlled spatiotemporal spread, which can be ne-tuned to match the shock propagation on the sample surface, to maximize and add to the laser excitation of the shock front. Motivated by the advantages that mechanophores [2] provide, materials that undergo chemical and optical changes in response to mechanical impulses, we will focus on the development of a new methodology to activate and characterize mechanophore transformations at a solid interface under shock loading conditions. Speci cally, we intend to discern and differentiate the molecular attributes that are critical to the mechanophore transformations during shock loading, where shock-induced stress and strain-rates would be coupled. In parallel, a research effort will be accomplished on metallic nano-alloys with extremely interesting shock mitigation processes that are far from being understood at the moment.

These experimental results will help build an understanding of the ultrafast physical processes involved during shock loading of mechanophore or metallic nano-alloys samples, in conjunction with providing a tool to study the fundamental aspects of a new process for laser-schock excitation based on synchronous acoustic energy build-up.

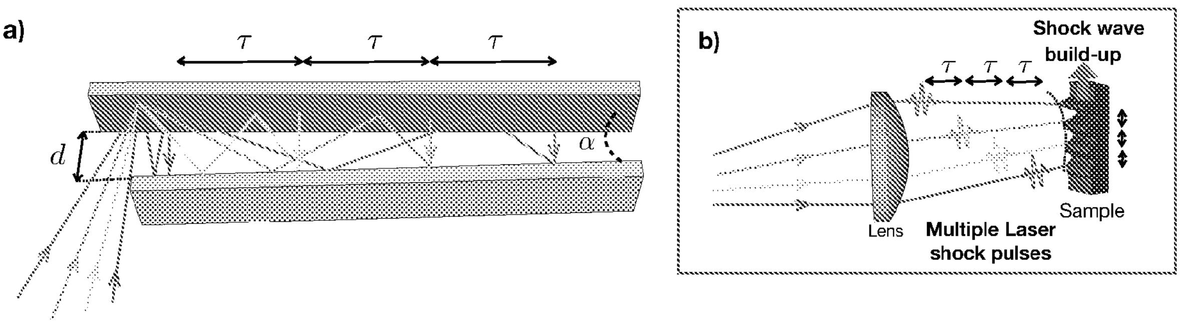

Fig. 1: **(a)** A tilted optical cavity produces different optical delays for a single converging input beam with different incoming angles. [3] **(b)** Each of these sub-beams can be focused on the sample surface at different times τ, that can be modi ed by tuning the cavity spacing d, and at different locations controlled with the tilt angle α. A scan of the delay time τ can be performed to track the shock build-up - i.e. the synchronous laser excitation of multiple shock waves.

CONTEXT AND OBJECTIVES OF THE PROPOSAL

Shock waves, characterized by an abrupt, nearly discontinuous change in the mechanical characteristics of a medium, convey pressures and extreme temperatures. Shock waves are of keen interest of many fields of applications ranging from material physics, plasmas, planetary science, new surgical therapies, etc. Nowadays, the possibility of using high-power lasers for the production of shock waves has greatly facilitated the expansion of this research field. In contrast to bulk sample shock experiments which are difficult and time consuming, shock waves can be studied at the microscale with high-power lasers, enabling the study of micro-samples and multiple shock experiments can be performed on a one day basis.

In laser shock experiments, the shock wave is generated from the absorption of laser energy in a planar photoacoustic transducer, launching an out-of-plane shock wave to the surrounding sample of interest and is typically detected optically along the normal of the sample surface. Since 2006, we have developed an alternate approach based on 2D acoustic focusing of shock waves generated by a laser, see Fig. 2 and the references in [1]. In this case, the shock wave propagates laterally in-plane within the sample. This approach provides ample accessibility for optical spectroscopy and diagnostics enabling the direct visualization of shock waves in solid or liquid samples.

In the proposed project, we plan to go beyond the 2D focusing laser shock geometry and investigate alternative possibilities to drive multiple additive shock waves in a variety of materials, without the drawbacks of laser sample damage. In fact the key point of the multi-shock technique we plan to develop in this project, is that it will enable the laser excitation and superposition of tens of weak shock waves. Each of these laser excited weak shock waves will carry a moderate pressure range, well below sample damage from the absorption of laser energy, and under appropriate acoustic phase matching conditions, will spatiotemporally overlap with the many other laser excited weak shock waves - linear acoustic waves. The advantage of this technique is that it will enable the excitation of high pressure shock waves from many linear acoustic waves. From the fundamental point of view, this innovative technique will shed light on the aspects of laser excitation of multiple overlapping ultrasonic waves, to form a single highly nonlinear shock wave via superposition. This new technique will enable the fundamental investigation of shock formation from linear processes and will give an opportunity to reveal the transition between linear and nonlinear mechanics in many materials. This is unique in the frame of shock research which is always based on irreversible nonlinear processes for shock excitation.

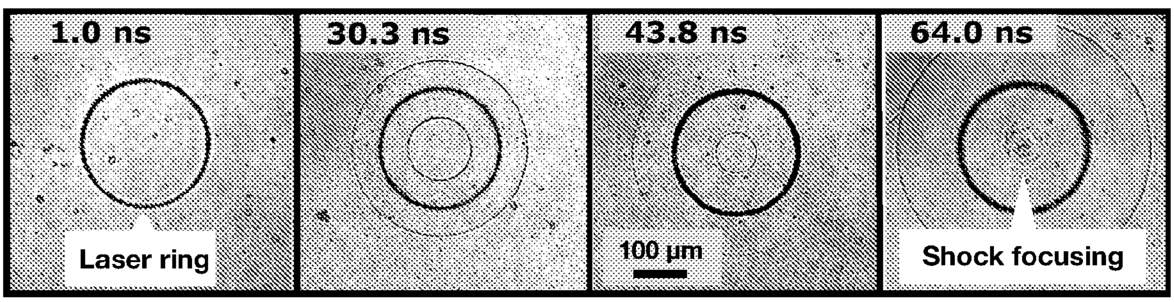

Fig. 2: Snapshot images taken at different times during the shock propagation along the surface of a water sample. The laser, shaped as a ring, excites two annular shock waves. The shock wave that travels toward the center of the ring, acoustically focuses at the center where the shock pressure is the greatest [1].

Another aspect of linear shock excitation is that, contrary to direct mechanisms of laser excitation of shock waves that are based on irreversible processes (plasma formation, ablation, cavitation, etc.), the mechanisms for laser excitation of linear ultrasonics are very well established for a plethora of sample types. Therefore, from the technical point of view, we expect that the estimation of the overall shock pressure obtained from this new technique will be highly reliable and probably more straightforward than in traditional shock physics.

Since there is no restriction concerning the type of samples that could be investigated with the multi-shock technique, we plan to investigate several kinds of materials, ranging from stiff solids (metallic alloys) to soft solids (polymers, gels) or even liquids. The primary motivation is to provide insight into the mechanical behavior of materials under the extreme conditions of very high strain rates. Applications include ballistic threat protection, micrometeorite impacts on spacecraft, high-speed particle impact erosion (such as in jet engine turbine blades), and infrastructure protection against shock waves following explosions.

EXPERIMENTAL APPROACH

The multi-shock technique that we plan to probe and optimize in this proposal is inspired from the FACED (Free-space Angular-Chirp-Enhanced Delay) device that has been designed in the context of uorescence imaging [3]. It uses an optical cavity composed of two slightly titled mirrors illuminated with a converging laser beam. Each portion of the laser beam experiences different delays inside the cavity, see the schemes of Fig. 1 and Fig. 3. The main advantage of the FACED device for our purpose is that without requiring sophisticated optics, enables ne tuning of the time delay and/or the spacing between the individual sources to match the characteristic timescale of the shock propagation in the sample. As shown on Fig. 4, the tilt angle governs the spatial separation between each source and the time delay is simply linked to the light time of ight between the two main mirrors. In practice, the FACED device is commonly used to focus close to one hundred sources with a spatial separation of about 1 micron and a time difference between sources of about 0.2 ns. In the scope of reaching acoustic phase matching, the spatiotemporal separation should match the speed

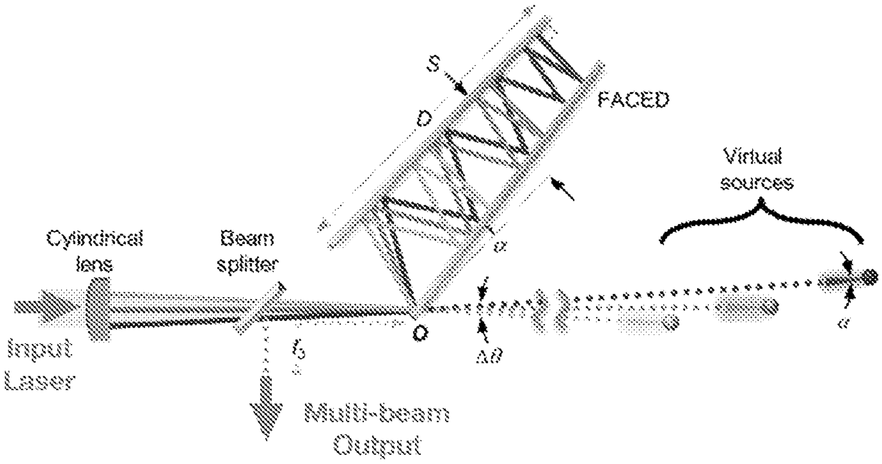

Fig. 3: Schematic of the FACED cavity, adapted from [4]. Each portion of the input Laser beam form a speci c virtual source that experience a different time delay inside the tilted cavity that is related to its optical zigzag path inside the two plane mirrors. The output beam is formed from the overlap of all these virtual sources of different time delays. A single microscope objective is used to focus the multiple sources on different locations on the sample surface

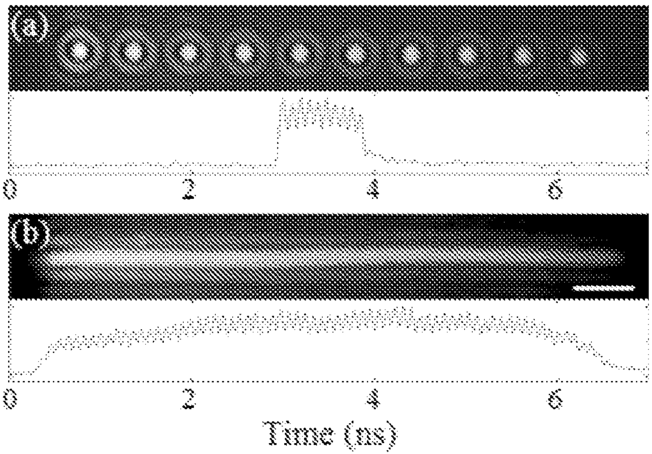

Fig. 4: Images and corresponding time traces of the multiple laser source arrays focused on the sample surface for different tilt angles (a) and (b). The titl angle governs the total number of sources as well as their spacing. The scale bar indicated in yellow is 5 μm. Adapted from [3].

of sound of the material. For many materials, the speed of sound ranges from 1 μm/ns to 5 μm/ns, which is perfectly in line with the spatiotemporal distribution of the output of the FACED device. Therefore, as illustrated on Fig. 4, fine tuning the tilt angle of the cavity can be used to closely reach the acoustic phase matching where all the acoustic sources will be in phase and are expected to result in the build-up of a single intense shock wave.

In practice, we will record time-resolved data and images of the acoustic propagation in the studied materials at many different tilt angles and optimize the acoustic phase matching conditions. The data will be collected from a probe beam focused on the sample surface in order to measure the change in light intensity concomitant with the propagation of the overall acoustic field corresponding to the superposition of the multiple acoustic sources. This pump-probe optical scheme is similar to the transient grating (TG) experiment that we have used extensively, and that has become a wide spread technique covering a wide range of applications and scientific needs [5-6]. TG experiments are based on the excitation of acoustic waves from the optical interference of two optically crossed pump beams on a sample surface. The intensity pattern of the optical fringes on the sample surface governs the acoustic wavelength excited, see Fig. 5(a)(b). A probe beam records the time evolution of the light intensity change due to the propagation of the acoustic wave along the sample surface, see Fig. 5(c). In the TG scheme, since the two crossed pump beams coincide in time on the sample surface, all the fringes are excited coherently at the same time. There is no possibility to time delay the excitation of the first fringe from the last fringe. The TG is not appropriate for the investigation of the acoustic phase matching process. On the contrary, the multi-shock setup that we plan to implement can. The multi-shock setup, due to its simpler optical scheme as compared to TG experiments, could become in a near future a widely used experimental scheme. In addition, the overlap of the two pump beams in the TG experiments require customized optical gratings that are costly and wavelength specific. The multi-shock setup requires only two large planer mirrors that are comparably cheap and achromatic for a wide range of optical wavelengths. These mirrors also offer the possibility to continuously vary the spacing between the laser sources. All of these advantages will be highly beneficial for the linear-nonlinear shock study in materials that we plan to investigate in the framework of this project.

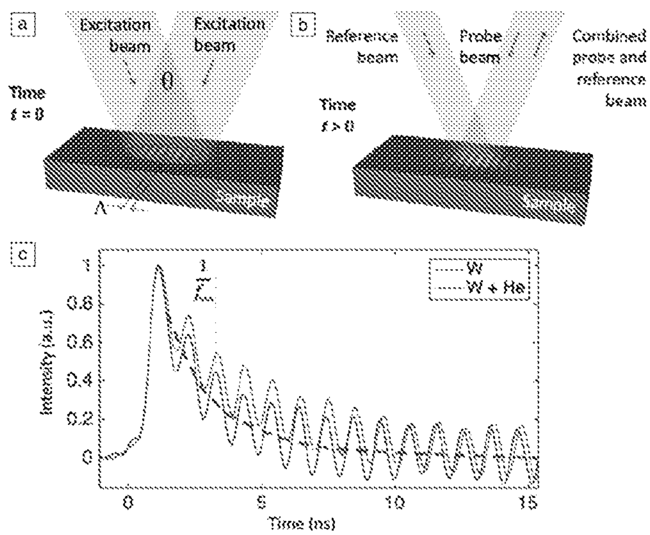

Fig. 5: (a) The optical transient grating is formed on the sample surface from the overlap of two crossed pump beams. (b) A probe beam is used to read out the acoustic wave that matches the transient grating pattern. The diffracted portion of the probe beam is directed to a photodetector coupled to a fast oscilloscope. (c) Transient grating signal from a tungsten sample (blue) and a helium-ion implanted region on the same sample (red). The nanoseconds oscillations of the signal reveal the frequency of the acoustic wave. From this frequency and the known fringe spacing, we can extract the acoustic velocity. Adapted from [6].

To go further beyond our traditional 2D single ring shock focusing technique, we plan as well to adapt the multi-shock technique to laser excite acoustic phase-matched multiple shock rings. Technically, the multiple laser sources of the FACED setup can be converted into multiple rings of different diameters by use of a customized phase mask with a well-de ned diffraction pattern designed to optically transform a line source into a ring source at the focus of a lens. This simple optical scheme, that only requires a phase mask, will be tested in order to implement our standard 2D laser shock focusing technique. We expect to signi cantly increase the overall shock pressure at the center of the multiple laser ring sources. Applications include the production of high shock pressures for the inventory of materials with the highest shock mitigation.

Mechanophore samples

Among the samples that could be studied using the proposed multi-shock methodology, mechanophores are extremely good candidates. These compounds are highly sensitive to external pressures that result in a signi cant modi cation of their structure and physical characteristics (uorescence/color change, catalyst transformation, electrical conductivity etc..), see Fig. 6 and [7].

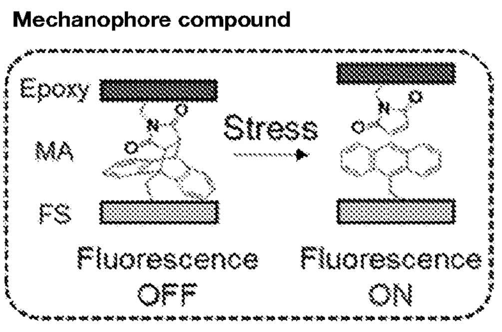

Fig. 6: Schematic representations of the mechanical activation of covalently anchored maleimide–anthracene (MA) mechanophores. A stress can bond or debond the mechanophore and drastically in uence the uorescence behavior of the compound. Adapted from [2]

However, the underlying mechanisms of many mechanochemical processes remain poorly understood due to lack of reliable techniques to investigate the fundamental aspects of these pressure-mediated phase transitions. We intend to perform systematic investigations of mechanophore activation at solid interfaces under the shock conditions provided by our new technique, as described on Fig. 5. Speci cally, we intend to discern and differentiate the molecular attributes that are critical to the mechanophore transformations during shock loading, where shock-induced stress and strain-rates would be coupled. The results will help us to understand the fundamentals of fast molecular processes that underpin the mechanics of debonding and other interfacial phenomena, and provide a tool to study the buildup mechanism and ultimate pressures reached in laser induced shock waves.

As sketched in Fig. 7, the experiments will be based on the excitation of multiple ultrasonics waves on the surface of mechanophore compounds. As in [2], the mechanophore compound will be coated on a metallic thin lm in order to efficiently laser excite the acoustic waves. We will perform post-shocked uorescence analyses to quantify the pressure threshold for the uorescence activation. Since distinct positions along the sample surface corresponds to different pressures, due to a well-de ned step-like pressure increment between each laser source, we can calibrate the shock pressure at each location to obtain information on the pressure threshold needed for uorescence activation. In order to understand the characteristic time for uorescence activation through transient pressures, time-resolved experiments will be performed as well. We will use our multi-frame camera [8] which is fast enough to capture on a single shot a sequence of frames with a nanosecond resolution, to take uorescence images of the sample surface while the multi-shocks propagate across the mechanophore compound. These experiments, that are in line with our technical competence should uncover crucial information about the timescale of the mechanophore process. Once the bases of the mechanophore parameters, such as pressure threshold and characteristic timescale, will be fully characterized for a selected compound, we could use mechanophore as visual pressure sensors for many of traditional shock experiments where the determination of the shock pressure is often elusive. For instance, we could apply our 2D shock focusing technique described in Fig. 2 to determine the shock pressure right at the shock focus for many different laser energies. Data, obtained from mechanophores samples in the context of 2D shock focusing, could bene t the understanding of the shock focusing mechanisms that are of critical importance for future improvement of measurements of the shock pressure.

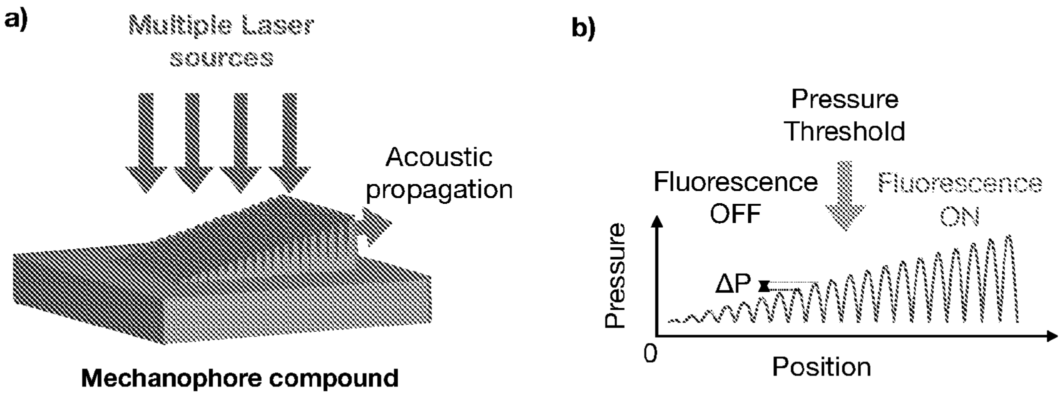

Fig. 7: (a) Application concept. Once the acoustic phase matching conditions are ful lled, a unidirectional shock wave builds up from the laser excitation of many laser ultrasonics line sources. The multi-shock experiment will be tested in a mechanophore material. Before the shock treatment, the mechanophore is not uorescent. Under a certain pressure threshold, to be determined experimentally, the mechanophore compound becomes uorescent.

Nano-Alloys

Alloys are mixtures of different metallic materials that have extremely different properties (mechanical, thermal etc…) as compared to each of its individual constituants. Alloys can be tailored and synthesized from bulk nanocrystalline metals to optimize a specific property such as its hardness, stiffness, melting temperature and wear resistance. The unusually high mechanical strength of these solid solutions of nanocrystalline metals comes mostly from the presence of a large fraction of grain boundaries. Many recent molecular dynamic simulations indicate that nano-alloys have unprecedented ultrahigh strength that could be extremely advantageous for shock mitigation [9-11]. However, the understanding of the link between the alloy nano-morphology with its physical parameters are scarce. We propose to apply the multi-shock technique to get understanding on the intricacy between nano-alloys structural characteristics and shock mitigation.

The basics of the experimental investigation of nano-alloys rely on the multi-shock technique and realtime or post-mortem characterization of the shock mitigation. Similarly to the investigation of mechanophore samples, we will shock nano-alloys with our novel shock technique and track the irrevocable structural changes produced by the shock waves, at the microscale (visual sample damage on a microscope, after or during shock loading) and up to the nanoscale (grains dislocations on TEM images). We anticipate that owing to the multi-step shock excitation, it will be straightforward and simple to visually inspect the damage produced on the sample at different pressures thresholds. As sketched in Fig. 8, since each acoustic source position along the sample surface correspond to an incremental shock pressure, the overall shock pressure can be quantitatively determined at each position on the sample surface. From this simple experimental procedure, we will be able to disentangle the link between shock mitigation and sample damage at incremental shock pressures.

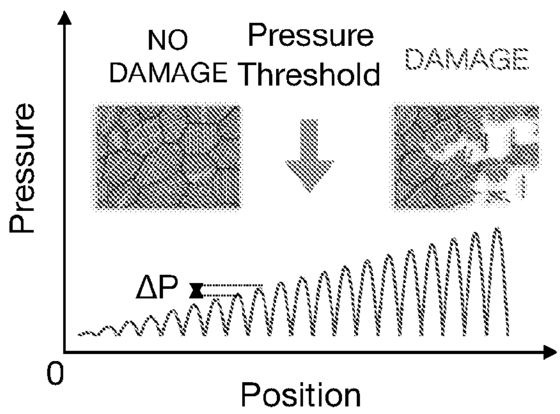

Fig. 8: Schematic of the shock mitigation in nano-alloys. The multi-shock setup will be used to quantify the shock pressure threshold that entails sample damage.

REFERENCES

[1] **Our recent publications on laser shock waves**. D. Veysset, S. E. Kooi, R. Haferssas, M. Hassani-Gangaraj, M. Islam, A. Maznev, Y. Chernukha, X. Zhao, K. Nakagawa, D. Martynowich, X. Zhang, A. Lomonosov, C. Schuh, R. Radovitzky, T. Pezeril, Keith A. Nelson, *Scr. Mater.* 158, 42 (2019). // D. Veysset, U. Gutiérez-Hernandez, L. Dresselhaus-Cooper, F. De Colle, S. Kooi, K. A. Nelson, P. A. Quinto-Su, T. Pezeril, *Phys. Rev. E* 97, 053112 (2018). // D. Veysset, A. Maznev, István A. Veres, T. Pezeril, S. Kooi, Alexey M. Lomonosov, Keith A. Nelson, *Appl. Phys. Lett.* 111, 031901 (2017). // D. Veysset, A. Maznev, T. Pezeril, S. Kooi, Keith A. Nelson, Scienti c Reports 6, 24 (2016). // D. Veysset, T. Pezeril, S. Kooi, A. Bulou, Keith A. Nelson, Appl. Phys. Lett. 106, 161902 (2015). // C. Klieber, V. Gusev, T. Pezeril, Keith A. Nelson, Phys. Rev. Lett. 114, 065701 (2015). // J.-H. Lee, D. Veysset, J. P. Singer, M. Retsch, G. Saini, T. Pezeril, K. A. Nelson, E. L. Thomas, *Nature Communications* 3, 1164 (2012). // T. Pezeril, G. Saini, D. Veysset, S. Kooi, P. Fidkowski, R. Radovitzky, Keith A. Nelson, *Phys. Rev. Lett.* 106, 214503 (2011).

[2] J. Sung, M. Robb, S. White, J. Moore, N. Sottos, J. Am. Chem. Soc. 140, 5000 (2018).

[3] J.-L. Wu et al., Light: Science & Applications 6, 16196 (2017).

[4] J. Wu et al. Biomedical OPt. Express 8, 4160.

[5] F. Hofmann, M. Short, C. Dennett, MRS Bulletin 44, 392 (2019).

[6] G. Saini, T. Pezeril, D. H. Torchinsky, J. Yoon, S. E. Kooi, E.L. thomas, K.A. Nelson, J. Mat. Research 22, 719 (2007).

[7] E. Boldyreva, Chem. Soc. Rev. 42, 7719-7738 (2013).

[8] L. Dresselhaus-Cooper, J. Gorfain, C. Key, B. Ofori-Okai, S. Ali, D. Martynowych, A. Gleason, S. Kooi, K. A. Nelson, Sci. Rep. 9, 3689 (2019).

[9] J. Chen, M. Tschopp, A. Dongare, J. Appl. Physics 122, 225901 (2017).

[10] E. Bringa, A. Caro, Y. Wang, M. Victoria, J. McNaney, B. Remington, R. Smith, B. Torralva, H. Swygenhoven, Science 309, 1838 (2005).

[11] E. Bringa, K. Rosolankova, R. Rudd, B. Remington, J. Wark, M. Duchaineau, D. Kalantar, J. Hawreliak, J. Belak, Nature Materials 5, 805 (2006).

SYNCHRONOUS EXCITATION OF MULIPLE SHOCK WAVES FOR FUSION

DESCRIPTION OF THE INVENTION

This invention relies on a new technique to efficiently excite multiple shock waves in a sample, allowing it to reach the pressure and temperature conditions required for thermonuclear fusion. A high-energy laser pulse is split into multiple beams, spatially shaped into a set of concentric rings of different predetermined diameters (see Fig.1), with the time intervals between pulses in different rings controlled to match the propagation time of the laser shock waves from one ring to the next. This is done in order to ful ll the acoustic phase matching conditions for coherent excitation and build-up of a primary shock wave travelling toward the center of the rings where focusing takes place. In most cases the sample of interest will be a thin layer, less than 1 mm thick and often less than 0.1 mm thick, and the shock propagation will be within the plane of the sample, converging toward the focal region.

Multiple shock waves are optically excited at speci cally chosen locations and at controlled delay times. The spatio-temporal control of the laser excitation of phase-matched shock waves can be based on any of a variety of opto-mechanical designs. For example, the apparatus can incorporate the free-space angular-chirp-enhanced delay (FACED) device [1], that can use multiple re ections between two non-parallel re ectors to produce an optical array of stripes or lines in the focal plane of a lens, with a controllable and well-de ned inter-line spacing and with a controllable incremental delay time between successive stripes or lines, and an optical phase mask can be designed to transform the stripes onto concentric rings of different diameters. The optical phase mask can be a xed imprinted pattern on a substrate or a recon gurable spatial light modulator (SLM). Another example of such an opto-mechanical device would be an optical cavity merging a Herriott multipass cavity and the FACED device that would, in conjunction with an axicon (conical prism) and a focusing lens, produce concentric rings of different diameters on the sample surface. The main point of the optical ring con guration is to acoustically focus the shock energy of the laser-excited phase-matched shock waves at the center of the rings, in a similar manner to that demonstrated in [2] but with multiple concentric excitation rings instead of just one excitation ring. This acoustic focusing at the center of the rings, in conjunction with the acoustic-phase matching approach, is expected to create giant pressures and temperatures conditions at the center of the rings, that would yield measurable amounts of thermonuclear fusion. Some other applications of the high pressures and temperatures reached would be possible as well, for example fabrication of materials or samples that require such pressures and/or temperatures.

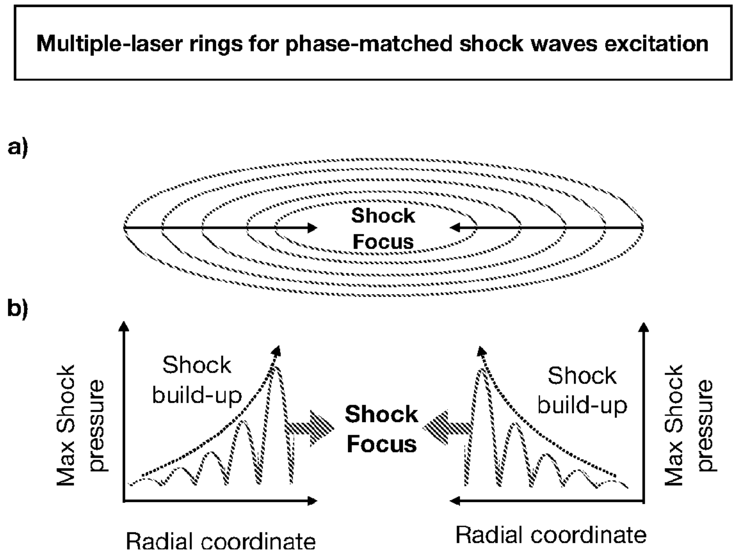

Figure 1: a) Several laser beams shaped as rings of different sizes are focused along the surface of a sample. Each of these excitation rings produces an independent shock wave that travels toward the center of the rings. The timing of the pulses in the excitation rings can be controlled to fulfill the acoustic phase-matching conditions such that all the shock waves overlap in time and space. b) The acoustic phase- matching conditions allow a build-up of the shock amplitude as it propagates toward the center of the rings where it focuses.

There are alternative techniques that would not need to optically convert the stripes into rings in order to achieve acoustic focusing of the phase-matched multi-shocks. For instance, multiple parallel excitation line sources on the sample surface, rather than rings, could be used with timing to allow acoustic phase-matching in order to excite a line-shaped shock wave propagating along the sample surface, see Fig. 2. A curved element incorporated into the sample layer could be used as a reflective or transmissive lens which would focus the linear shock wave to a small focal region. Hereafter we will refer to excitation rings, but it is understood that in each case other excitation geometries are possible.

Since shock waves are non-linear ultrasonic waves whose speeds increase with pressure, the main shock wave that builds up during propagation toward the center will increase in speed as it gets closer to the center. Therefore, in order to achieve an efficient build-up of the main shock wave, either the time delay or the spacing between each excitation ring source has to be tuned in order to match the variation of the shock speed toward the center. In general, this would mean that the spacing or the time delay between successive rings on the sample surface should not be constant. There are several technical possibilities to fulfill this requirement. For instance, the optical phase mask used to convert the array of lines, with constant inter-line spacing from the FACED device, into concentric rings could be designed such that it would lead to concentric rings with non-constant inter-ring spacings that would match the variation of the shock speed along the sample surface. Another possibility would be to modify the FACED device to directly output an array of lines with non-constant inter-line spacings that would match the variation of the shock speed. This could be achieved by replacing one of the large FACED reflectors with multiple small reflectors whose positions and reflection angles that can be adjusted, or by a deformable mirror. One more possibility would be to insert optical elements inside or outside the FACED cavity in order to temporally delay the pulses that pass through them, in order to obtain a non-constant time delay between lines or stripes. One or more of these approaches could be used to control the inter-line spacing and timing as required.

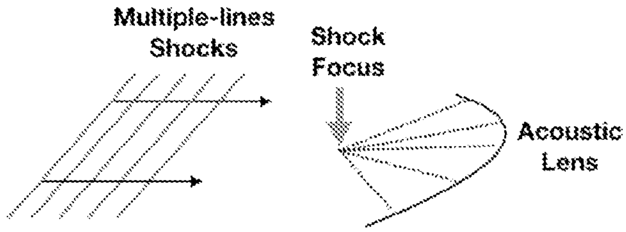

Figure 2: Several laser beams shaped as lines are optically focused along the surface of a sample with appropriate spatio-temporal timing that fulfill the acoustic-phase matching conditions. An acoustic lens is placed along the pathway of the line-shaped shock wave to acoustically focus the shock energy on the sample surface.

The present invention allows efficient laser excitation of phase-matched multi-shocks to obtain a main shock wave that focuses in the plane of a sample. The resulting 2D focusing of the phase-matched multi-shocks is expected to yield the extreme pressures and temperatures required for thermonuclear fusion. In contrast to the laser-based fusion experiments performed at the National Ignition Facility or elsewhere, in which multiple laser beams are focused on the opaque surface of a target sphere in order to focus in three dimensions (3D) a shock wave at the center of the sphere, our technique has the advantage that the sample through which the in-plane shock propagates is optically accessible and can be exposed to further shock excitation with multiple laser beams. Therefore, the multi-shock technique described herein can circumvent the problems of plateauing of the shock pressure that drastically decreases the benefit of the 3D focusing in case of a spherical opaque target. In addition, our invention allows additional shock focusing or shock propagation beyond a planar shock geometry. For example coincident with the arrival of the planar shock at the focal region, through-plane shocks could be launched from above and below the focal region to increase the overall shock pressure, as shown schematically in Figure 3(a). The through-plane shocks could be launched by intense laser pulses that irradiate absorbing layers on the insides of the substrates surrounding the shock propagation medium, with the sample that would undergo fusion pre- positioned at the planar shock focus in between the two absorbing layers. Thus the fusion sample could be subjected to both the focusing in-plane shock and the through-plane shocks, increasing the total pressure and temperature. In a different embodiment, the intense laser pulses from above and below could irradiate the fusion sample itself, or a thin absorbing containment vessel for the fusion sample, rather than absorbing layers on the substrates. The sample could be excited this way prior to or during planar shock focusing. In some configurations, it may be possible to laser-excite the sample with intense light in any frequency range from far-infrared (terahertz frequency range) to x-rays. Another possibility for more than 2D planar shock focusing would be to use curved or tapered substrates instead of flat parallel substrates, such that the thickness of the shock

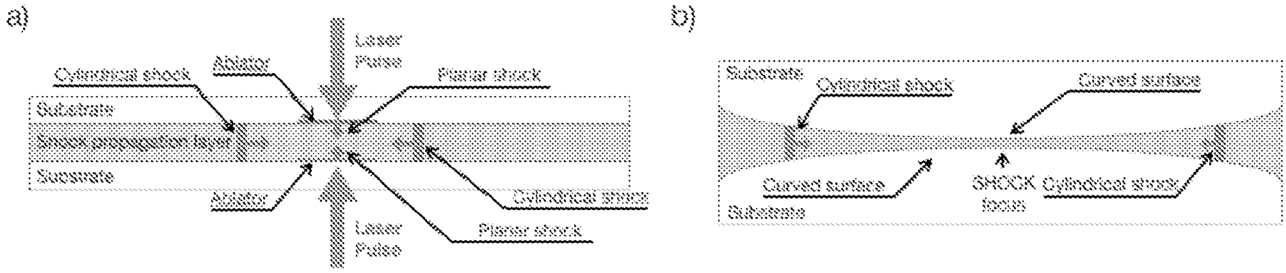

Figure 3: a) In-plane and through-plane laser shock focusing in a planar fusion sample. b) In-plane Laser shock focusing and though-plane shock confinement from a curved fusion sample of decreasing thickness through the shock focus.

propagation medium is decreased as the shock focal region is approached. In this way, the propagating in-plane shock wave would be more and more confined in the through-plane dimension while approaching the shock focus. See Fig. 3(b).

Many different sample configurations for fusion can be tested with this multi-shock invention. For the shock- induced fusion process, samples made of a mixture of Deuterium and Tritium are likely to produce the highest net energy gain during the fusion process. Samples of this type could take various forms including the following:

- Liquid thin film of heavy water with a Deuterium-Tritium bubble trapped at the center of the laser rings.
- Frozen thin film of heavy water with a Deuterium-Tritium bubble trapped at the center of the laser rings.
- Liquid thin film of Deuterium-Tritium.
- Solid thin film Deuterium-Tritium.

Since Deuterium alone can produce fusion, the Deuterium-Tritium mixture can be replaced by pure Deuterium which is a less hazardous material. The bubbles can be trapped in a resonant acoustic field, similarly to sonoluminescence experiments.

Considering the extreme temperature and pressure conditions needed for thermonuclear fusion, the sample will be irreversibly damaged after each laser shot. The energy released during the fusion process can be collected via the emission of high-energy neutrons escaping from the fusion core at the center of the laser rings, see Fig 4. The characteristic dimensions of the excitation laser rings that launch the shocks are likely to be hundreds or tens of micrometers in diameter. The damaged sample area will be of the same order in size. There are many possibilities to run the thermonuclear fusion far larger, and rastering of the sample can be performed. After each laser shot, the sample can be moved to a non-damaged area and the thermonuclear fusion can be fired initiated again to produce high-energy neutrons from a fresh area. An alternative would be to fabricate many smaller samples (perhaps millimeter dimensions) such as the one sketched on Fig. 4 and to use a new sample for each laser shot.

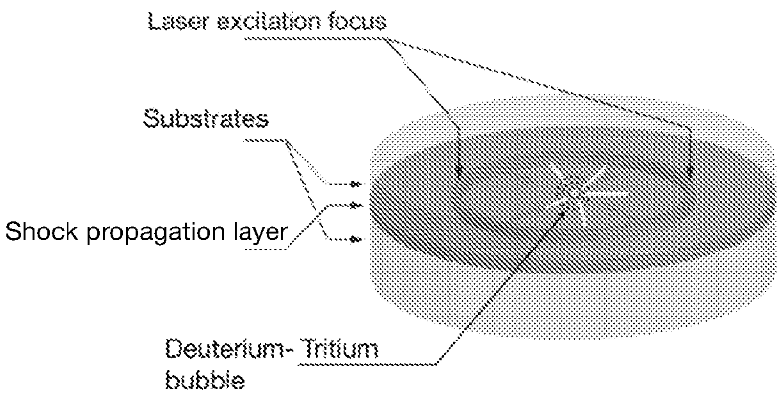

Figure 4: Schematic illustration of the laser shock excitation in a target, in the case of a single excitation laser ring. The laser target can be a multilayer sample assembly in which a thin shock propagation layer (which could be liquid, polymer, or other material type) is sandwiched between two solid samples. A Deuterium-Tritium bubble or droplet can be placed at the center of shock focus for fusion ignition. Adapted from [2].

ADVANTAGES AND IMPROVEMENTS OVER EXISTING METHODS

The main advantage of the invention is that the laser energy is split into many laser sources. Each of these laser sources efficiently excites a phase-matched shock wave to produce extreme total pressure and temperature, circumventing the plateauing of the shock pressure due to lack of full absorption of the laser energy. This plateau effect is one of the main problems related to laser-based shock fusion ignition where the formation of plasma drastically alters the efficiency of the shock excitation. In laser-based inertial confinement fusion experiments, most of the laser energy is reflected by the plasma and only a small portion of the laser energy couples to the excitation of shock waves. This present technique solves the problems of plateauing, and opens the way to orders of magnitude higher efficiency for shock excitation. Figure 5 shows the type of plateauing that can occur when high laser pulse energies are used to excite a sample.

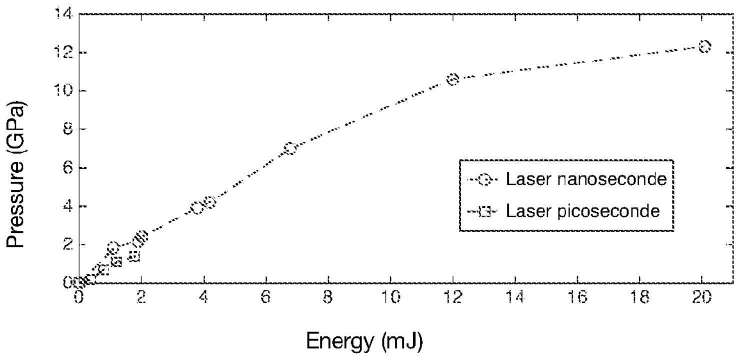

Figure 5: Measured shock pressures in a water sample sandwiched between two glass substrates, plotted versus excitation laser pulse energy from a nanosecond or picosecond duration single pulse laser pulse focused to a 100-micron diameter ring at the sample. The efficiency of the laser shock excitation from a single laser pulse does not scale linearly with laser energy and tends to saturate at increasing energies, reaching a plateau. The new technique solves this problem encountered in laser-based inertial confinement fusion experiments.

COMMERCIAL APPLICATIONS

The main field of application is thermonuclear fusion for the production of energy. Several other applications include the production of high pressures and high temperatures for the characterization or synthesis of materials under extreme conditions which can be attractive for many academic or R&D laboratories. Research on microscale shock waves based on relatively low-cost lasers can be conducted in many laboratories without the use of a gas gun or dangerous explosives. The technique is rather simple and affordable for many institutions. It is not based on customized and expensive lasers. It does not require access to specialized laser facilities such as those at LLNL (Lawrence Livermore National Laboratory), MegaJoule Laser, or others. The device would fit in an ordinary research laboratory.

Furthermore, the fact that the fusion will be downscaled to micro-samples will profoundly alter the present energy infrastructure scheme. Large-scale power plants may not be needed anymore. It could be envisioned that many small devices such as the one described here could operate close to the customer's needs (district, building, house...). This will solve the problems of electric transportation losses from the power plant to the customers.

INDUSTRIAL REQUIREMENTS

Until now, hundreds of billions of dollars have been spent on the quest for fusion ignition, either with lasers or with magnetic confinement. Concerning the laser-based fusion initiation research program, the first step has been to design and to build gigantic lasers that produce megajoule pulse energy at an extremely high cost.. Even if recent experiments have shown that the fusion process can be achieved with a fusion energy output twice the peak kinetic energy of the imploding shell [3], the concept is far away from being energy efficient. The energy needed to power the laser facility is enormous in comparison with the fusion energy output achieved so far. The same drawbacks obtain for magnetic confinement fusion where the net energy gain is far from useful at present. There are no clear indications that fusion ignition based on huge facilities can realistically fulfill the needs for clean energy in the near or far future.

Once successful and optimized, the multishock apparatus will be easily replicated and ready for industrial production worldwide. Indeed, the pulsed lasers needed for the multishock technique are based on the most energy efficient pulsed lasers, Nd:YAG Lasers, commercially available at a relatively low cost. All the parts of the apparatus are commercially available and can be mass produced.

REFERENCES

[1] J.-L. Wu et al., Light: Science & Applications 6, 16196 (2017).
[2] D. Veysset, S. E. Kooi, R. Haferssas, M. Hassani-Gangaraj, M. Islam, A. Maznev, Y. Chernukha, X. Zhao, K. Nakagawa, D. Martynowich, X. Zhang, A. Lomonosov, C. Schuh, R. Radovitzky, T. Pezeril, Keith A. Nelson, Scr. Mater. 158, 42 (2019). // D. Veysset, U. Gutiérez-Hernandez, L. Dresselhaus-Cooper, F. De Colle, S. Kooi, K. A. Nelson, P. A. Quinto-Su, T. Pezeril, Phys. Rev. E 97, 053112 (2018). // D. Veysset, A. Maznev, István A. Veres, T. Pezeril, S. Kooi, Alexey M. Lomonosov, Keith A. Nelson, Appl. Phys. Lett. 111, 031901 (2017). // D. Veysset, A. Maznev, T. Pezeril, S. Kooi, Keith A. Nelson, Scienti c Reports 6, 24 (2016). // D. Veysset, T. Pezeril, S. Kooi, A. Bulou, Keith A. Nelson, Appl. Phys. Lett. 106, 161902 (2015). // J.-H. Lee, D. Veysset, J. P. Singer, M. Retsch, G. Saini, T. Pezeril, K. A. Nelson, E. L. Thomas, Nature Communications 3, 1164 (2012). // T. Pezeril, G. Saini, D. Veysset, S. Kooi, P. Fidkowski, R. Radovitzky, Keith A. Nelson, Phys. Rev. Lett. 106, 214503 (2011).
[3] S. Le Pape et al., Fusion Energy Output Greater than the Kinetic Energy of an Imploding Shell at the National Ignition Facility, Phys. Rev. Lett. 120, 245003 (2018).

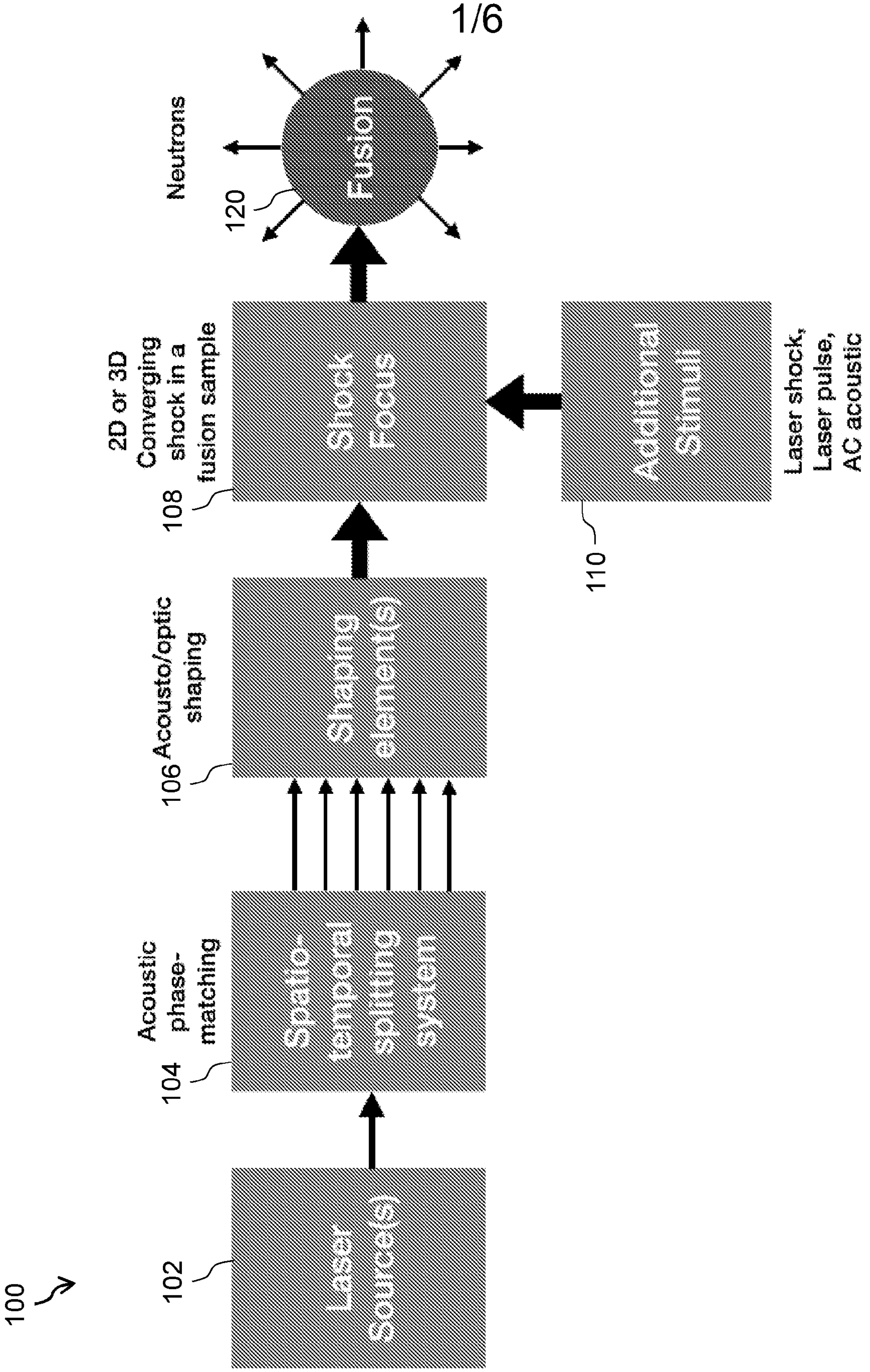
100
102
Laser Source(s)
104
Acoustic phase-matching
Spatio-temporal splitting system
106
Acousto/optic shaping
Shaping element(s)
108
2D or 3D Converging shock in a fusion sample
Shock Focus
110
Additional Stimuli
Laser shock, Laser pulse, AC acoustic field...
120
Neutrons
Fusion

FIG. 1

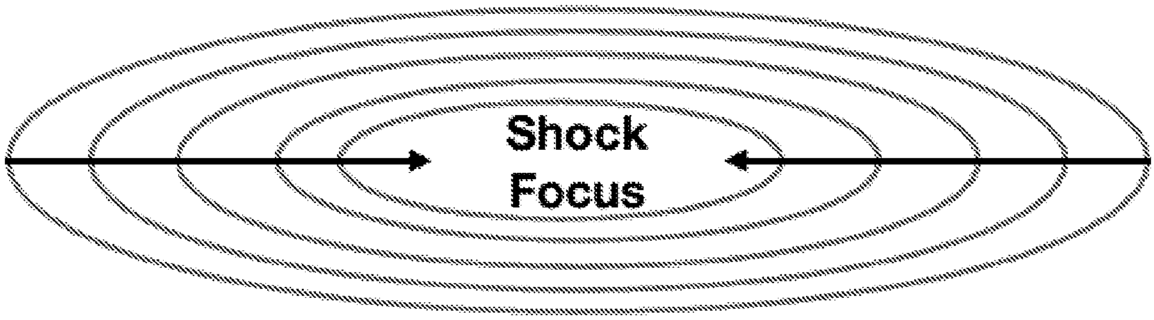
Shock
Focus

FIG. 2A

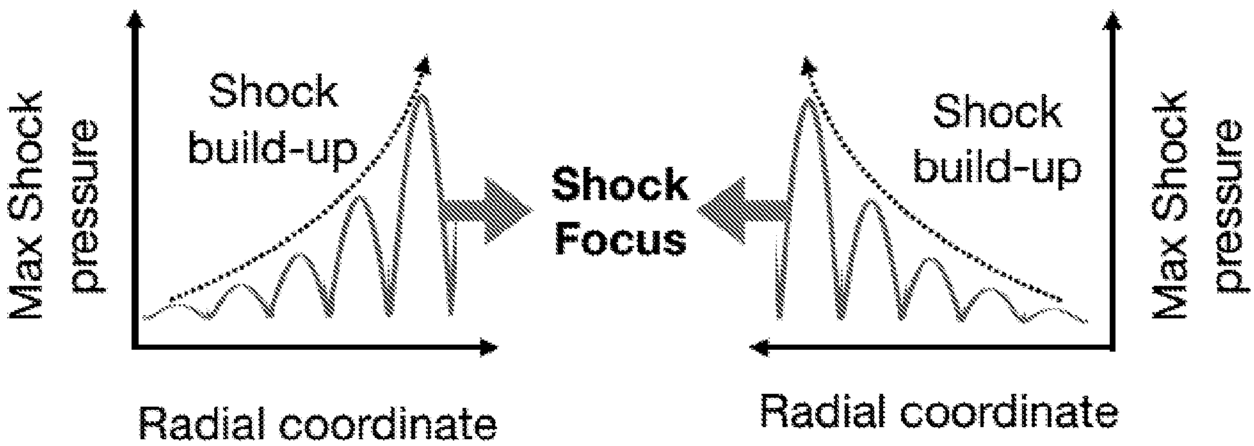
Max Shock pressure
Shock build-up
Radial coordinate
Shock
Focus
Shock build-up
Max Shock pressure
Radial coordinate

FIG. 2B

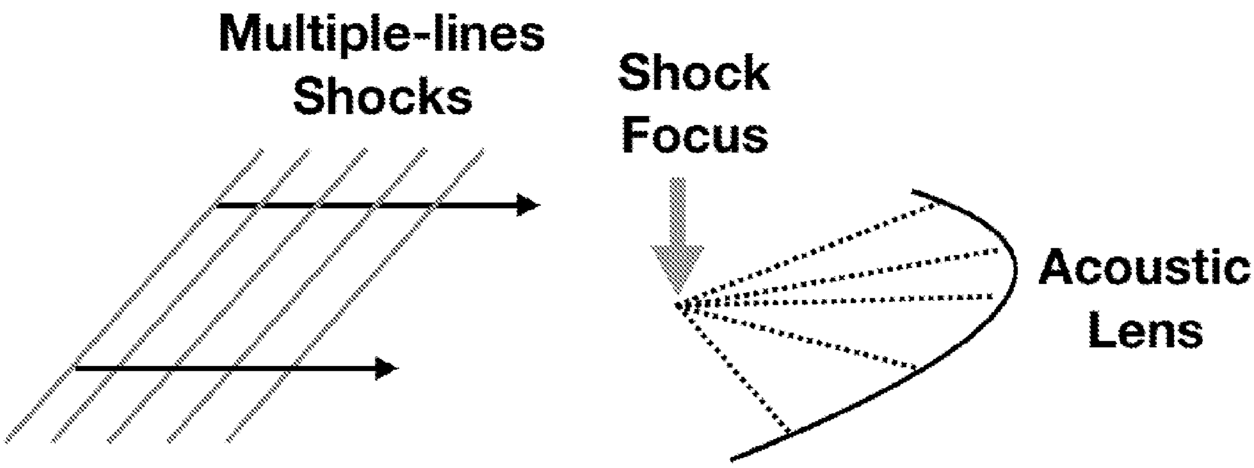
Multiple-lines
Shocks
Shock
Focus
Acoustic
Lens

FIG. 3A

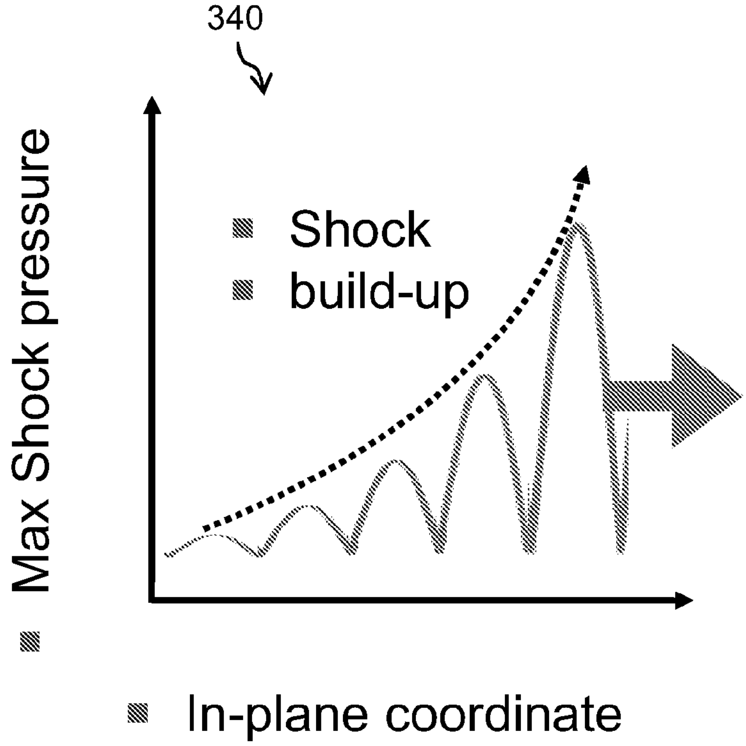
340
Max Shock pressure
Shock
build-up
In-plane coordinate

FIG. 3B

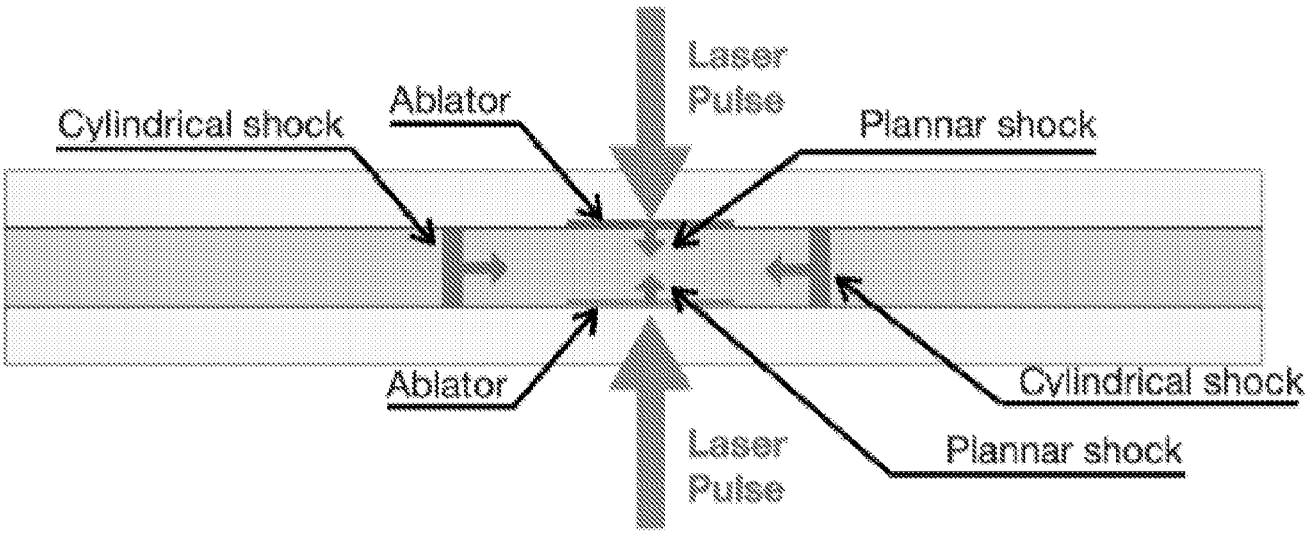
Laser
Pulse
Ablator
Cylindrical shock
Plannar shock
Ablator
Cylindrical shock
Plannar shock
Laser
Pulse

FIG. 4A

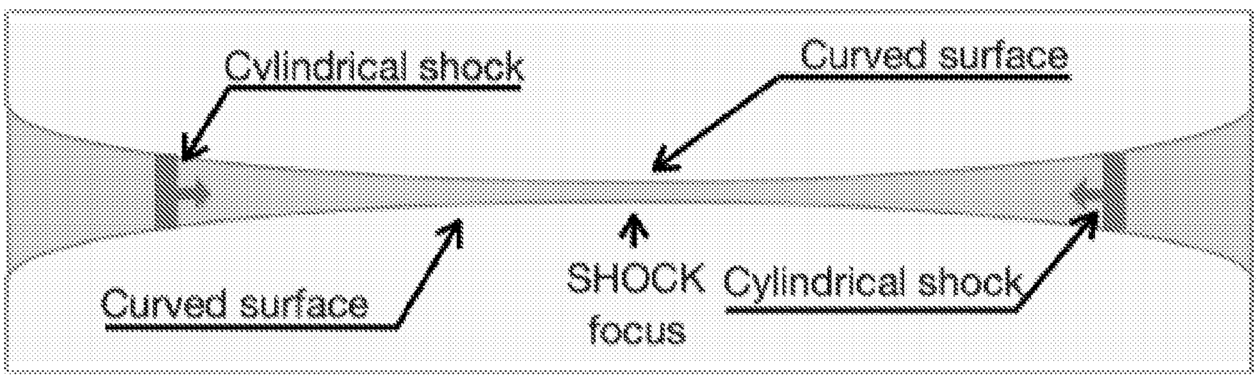
Cylindrical shock
Curved surface
Curved surface
SHOCK
focus
Cylindrical shock

FIG. 4B

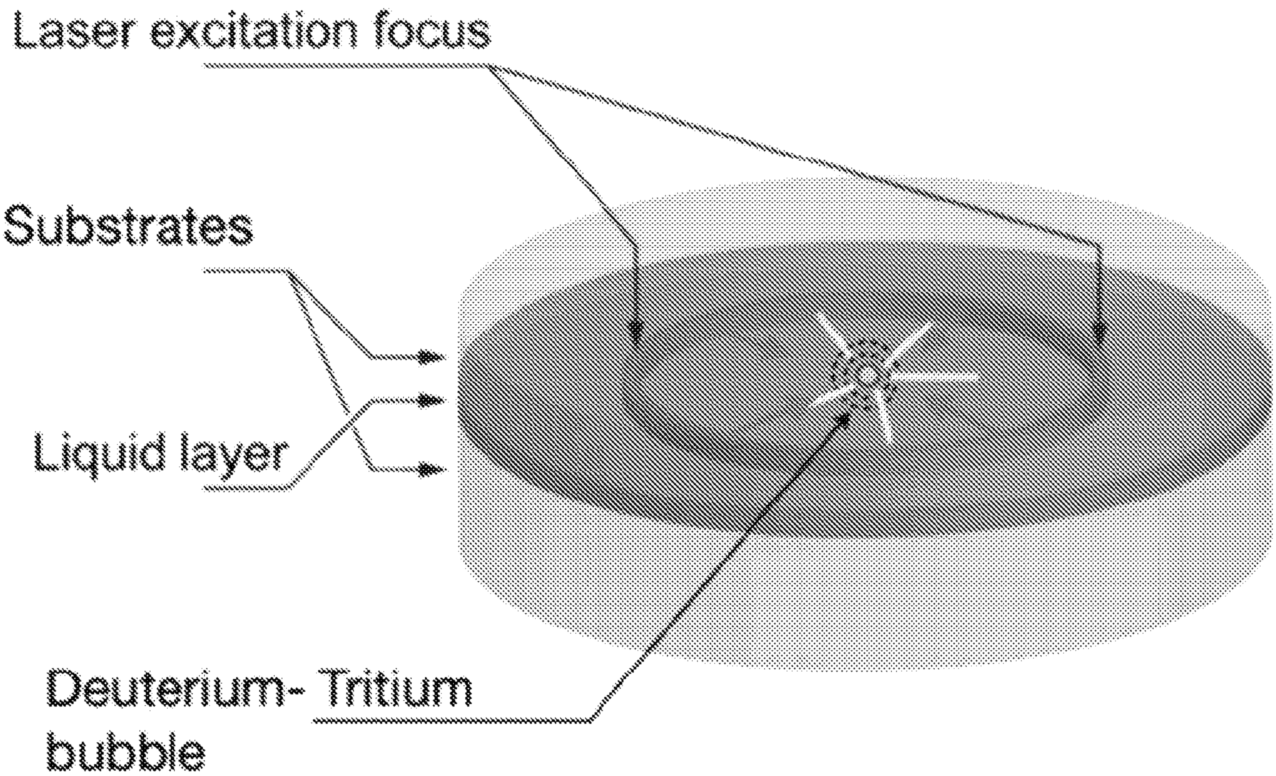
Laser excitation focus
Substrates
Liquid layer
Deuterium- Tritium bubble

FIG. 5

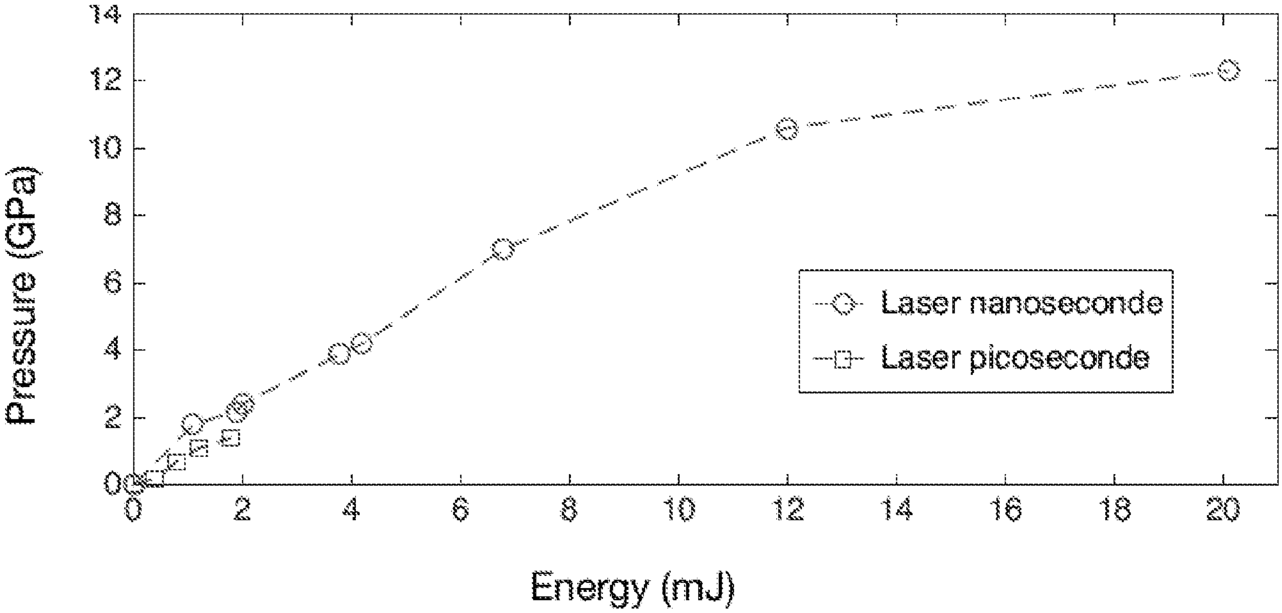
Pressure (GPa)
Energy (mJ)
Laser nanoseconde
Laser picoseconde
0
2
4
6
8
10
12
14
16
18
20

FIG. 6

Electronic Acknowledgement Receipt

EFS ID:	37433224
Application Number:	62913940
International Application Number:	
Confirmation Number:	2177
Title of Invention:	SYNCHRONOUS EXCITATION OF MULTIPLE SHOCK WAVES FOR FUSION
First Named Inventor/Applicant Name:	Keith Nelson
Customer Number:	19127
Filer:	Kristoffer W. Lange/Jillian Hafferty
Filer Authorized By:	Kristoffer W. Lange
Attorney Docket Number:	MIT-462PUSP/21869
Receipt Date:	11-OCT-2019
Filing Date:	
Time Stamp:	14:00:41
Application Type:	Provisional

Payment information:

Submitted with Payment	yes
Payment Type	DA
Payment was successfully received in RAM	$140
RAM confirmation Number	E20190AE00554908
Deposit Account	
Authorized User	

The Director of the USPTO is hereby authorized to charge indicated fees and credit any overpayment as follows:

File Listing:

Document Number	Document Description	File Name	File Size(Bytes)/ Message Digest	Multi Part /.zip	Pages (if appl.)
1	Provisional Cover Sheet (SB16)	TO_PTO_PROV_COVER_SHEET.pdf	1496228 7d5a87fa70d4b25f0419740dbba4ae90ef3b9ebc	no	3

Warnings:

Information:

Document Number	Document Description	File Name	File Size(Bytes)/ Message Digest	Multi Part /.zip	Pages (if appl.)
2	Application Data Sheet	TO_PTO_ADS.pdf	1337542 54a34272641c83b7c75d3ef6bd52b5099c6392f5	no	9

Warnings:

Information:

Document Number	Document Description	File Name	File Size(Bytes)/ Message Digest	Multi Part /.zip	Pages (if appl.)
3		TO_PTO_PROVISIONAL_PATENT_APPLN.pdf	7102380 50c258176f59205024f240816efb894832b5be39	yes	37

Multipart Description/PDF files in .zip description

Document Description	Start	End
Transmittal of New Application	1	1
Specification	2	11
Claims	12	13
Appendix to the Specification	14	37

Warnings:

Information:

Document Number	Document Description	File Name	File Size(Bytes)/ Message Digest	Multi Part /.zip	Pages (if appl.)
4	Drawings-only black and white line drawings	TO_PTO_DRAWINGS.pdf	1553833 54f0c690c70d6c0f9f5e843213eccb40632574d7	no	6

Warnings:

Information:

5	Fee Worksheet (SB06)	fee-info.pdf	29988 0d31310b228dbdb8e8028ef4d0964024419ec1db	no	2

Warnings:

Information:

Total Files Size (in bytes):	11519971

This Acknowledgement Receipt evidences receipt on the noted date by the USPTO of the indicated documents, characterized by the applicant, and including page counts, where applicable. It serves as evidence of receipt similar to a Post Card, as described in MPEP 503.

<u>New Applications Under 35 U.S.C. 111</u>
If a new application is being filed and the application includes the necessary components for a filing date (see 37 CFR 1.53(b)-(d) and MPEP 506), a Filing Receipt (37 CFR 1.54) will be issued in due course and the date shown on this Acknowledgement Receipt will establish the filing date of the application.
<u>National Stage of an International Application under 35 U.S.C. 371</u>
If a timely submission to enter the national stage of an international application is compliant with the conditions of 35 U.S.C. 371 and other applicable requirements a Form PCT/DO/EO/903 indicating acceptance of the application as a national stage submission under 35 U.S.C. 371 will be issued in addition to the Filing Receipt, in due course.
<u>New International Application Filed with the USPTO as a Receiving Office</u>
If a new international application is being filed and the international application includes the necessary components for an international filing date (see PCT Article 11 and MPEP 1810), a Notification of the International Application Number and of the International Filing Date (Form PCT/RO/105) will be issued in due course, subject to prescriptions concerning national security, and the date shown on this Acknowledgement Receipt will establish the international filing date of the application.

Provisional Application for Patent Cover Sheet

This is a request for filing a PROVISIONAL APPLICATION FOR PATENT under 37 CFR 1.53(c)

Inventor(s)

Inventor 1 — Remove

Given Name	Middle Name	Family Name	City	State	Country ¡
Keith		Nelson	Newton	MA	US

Inventor 2 — Remove

Given Name	Middle Name	Family Name	City	State	Country ¡
Steven		Kooi	Lexington	MA	US

Inventor 3 — Remove

Given Name	Middle Name	Family Name	City	State	Country ¡
Thomas		Pezeril	Le Mans		FR

All Inventors Must Be Listed – Additional Inventor Information blocks may be generated within this form by selecting the **Add** button. — Add

Title of Invention	SYNCHRONOUS EXCITATION OF MULTIPLE SHOCK WAVES FOR FUSION
Attorney Docket Number (if applicable)	MIT-462PUSP/21869

Correspondence Address

Direct all correspondence to (select one):

◉ The address corresponding to Customer Number	○ Firm or Individual Name
Customer Number	19127

The invention was made by an agency of the United States Government or under a contract with an agency of the United States Government.

- No.
- Yes, the invention was made by an agency of the United States Government. The U.S. Government agency name is:
- ● Yes, the invention was under a contract with an agency of the United States Government. The name of the U.S. Government agency and Government contract number are:

Army Research Office - Grant No. W911-NF-18-2-0048

Doc Code: **TR.PROV**
Document Description: Provisional Cover Sheet (SB16)

PTO/SB/16 (11-08)
Approved for use through 05/31/2015. OMB 0651-0032
U.S. Patent and Trademark Office: U.S. DEPARTMENT OF COMMERCE
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Entity Status
Applicant asserts small entity status under 37 CFR 1.27 or applicant certifies micro entity status under 37 CFR 1.29

- (◉) Applicant asserts small entity status under 37 CFR 1.27
- ( ) Applicant certifies micro entity status under 37 CFR 1.29. Applicant must attach form PTO/SB/15A or B or equivalent.
- ( ) No

Warning

Petitioner/applicant is cautioned to avoid submitting personal information in documents filed in a patent application that may contribute to identity theft. Personal information such as social security numbers, bank account numbers, or credit card numbers (other than a check or credit card authorization form PTO-2038 submitted for payment purposes) is never required by the USPTO to support a petition or an application. If this type of personal information is included in documents submitted to the USPTO, petitioners/applicants should consider redacting such personal information from the documents before submitting them to USPTO. Petitioner/applicant is advised that the record of a patent application is available to the public after publication of the application (unless a non-publication request in compliance with 37 CFR 1.213(a) is made in the application) or issuance of a patent. Furthermore, the record from an abandoned application may also be available to the public if the application is referenced in a published application or an issued patent (see 37 CFR1.14). Checks and credit card authorization forms PTO-2038 submitted for payment purposes are not retained in the application file and therefore are not publicly available.

Signature

Please see 37 CFR 1.4(d) for the form of the signature.

Signature	/Kris Lange/			Date (YYYY-MM-DD)	2019-10-11
First Name	Kris	Last Name	Lange	Registration Number (If appropriate)	68084

This collection of information is required by 37 CFR 1.51. The information is required to obtain or retain a benefit by the public which is to file (and by the USPTO to process) an application. Confidentiality is governed by 35 U.S.C. 122 and 37 CFR 1.11 and 1.14. This collection is estimated to take 8 hours to complete, including gathering, preparing, and submitting the completed application form to the USPTO. Time will vary depending upon the individual case. Any comments on the amount of time you require to complete this form and/or suggestions for reducing this burden, should be sent to the Chief Information Officer, U.S. Patent and Trademark Office, U.S. Department of Commerce, P.O. Box 1450, Alexandria, VA 22313-1450. DO NOT SEND FEES OR COMPLETED FORMS TO THIS ADDRESS. **This form can only be used when in conjunction with EFS-Web. If this form is mailed to the USPTO, it may cause delays in handling the provisional application.**

Privacy Act Statement

The Privacy Act of 1974 (P.L. 93-579) requires that you be given certain information in connection with your submission of the attached form related to a patent application or paten. Accordingly, pursuant to the requirements of the Act, please be advised that : (1) the general authority for the collection of this information is 35 U.S.C. 2(b)(2); (2) furnishing of the information solicited is voluntary; and (3) the principal purpose for which the information is used by the U.S. Patent and Trademark Office is to process and/or examine your submission related to a patent application or patent. If you do not furnish the requested information, the U.S. Patent and Trademark Office may not be able to process and/or examine your submission, which may result in termination of proceedings or abandonment of the application or expiration of the patent.

The information provided by you in this form will be subject to the following routine uses:

1. The information on this form will be treated confidentially to the extent allowed under the Freedom of Information Act (5 U.S.C. 552) and the Privacy Act (5 U.S.C 552a). Records from this system of records may be disclosed to the Department of Justice to determine whether disclosure of these records is required by the Freedom of Information Act.
2. A record from this system of records may be disclosed, as a routine use, in the course of presenting evidence to a court, magistrate, or administrative tribunal, including disclosures to opposing counsel in the course of settlement negotiations.
3. A record in this system of records may be disclosed, as a routine use, to a Member of Congress submitting a request involving an individual, to whom the record pertains, when the individual has requested assistance from the Member with respect to the subject matter of the record.
4. A record in this system of records may be disclosed, as a routine use, to a contractor of the Agency having need for the information in order to perform a contract. Recipients of information shall be required to comply with the requirements of the Privacy Act of 1974, as amended, pursuant to 5 U.S.C. 552a(m).
5. A record related to an International Application filed under the Patent Cooperation Treaty in this system of records may be disclosed, as a routine use, to the International Bureau of the World Intellectual Property Organization, pursuant to the Patent Cooperation Treaty.
6. A record in this system of records may be disclosed, as a routine use, t o a n other federal agency for purposes of National Security review (35 U.S.C. 181) and for review pursuant to the Atomic Energy Act (42 U.S.C. 218(c)).
7. A record from this system of records may be disclosed, as a routine use, to the Administrator, General Services, or his/her designee, during an inspection of records conducted by GSA as part of that agency's responsibility to recommend improvements in records management practices and programs, under authority of 44 U.S.C. 2904 and 2906. Such disclosure shall be made in accordance with the GSA regulations governing inspection of records for this purpose, and any other relevant (i.e., GSA or Commerce) directive. Such disclosure shall not be used to make determinations about individuals.
8. A record from this system of records may be disclosed, as a routine use, to the public after either publication of the application pursuant to 35 U.S.C. 122(b) or issuance of a patent pursuant to 35 U.S.C. 151. Further, a record may be disclosed, subject to the limitations of 37 CFR 1.14, as a routine use, to the public if the record was filed in an application which became abandoned or in which the proceedings were terminated and which application is referenced by either a published application, an application open to public inspection or an issued patent.
9. A record from this system of records may be disclosed, as a routine use, to a Federal, State, or local law enforcement agency, if the USPTO becomes aware of a violation or potential violation of law or regulation.

Application Data Sheet 37 CFR 1.76	Attorney Docket Number	MIT-462PUSP/21869
	Application Number	

Title of Invention	SYNCHRONOUS EXCITATION OF MULTIPLE SHOCK WAVES FOR FUSION

The application data sheet is part of the provisional or nonprovisional application for which it is being submitted. The following form contains the bibliographic data arranged in a format specified by the United States Patent and Trademark Office as outlined in 37 CFR 1.76.
This document may be completed electronically and submitted to the Office in electronic format using the Electronic Filing System (EFS) or the document may be printed and included in a paper filed application.

Secrecy Order 37 CFR 5.2:

☐ Portions or all of the application associated with this Application Data Sheet may fall under a Secrecy Order pursuant to 37 CFR 5.2 (Paper filers only. Applications that fall under Secrecy Order may not be filed electronically.)

Inventor Information:

Inventor 1 Remove

Legal Name

Prefix	Given Name	Middle Name	Family Name	Suffix
	Keith		Nelson	

Residence Information (Select One) ● US Residency ○ Non US Residency ○ Active US Military Service

City	Newton	State/Province	MA	Country of Residence	US

Mailing Address of Inventor:

Address 1	68 Sevland Road		
Address 2			
City	Newton	State/Province	MA
Postal Code	02459-2840	Country	US

Inventor 2 Remove

Legal Name

Prefix	Given Name	Middle Name	Family Name	Suffix
	Steven		Kooi	

Residence Information (Select One) ● US Residency ○ Non US Residency ○ Active US Military Service

City	Lexington	State/Province	MA	Country of Residence	US

Mailing Address of Inventor:

Address 1	14 Crescent Hill Avenue		
Address 2			
City	Lexington	State/Province	MA
Postal Code	02420	Country	US

Inventor 3 Remove

Legal Name

Prefix	Given Name	Middle Name	Family Name	Suffix
	Thomas		Pezeril	

Residence Information (Select One) ○ US Residency ● Non US Residency ○ Active US Military Service

Application Data Sheet 37 CFR 1.76	Attorney Docket Number	MIT-462PUSP/21869
	Application Number	
Title of Invention	SYNCHRONOUS EXCITATION OF MULTIPLE SHOCK WAVES FOR FUSION	

City	Le Mans	Country of Residence i	FR

Mailing Address of Inventor:

Address 1	8 rue Saint Flaceau		
Address 2			
City	Le Mans	**State/Province**	
Postal Code	72000	**Country** i	FR

All Inventors Must Be Listed - Additional Inventor Information blocks may be generated within this form by selecting the **Add** button. Add

Correspondence Information:

Enter either Customer Number or complete the Correspondence Information section below.
For further information see 37 CFR 1.33(a).

☐ **An Address is being provided for the correspondence Information of this application.**

Customer Number	19127
Email Address	docketing@dc-m.com

Add Email Remove Email

Application Information:

Title of the Invention	SYNCHRONOUS EXCITATION OF MULTIPLE SHOCK WAVES FOR FUSION		
Attorney Docket Number	MIT-462PUSP/21869	**Small Entity Status Claimed**	☒
Application Type	Provisional		
Subject Matter	Utility		
Total Number of Drawing Sheets (if any)	6	**Suggested Figure for Publication (if any)**	

Filing By Reference:

Only complete this section when filing an application by reference under 35 U.S.C. 111(c) and 37 CFR 1.57(a). Do not complete this section if application papers including a specification and any drawings are being filed. Any domestic benefit or foreign priority information must be provided in the appropriate section(s) below (i.e., "Domestic Benefit/National Stage Information" and "Foreign Priority Information").

For the purposes of a filing date under 37 CFR 1.53(b), the description and any drawings of the present application are replaced by this reference to the previously filed application, subject to conditions and requirements of 37 CFR 1.57(a).

Application number of the previously filed application	Filing date (YYYY-MM-DD)	Intellectual Property Authority or Country i

Application Data Sheet 37 CFR 1.76	Attorney Docket Number	MIT-462PUSP/21869
	Application Number	
Title of Invention	SYNCHRONOUS EXCITATION OF MULTIPLE SHOCK WAVES FOR FUSION	

Publication Information:

☐	Request Early Publication (Fee required at time of Request 37 CFR 1.219)
☐	**Request Not to Publish.** I hereby request that the attached application not be published under 35 U.S.C. 122(b) and certify that the invention disclosed in the attached application **has not and will not** be the subject of an application filed in another country, or under a multilateral international agreement, that requires publication at eighteen months after filing.

Representative Information:

Representative information should be provided for all practitioners having a power of attorney in the application. Providing this information in the Application Data Sheet does not constitute a power of attorney in the application (see 37 CFR 1.32).
Either enter Customer Number or complete the Representative Name section below. If both sections are completed the customer Number will be used for the Representative Information during processing.

Please Select One:	● Customer Number	US Patent Practitioner	◯ Limited Recognition (37 CFR 11.9)
Customer Number	19127		

Domestic Benefit/National Stage Information:

This section allows for the applicant to either claim benefit under 35 U.S.C. 119(e), 120, 121, 365(c), or 386(c) or indicate National Stage entry from a PCT application. Providing benefit claim information in the Application Data Sheet constitutes the specific reference required by 35 U.S.C. 119(e) or 120, and 37 CFR 1.78.
When referring to the current application, please leave the "Application Number" field blank.

Prior Application Status			Remove
Application Number	Continuity Type	Prior Application Number	Filing or 371(c) Date (YYYY-MM-DD)

Additional Domestic Benefit/National Stage Data may be generated within this form by selecting the **Add** button. Add

Foreign Priority Information:

This section allows for the applicant to claim priority to a foreign application. Providing this information in the application data sheet constitutes the claim for priority as required by 35 U.S.C. 119(b) and 37 CFR 1.55. When priority is claimed to a foreign application that is eligible for retrieval under the priority document exchange program (PDX)[i] the information will be used by the Office to automatically attempt retrieval pursuant to 37 CFR 1.55(i)(1) and (2). Under the PDX program, applicant bears the ultimate responsibility for ensuring that a copy of the foreign application is received by the Office from the participating foreign intellectual property office, or a certified copy of the foreign priority application is filed, within the time period specified in 37 CFR 1.55(g)(1).

Application Data Sheet 37 CFR 1.76	Attorney Docket Number	MIT-462PUSP/21869
	Application Number	
Title of Invention	SYNCHRONOUS EXCITATION OF MULTIPLE SHOCK WAVES FOR FUSION	

Remove

Application Number	Country[i]	Filing Date (YYYY-MM-DD)	Access Code[i] (if applicable)

Additional Foreign Priority Data may be generated within this form by selecting the **Add** button. Add

Statement under 37 CFR 1.55 or 1.78 for AIA (First Inventor to File) Transition Applications

☐ This application (1) claims priority to or the benefit of an application filed before March 16, 2013 and (2) also contains, or contained at any time, a claim to a claimed invention that has an effective filing date on or after March 16, 2013.
NOTE: By providing this statement under 37 CFR 1.55 or 1.78, this application, with a filing date on or after March 16, 2013, will be examined under the first inventor to file provisions of the AIA.

Application Data Sheet 37 CFR 1.76	Attorney Docket Number	MIT-462PUSP/21869
	Application Number	
Title of Invention	SYNCHRONOUS EXCITATION OF MULTIPLE SHOCK WAVES FOR FUSION	

Authorization or Opt-Out of Authorization to Permit Access:

When this Application Data Sheet is properly signed and filed with the application, applicant has provided written authority to permit a participating foreign intellectual property (IP) office access to the instant application-as-filed (see paragraph A in subsection 1 below) and the European Patent Office (EPO) access to any search results from the instant application (see paragraph B in subsection 1 below).

Should applicant choose not to provide an authorization identified in subsection 1 below, applicant **must opt-out** of the authorization by checking the corresponding box A or B or both in subsection 2 below.

NOTE: This section of the Application Data Sheet is **ONLY** reviewed and processed with the **INITIAL** filing of an application. After the initial filing of an application, an Application Data Sheet cannot be used to provide or rescind authorization for access by a foreign IP office(s). Instead, Form PTO/SB/39 or PTO/SB/69 must be used as appropriate.

1. Authorization to Permit Access by a Foreign Intellectual Property Office(s)

A. Priority Document Exchange (PDX) - Unless box A in subsection 2 (opt-out of authorization) is checked, the undersigned hereby **grants the USPTO authority** to provide the European Patent Office (EPO), the Japan Patent Office (JPO), the Korean Intellectual Property Office (KIPO), the State Intellectual Property Office of the People's Republic of China (SIPO), the World Intellectual Property Organization (WIPO), and any other foreign intellectual property office participating with the USPTO in a bilateral or multilateral priority document exchange agreement in which a foreign application claiming priority to the instant patent application is filed, access to: (1) the instant patent application-as-filed and its related bibliographic data, (2) any foreign or domestic application to which priority or benefit is claimed by the instant application and its related bibliographic data, and (3) the date of filing of this Authorization. See 37 CFR 1.14(h)(1).

B. Search Results from U.S. Application to EPO - Unless box B in subsection 2 (opt-out of authorization) is checked, the undersigned hereby **grants the USPTO authority** to provide the EPO access to the bibliographic data and search results from the instant patent application when a European patent application claiming priority to the instant patent application is filed. See 37 CFR 1.14(h)(2).

The applicant is reminded that the EPO's Rule 141(1) EPC (European Patent Convention) requires applicants to submit a copy of search results from the instant application without delay in a European patent application that claims priority to the instant application.

2. Opt-Out of Authorizations to Permit Access by a Foreign Intellectual Property Office(s)

☐ A. Applicant **DOES NOT** authorize the USPTO to permit a participating foreign IP office access to the instant application-as-filed. If this box is checked, the USPTO will not be providing a participating foreign IP office with any documents and information identified in subsection 1A above.

☐ B. Applicant **DOES NOT** authorize the USPTO to transmit to the EPO any search results from the instant patent application. If this box is checked, the USPTO will not be providing the EPO with search results from the instant application.

NOTE: Once the application has published or is otherwise publicly available, the USPTO may provide access to the application in accordance with 37 CFR 1.14.

Application Data Sheet 37 CFR 1.76	Attorney Docket Number	MIT-462PUSP/21869
	Application Number	
Title of Invention	SYNCHRONOUS EXCITATION OF MULTIPLE SHOCK WAVES FOR FUSION	

Applicant Information:

Providing assignment information in this section does not substitute for compliance with any requirement of part 3 of Title 37 of CFR to have an assignment recorded by the Office.

Applicant 1 — Remove

If the applicant is the inventor (or the remaining joint inventor or inventors under 37 CFR 1.45), this section should not be completed. The information to be provided in this section is the name and address of the legal representative who is the applicant under 37 CFR 1.43; or the name and address of the assignee, person to whom the inventor is under an obligation to assign the invention, or person who otherwise shows sufficient proprietary interest in the matter who is the applicant under 37 CFR 1.46. If the applicant is an applicant under 37 CFR 1.46 (assignee, person to whom the inventor is obligated to assign, or person who otherwise shows sufficient proprietary interest) together with one or more joint inventors, then the joint inventor or inventors who are also the applicant should be identified in this section. Clear

● Assignee	Legal Representative under 35 U.S.C. 117	Joint Inventor
Person to whom the inventor is obligated to assign.	Person who shows sufficient proprietary interest	

If applicant is the legal representative, indicate the authority to file the patent application, the inventor is:

Name of the Deceased or Legally Incapacitated Inventor:

If the Applicant is an Organization check here. ☐

Prefix	**Given Name**	Middle Name	**Family Name**	Suffix

Mailing Address Information For Applicant:

Address 1			
Address 2			
City		**State/Province**	
Country		Postal Code	
Phone Number		Fax Number	
Email Address			

Additional Applicant Data may be generated within this form by selecting the Add button. Add

Assignee Information including Non-Applicant Assignee Information:

Providing assignment information in this section does not substitute for compliance with any requirement of part 3 of Title 37 of CFR to have an assignment recorded by the Office.

Application Data Sheet 37 CFR 1.76	Attorney Docket Number	MIT-462PUSP/21869
	Application Number	
Title of Invention	SYNCHRONOUS EXCITATION OF MULTIPLE SHOCK WAVES FOR FUSION	

Assignee 1

Complete this section if assignee information, including non-applicant assignee information, is desired to be included on the patent application publication. An assignee-applicant identified in the "Applicant Information" section will appear on the patent application publication as an applicant. For an assignee-applicant, complete this section only if identification as an assignee is also desired on the patent application publication.

Remove

If the Assignee or Non-Applicant Assignee is an Organization check here. ☐

Prefix	**Given Name**	Middle Name	**Family Name**	Suffix

Mailing Address Information For Assignee including Non-Applicant Assignee:

Address 1			
Address 2			
City		**State/Province**	
Country i		Postal Code	
Phone Number		Fax Number	
Email Address			

Additional Assignee or Non-Applicant Assignee Data may be generated within this form by selecting the Add button. Add

Signature:

Remove

NOTE: This Application Data Sheet must be signed in accordance with 37 CFR 1.33(b). **However, if this Application Data Sheet is submitted with the <u>INITIAL</u> filing of the application <u>and</u> either box A or B is <u>not</u> checked in subsection 2 of the "Authorization or Opt-Out of Authorization to Permit Access" section, then this form must also be signed in accordance with 37 CFR 1.14(c).**

This Application Data Sheet **must** be signed by a patent practitioner if one or more of the applicants is a **juristic entity** (e.g., corporation or association). If the applicant is two or more joint inventors, this form must be signed by a patent practitioner, **all** joint inventors who are the applicant, or one or more joint inventor-applicants who have been given power of attorney (e.g., see USPTO Form PTO/AIA/81) on behalf of **all** joint inventor-applicants.

See 37 CFR 1.4(d) for the manner of making signatures and certifications.

Signature	/Kris Lange/			Date (YYYY-MM-DD)	2019-10-11
First Name	Kris	Last Name	Lange	Registration Number	68084

Additional Signature may be generated within this form by selecting the Add button. Add

Application Data Sheet 37 CFR 1.76	Attorney Docket Number	MIT-462PUSP/21869
	Application Number	
Title of Invention	SYNCHRONOUS EXCITATION OF MULTIPLE SHOCK WAVES FOR FUSION	

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UNITED STATES PROVISIONAL PATENT APPLICATION

of

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for

SYNCHRONOUS EXCITATION OF MULTIPLE SHOCK WAVES FOR FUSION

U.S. Patent and Trademark Office
Customer Number 19127

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SYNCHRONOUS EXCITATION OF MULTIPLE SHOCK WAVES FOR FUSION

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH

[0001] This invention was made with Government support under Grant No. W911-NF-18-2-0048 awarded by the Army Research Office (ARO). The Government has certain rights in the invention.

BACKGROUND

[0002] As is known in the art, hundreds of billions of dollars have been spent on research and development of fusion ignition, a potential source of clean energy. Existing fusion ignition research has generally focused on two approaches: using lasers or with magnetic confinement. Existing research into laser-based fusion initiation has focused on the design and construction of lasers that produce megajoule pulse energy. While experiments have shown that the fusion process can be achieved with a fusion energy output twice the peak kinetic energy of the imploding shell, the concept is far away from being energy efficient. The energy needed to power such a laser facility may be much larger than the fusion energy output. Likewise, research into magnetic confinement-based fusion has so far failed to achieve useful net energy gain. Presently, there are no indications that these approaches will be practical for achieving fusion-based clean energy.

SUMMARY

[0003] According to one aspect of the present disclosure, a method to excite shock waves in a sample can include (a) splitting a pulsed laser beam into a plurality of pulsed laser beams; (b) spatially shaping the plurality of pulsed laser beams into a set of concentric pulsed laser rings of different predetermined diameters; and (c) controlling time intervals between ring-shaped laser pulses so as to match a propagation time in the sample of ring-shaped laser shock waves from one ring to the next.

BRIEF DESCRIPTION OF THE DRAWINGS

[0004] Various objectives, features, and advantages of the disclosed subject matter can be more fully appreciated with reference to the following detailed description of the disclosed subject matter when considered in connection with the following drawings, in which like reference numerals identify like elements.

[0005] FIG. 1 is a block diagram of a system for fusion ignition, according to some embodiments of the present disclosure.

[0006] FIG. 2A is a pictorial diagram of a multiple-laser configuration for shock wave excitation in a fusion ignition system, according to some embodiments of the present disclosure.

[0007] FIG. 2B is a graphical diagram showing an example of shock build-up using the multiple-laser configuration of FIG. 2A.

[0008] FIG. 3A is a pictorial diagram showing another multiple-laser configuration for shock wave excitation in a fusion ignition system, according to some embodiments of the present disclosure.

[0009] FIG. 3B is a plot showing an example of shock build-up using the multiple-laser configuration of FIG. 3A.

[0010] FIG. 4A is a pictorial diagram showing how multiple laser beams (or “sub-beams”) shaped as rings of different sizes can be focused along the surface of a sample, according to some embodiments of the present disclosure.

[0011] FIG. 4B is a pictorial diagram showing how the multiple sub-beams can produce a shock in the sample, according to some embodiments of the present disclosure.

[0012] FIG. 5 is a schematic diagram showing laser shock excitation in a target, in the case of a single excitation laser ring, according to some embodiments of the present disclosure.

[0013] FIG. 6 is a plot showing measured shock pressures in a sample versus excitation laser pulse energy, according to some embodiments of the present disclosure.

[0014] The drawings are not necessarily to scale, or inclusive of all elements of a system, emphasis instead generally being placed upon illustrating the concepts, structures, and techniques sought to be protected herein.

DETAILED DESCRIPTION

[0015] Disclosed herein are systems, structures, and techniques to efficiently excite multiple shock waves in a sample, allowing the sample to reach the pressure and temperature conditions required for thermonuclear fusion.

[0016] Referring to FIG. 1, a system 100 for fusion ignition can include one or more laser sources 102, a spatio-temporal splitting system 104, one or more shaping elements 106, and a sample (or “shock focus”) 108. In some embodiments, the system 100 can further include additional stimuli 110, such as a laser shock, laser pulses, or an AC acoustic field. A laser source 102 can generate a high-energy laser beam or pulse that can be split into multiple beams via spatio-temporal splitting system 104. By operation of shaping elements 106 and possibly using additional stimuli 110, multiple shock waves can be optically excited at specifically chosen locations and at controlled delay times to converge shock (in two-dimensions or three-dimensions) in a fusion sample 108. Using the structures and techniques described herein below, the system can operate to produce fusion 120.

[0017] The spatio-temporal control of the laser excitation of phase-matched shock waves can be based on any of a variety of opto-mechanical designs. As illustrated in FIG. 2A, in some embodiments, the beams may be spatially shaped (e.g., using shaping elements 106) into a set of concentric rings of different predetermined diameters, with the time intervals between pulses in different rings controlled to match the propagation time of the laser shock waves from one ring to the next. This can be done in order to fulfill the acoustic phase matching conditions for coherent excitation and build-up of a primary shock wave travelling toward the center of the rings where focusing takes place. The sample of interest can be provided as a thin layer (e.g., less than 1 mm thick or less than 0.1 mm thick), and the shock propagation will be within the plane of the sample, converging toward the focal region.

[0018] For example, referring to FIG. 2A, an apparatus can incorporate the free-space angular-chirp-enhanced delay (FACED) device described in J.-L. Wu et al., Light: Science & Applications 6, 16196 (2017), which publication is hereby incorporated by reference in its entirety. The opto-mechanical device can use multiple reflections between two non-parallel reflectors to produce an optical array of stripes or lines in the focal plane of a lens, with a controllable and well-defined inter-line spacing and with a controllable incremental delay time between successive stripes or lines, and an optical phase mask can be designed to transform the stripes onto concentric rings of different diameters. The optical phase mask can be a fixed imprinted pattern on a substrate or a reconfigurable spatial light modulator (SLM).

[0019] Another example of such an opto-mechanical device would be an optical cavity merging a Herriott multipass cavity and the opto-mechanical device (e.g., a FACED device) that would, in conjunction with an axicon (conical prism) and a focusing lens, produce concentric rings of different diameters on the sample surface. The main point of the optical ring configuration is to acoustically focus the shock energy of the laser-excited phase-matched shock waves at the center of the rings, in a similar manner to that demonstrated in the following publications, each of which is hereby incorporated by reference in its entirety.

- D. Veysset, S. E. Kooi, R. Haferssas, M. Hassani-Gangaraj, M. Islam, A. Maznev, Y. Chernukha, X. Zhao, K. Nakagawa, D. Martynowich, X. Zhang, A. Lomonosov, C. Schuh, R. Radovitzky, T. Pezeril, Keith A. Nelson, Scr. Mater. 158, 42 (2019).

- D. Veysset, U. Gutiérez-Hernandez, L. Dresselhaus-Cooper, F. De Colle, S. Kooi, K. A. Nelson, P. A. Quinto-Su, T. Pezeril, Phys. Rev. E 97, 053112 (2018).

- D. Veysset, A. Maznev, István A. Veres, T. Pezeril, S. Kooi, Alexey M. Lomonosov, Keith A. Nelson, Appl. Phys. Lett. 111, 031901 (2017).

- D. Veysset, A. Maznev, T. Pezeril, S. Kooi, Keith A. Nelson, Scientific Reports 6, 24 (2016).

- D. Veysset, T. Pezeril, S. Kooi, A. Bulou, Keith A. Nelson, Appl. Phys. Lett. 106, 161902 (2015).

- T. Pezeril, G. Saini, D. Veysset, S. Kooi, P. Fidkowski, R. Radovitzky, Keith A. Nelson, Phys. Rev. Lett. 106, 214503 (2011).

[0020] In contrast to the aforementioned publications, embodiments of the present disclosure can use multiple concentric excitation rings instead of just one excitation ring. This acoustic focusing at the center of the rings, in conjunction with the acoustic-phase matching approach, is expected to create giant pressures and temperatures conditions at the center of the rings, that would yield measurable amounts of thermonuclear fusion. Some other applications of the high pressures and temperatures reached would be possible as well, for example fabrication of materials or samples that require such pressures and/or temperatures.

[0021] As shown in FIG. 2A, several laser beams shaped as rings of different sizes are focused along the surface of a sample. Each of these excitation rings produces an independent shock wave that travels toward the center of the rings. The timing of the pulses in the excitation rings can be controlled to fulfill the acoustic phase-matching conditions such that all the shock waves overlap in time and space. FIG. 2B illustrates how acoustic phase-matching conditions allow a build-up of the shock amplitude as it propagates toward the center of the rings where it focuses.

[0022] FIG. 3A shows an alternative technique for achieving acoustic focusing of the phase-matched multishocks that does not require optically converting stripes into rings. For instance, multiple parallel excitation line sources on the sample surface, rather than rings, could be used with timing to allow acoustic phase-matching in order to excite a line-shaped shock wave propagating along the sample surface. A curved element incorporated into the sample layer could be used as a reflective or transmissive acoustic lens which would focus the linear shock wave to a small focal region. As illustrated in FIG. 3A, several laser beams shaped as lines can be optically focused along the surface of a sample with appropriate spatial-temporal timing that fulfill the acoustic-phase matching conditions. An acoustic lens may be placed along the pathway of the line-shaped shock wave to acoustically focus the shock energy on the sample surface. FIG. 3B shows shock build-up that may occur using the laser beam configuration of FIG. 3A. While certain embodiments may be described herein with reference to excitation rings, it should be understood that in each case other excitation geometries are possible.

[0023] Since shock waves are non-linear ultrasonic waves whose speeds increase with pressure, the main shock wave that builds up during propagation toward the center will increase in speed as it gets closer to the center. Therefore, in order to achieve an efficient build-up of the main shock wave, either the time delay or the spacing between each excitation ring source has to be tuned in order to match the variation of the shock speed toward the center. In general, this would mean that the spacing or the time delay between successive rings on the sample surface should not be constant. There are several technical possibilities to fulfill this requirement. For instance, the optical phase mask used to convert the array of lines, with constant inter-line spacing from the opto-mechanical device, into concentric rings could be designed such that it would lead to concentric rings with non-constant inter-ring spacings that would match the variation of the shock speed along the sample surface. Another possibility would be to modify the opto-mechanical device to directly output an array of lines with non-constant inter-line spacings that would match the variation of the shock speed. This could be achieved by replacing one of the large opto-mechanical device reflectors with multiple small reflectors whose positions and reflection angles can be adjusted, or by a deformable mirror. One more possibility would be to insert optical elements inside or outside the opto-mechanical device cavity in order to temporally delay the pulses that pass through them, in order to obtain a non-constant time delay between lines or stripes. One or more of these approaches could be used to control the inter-line spacing and timing as required.

[0024] The present disclosure allows efficient laser excitation of phase-matched multishocks to obtain a main shock wave that focuses in the plane of a sample. The resulting 2D focusing of the phase-matched multishocks is expected to yield the extreme pressures and temperatures required for thermonuclear fusion. In contrast to the laser-based fusion experiments performed at the National Ignition Facility or elsewhere, in which multiple laser beams are focused on the opaque surface of a target sphere in order to focus in three dimensions (3D) a shock wave at the center of the sphere, our technique has the advantage that the sample through which the in-plane shock propagates is optically accessible and can be exposed to further shock excitation with multiple laser beams. Therefore, the multishock technique described herein can circumvent the problems of plateauing of the shock pressure that drastically decreases the benefit of the 3D focusing in case of a spherical opaque target. In addition, our disclosure allows additional shock focusing or shock propagation beyond a planar shock geometry. For example coincident with the arrival of the planar shock at the focal region, through-plane shocks could be launched from above and below the focal region to increase the overall shock pressure, as shown schematically in FIG. 4A. The through-plane shocks could be launched by intense laser pulses that irradiate absorbing layers on the insides of the substrates surrounding the shock propagation medium, with the sample that would undergo fusion pre- positioned at the planar shock focus in between the two absorbing layers. Thus the fusion sample could be subjected to both the focusing in-plane shock and the through-plane shocks, increasing the total pressure and temperature. In a different embodiment, the intense laser pulses from above and below could irradiate the fusion sample itself, or a thin absorbing containment vessel for the fusion sample, rather than absorbing layers on the substrates. The sample could be excited this way prior to or during planar shock focusing. In some configurations, it may be possible to laser-excite the sample with intense light in any frequency range from far-infrared (terahertz frequency range) to x-rays. Another possibility for more than 2D planar shock focusing would be to use curved or tapered substrates instead of flat parallel substrates, such that the thickness of the shock propagation medium is decreased as the shock focal region is approached. In this way, the propagating in-plane shock wave would be more and more confined in the through-plane dimension while approaching the shock focus, such as illustrated in FIG. 4B.

[0025] Many different sample configurations for fusion can be tested with the multishock systems and techniques disclosed herein. For the shock-induced fusion process, samples made of a mixture of Deuterium and Tritium are likely to produce the highest net energy gain during the fusion process. Samples of this type could take various forms including the following.

- Liquid thin film of heavy water with a Deuterium-Tritium bubble trapped at the center of the laser rings.
- Frozen thin film of heavy water with a Deuterium-Tritium bubble trapped at the center of the laser rings.
- Liquid thin film of Deuterium-Tritium.
- Solid thin film Deuterium-Tritium.

[0026] Since Deuterium alone can produce fusion, the Deuterium-Tritium mixture can be replaced by pure Deuterium which is a less hazardous material.

[0027] FIG. 5 is a schematic illustration of the laser shock excitation in a target, in the case of a single excitation laser ring. The laser target can be a multilayer sample assembly in which a thin shock propagation layer (which could be liquid, polymer, or other material type) is sandwiched between two solid samples. A Deuterium-Tritium bubble or droplet can be placed at the center of shock focus for fusion ignition. The bubble or droplet can be trapped in a resonant acoustic field, similarly to sonoluminescence experiments.

[0028] Considering the extreme temperature and pressure conditions needed for thermonuclear fusion, the sample will be irreversibly damaged after each laser shot. The energy released during the fusion process can be collected via the emission of high-energy neutrons escaping from the fusion core at the center of the laser rings. The characteristic dimensions of the excitation laser rings that launch the shocks are likely to be hundreds or tens of micrometers in diameter. The damaged sample area will be of the same order in size. There are many possibilities to run the thermonuclear fusion far larger, and rastering of the sample can be performed. After each laser shot, the sample can be moved to a non-damaged area and the thermonuclear fusion can be initiated again to produce high-energy neutrons from a fresh area. An alternative would be to fabricate many smaller samples (perhaps millimeter dimensions) such as the one illustrated in FIG. 5 and to use a new sample for each laser shot.

[0029] One advantage of the structures and techniques disclosed herein is that the laser energy is split into many laser sources. Each of these laser sources efficiently excites a phase-matched shock wave to produce extreme total pressure and temperature, circumventing the plateauing of the shock pressure due to lack of full absorption of the laser energy. This plateau effect is one of the main problems related to laser-based shock fusion ignition where the formation of plasma drastically alters the efficiency of the shock the excitation. In laser-based inertial confinement fusion experiments, most of the energy is reflected by the plasma and only a small portion of the laser energy couples to the excitation of shock waves. The present disclosures addresses the problems of plateauing, and opens the way to orders of magnitude higher efficiency for shock excitation.

[0030] FIG. 6 shows the type of plateauing that can occur when high laser pulse energies are used to excite a sample. Measured shock pressures at 15 nanoseconds time delay in a water sample sandwiched between two glass substrates, plotted versus excitation laser pulse energy from a nanosecond or picosecond duration single pulse laser pulse focused to a 100-micron diameter ring at the sample. The efficiency of the laser shock excitation from a single laser pulse does not scale linearly with laser energy and tends to saturate at increasing energies, reaching a plateau. The technique disclosed herein solve this problem encountered in laser-based inertial confinement fusion experiments.

[0031] One application of present disclosure is thermonuclear fusion for the production of energy. Other applications include the production of high pressures and high temperatures for the characterization or synthesis of materials under extreme conditions which can be attractive for many research and development entities. Research on microscale shock waves based on relatively low-cost lasers can be conducted in many laboratories without the use of a gas gun or dangerous explosives. The technique is rather simple and affordable for many institutions. It is not based on customized and expensive lasers. It does not require access to specialized laser facilities. The device would fit in an ordinary research laboratory.

[0032] Furthermore, the fact that the fusion will be downscaled to micro-samples can profoundly alter the present energy infrastructure scheme. Large-scale power plants may not be needed any more. It could be envisioned that many small devices such as the one described herein could operate close the customer's needs (district, building, house, etc.). This will solve the problems of electric transportation losses from the power plant to the customers.

[0033] Once successful and optimized, the multishock apparatus will be easily replicated and ready for industrial production worldwide. Indeed, the pulsed lasers needed for the multishock technique are based on the most energy efficient pulsed lasers, Nd:YAG Lasers, commercially available at a relatively low cost. All the parts of the apparatus are commercially available and can be mass produced.

[0034] It is to be understood that the disclosed subject matter is not limited in its application to the details of construction and to the arrangements of the components set forth in the following description or illustrated in the drawings. The disclosed subject matter is capable of other embodiments and of being practiced and carried out in various ways. Also, it is to be understood that the phraseology and terminology employed herein are for the purpose of description and should not be regarded as limiting. As such, those skilled in the art will appreciate that the conception, upon which this disclosure is based, may readily be utilized as a basis for the designing of other structures, methods, and systems for carrying out the several purposes of the disclosed subject matter. Therefore, the claims should be regarded as including such equivalent constructions insofar as they do not depart from the spirit and scope of the disclosed subject matter.

[0035] Although the disclosed subject matter has been described and illustrated in the foregoing exemplary embodiments, it is understood that the present disclosure has been made only by way of example, and that numerous changes in the details of implementation of the disclosed subject matter may be made without departing from the spirit and scope of the disclosed subject matter.

[0036] What is claimed is: