Applied Physics Letters

Production of high fluence laser beams using ion wave plasma optics

Cite as: Appl. Phys. Lett. **120**, 200501 (2022); https://doi.org/10.1063/5.0086068
Submitted: 21 January 2022 • Accepted: 07 April 2022 • Published Online: 17 May 2022

R. K. Kirkwood, P. L. Poole, D. H. Kalantar, et al.

ARTICLES YOU MAY BE INTERESTED IN

AIP Publishing

Applied Physics Letters PERSPECTIVE scitation.org/journal/apl

Production of high fluence laser beams using ion wave plasma optics

Cite as: Appl. Phys. Lett. **120**, 200501 (2022); doi: 10.1063/5.0086068
Submitted: 21 January 2022 · Accepted: 7 April 2022 ·
Published Online: 17 May 2022

R. K. Kirkwood,[1,a)] P. L. Poole,[1] D. H. Kalantar,[1] T. D. Chapman,[1] S. C. Wilks,[1] M. R. Edwards,[1] D. P. Turnbull,[2] P. Michel,[1] L. Divol,[1] N. J. Fisch,[3] P. Norreys,[4] W. Rozmus,[5] J. Bude,[1] B. E. Blue,[1] K. B. Fournier,[1] B. M. Van Wonterghem,[1] and A. MacKinnon[1]

AFFILIATIONS

[1]Lawrence Livermore National Laboratory, P.O. Box 808, Livermore CA 94551, USA
[2]Laboratory for Laser Energetics, University of Rochester, 250 E. River Rd., Rochester, New York 14623-1299, USA
[3]Department of Astrophysical Sciences, Princeton University, Princeton, New Jersey 08540, USA
[4]Department of Physics, University of Oxford, Oxford OX1 2JD, United Kingdom
[5]Department of Physics, University of Alberta, 116 St & 85 Ave, Edmonton, Alberta T6G 2R3, Canada

[a)]Author to whom correspondence should be addressed: kirkwood1@llnl.gov

ABSTRACT

Optical components for laser beams with high peak and averaged powers are being developed worldwide using stimulated plasma scattering that occurs when plasmas interact with intense, coherent light. After decades of pursuit of pulse compressors, mirrors, and other plasma based components that can be created by stimulated scattering from electron density perturbations forming on ultra-short time scales (e.g., via Stimulated Raman Scattering), more recent work has produced optical components on longer time scales allowing ion motion as well [via Stimulated Brillouin Scattering (SBS)]. In the most recent work, ion wave plasma optics have had success in producing pulses of focusable coherent light with high energy and fluence by operating on ns time scales and now promise to enable numerous applications. Experiments have further shown that in some parameter regimes, even simple plasma response models can describe the output of such optics with sufficient accuracy that they can be used as engineering tools to design plasma optics for future applications, as is already being done to control power deposition in fusion targets. In addition, the development of more sophisticated models promises to enable still higher performance from SBS driven plasma optical components under a wider range of conditions. The present status and most promising directions for future development of ion wave plasma optic techniques are discussed here.

Overview

Plasma based optical components that are expected to produce extreme optical intensity and power have been under development for decades, not only through Raman backscattering[1–8] but also through Brillouin backscattering,[9–15] because of the potential of a plasma to provide precise control of the spatial profile and pulse shape of an optical beam at extreme peak and average power density, without suffering damage to the component. Presently, most implementations and designs of lasers that produce the extreme intensities and fluences needed for a range of applications use conventional optical materials and need to have their output performance limited to avoid damage to those materials.[16–24] As a result, replacing the most damage-sensitive components in future laser systems with plasma optics may advance many applications including high energy density science studies, sources of energetic particles and photons, and fusion energy. However, because the plasma optics will likely need to operate at close to the most extreme conditions in the beam, full scale tests of component are often not available until the rest of the system is constructed. As a result, reliable models of the plasma response to laser beams are needed before it will be possible to confidently propose and design future facilities which have their performance enhanced by plasma based optics. The numerical modeling of plasma optics that use electron plasma waves and stimulated Raman scattering on fs time scales has progressed from fluid models[25,26] to early PIC calculations,[27] to modern particle in cell based computational models[28–30] in a series of steps with increasing sophistication. However, even more detailed experimental validation of these models will be needed to design such plasma optics with confidence for future large laser facilities.[4] More recently, using Brillouin coupling, work has also progressed on plasma optic devices operating on sub-ps time scales by using plasma ion waves that are strongly coupled to the intense beams that drive them, allowing them to create pulses with durations comparable to the wave frequency.[31,32] This work has shown success in modeling ion wave plasma optics on such time scales using simulations that describe collisionless plasmas and which are now validated by experimental results in important regimes[30] for applications,[33,34] giving confidence for predictive modeling of ion wave optics in a wider range of conditions.

An important advancement in our confidence in the concepts and models of plasma optics that operate on the still longer multi-ps to ns time scales needed to create and control beams with much higher fluence and energy in the pulse came recently from studies in the inertial confinement fusion (ICF) program, where multiple laser beams with optical pulses of durations >1 ns were used to deliver unprecedented fluence and energy densities to targets containing fuel for fusion reactions. The work has been done largely at the National Ignition Facility (NIF),[17] which was designed with the goal of creating and studying ignition and thermonuclear burn in the laboratory.[35] In the early theoretical studies for the NIF facility, it was recognized that scattering cells would likely be created in the plasmas in the fusion targets on time scales long enough for ion waves to form and persist in the presence of binary particle collisions, and could potentially redirect significant laser power and energy, due to seeding the Stimulated Brillouin Scattering (SBS) of one beam when crossed by another.[36,37] The resulting interaction, Cross Beam Energy Transfer (CBET), was further expected to be controlled by small adjustments to the wavelengths of the crossing beams that would be near resonance for ion waves propagating in the plasma formed in the interaction volume.[37] Multi-beam SBS and CBET were also confirmed in a series of early experiments done on the smaller laser facilities that existed at the time,[38–42] where it was found that the short scale lengths of the plasmas produced therein pushed the ion wave amplitudes needed for efficient power transfer into the non-linear regime in which processes such as particle trapping in the presence of binary collisions modified the linear wave responses.[41] Although the prior understanding of CBET was sufficient that NIF was constructed with the capability to adjust the laser wavelengths to control it, it was only when the first NIF experiments commenced that efficient CBET and its dominant effect on power flow in a fusion target with large scale plasmas[41] was confirmed.[43] In fact, the adjustment of efficient CBET via wavelength tuning of the incident beams was found to be reliable and precise enough that it became a primary means to control the critical symmetry of the imploded fusion fuel in many fusion experiments at NIF,[43] and was soon used to generate the first implosions with sufficient yield to allow investigations into the effects of the self-heating mechanism essential for ignition[44] and subsequently has been used in fusion experiments including those that have produced the highest laser-fusion yield to date.[45] The most recent results from experiments to maximize fusion energy are continuing to provide validation for CBET modeling techniques, as was recently demonstrated in experimental observations confirming that the power deposition profile is well described by linear ion wave models of CBET in the case where the greatest fusion energy yield has been obtained.[45–47]

While the success of using controlled CBET to produce the desired power deposition in the fusion energy studies brought attention and confidence to ideas of creating optical elements out of plasma material for use with the high fluence and energy available on time scales >1 ns, those same experiments have also provided additional benchmarks of the theory of CBET produced by linear ion waves in plasmas under certain conditions[43,45–47] as well as clear evidence that non-linear wave effects become important and are difficult to model in others.[48] All of this then motivated experiments to accurately validate such models using smaller lasers[49] that can operate in these regimes. CBET in fusion experiments continues to be the subject of theoretical and computational research,[50–57] and a comprehensive model of power flow in the range of conditions in the fusion experiments is presently being developed and validated.[57] In addition, the NIF laser has also been a platform for experiments pursuing other applications, which have both provided the motivation for the further development of these plasma optical components,[58] as well as a platform for experiments to validate that the models could design an optic that increased the energy available in signal NIF beam by $3\times$.[59–63]

Because of these developments, it now seems appropriate to design ion wave plasma optics for specific future applications and this paper seeks to provide Perspectives on how to proceed with the research needed to do this by considering the techniques such design work will need. These Perspectives are informed by much of the previously published results in this area, which are reviewed, as well as by some very recent experimental demonstrations described herein. Design of these optics will likely proceed by first beginning with a consideration of the physical processes that are expected to be well described by linear models of the plasma response to the laser beams and applying them to the laser beam conditions demanded by the application and the plasma conditions expected to be formed by the beams. Next the potential limitations to the optic performance can be considered, which may be due to non-linear and other effects which are more difficult to model accurately. This can be done by beginning with experimentally validated, models such as HYDRA,[64] to predict the plasma conditions, then performing analytic calculations and numerical simulations to evaluate relevant effects which already have well validated models, such as inverse bremsstrahlung absorption[65] (for which numerous experimental validations can be found in the literature), thresholds for the onset of the deleterious filamentation instability (based on linear plasma models and their validation[66,67]) the linear threshold for significant un-seeded SBS[67,68] and Stimulated Raman Scatter (SRS)[69] from the individual beams used, and finally, and most importantly, the power gain (or loss) rate of the beams due to the seeded SBS instability that gives rise to CBET. The CBET process has received the most study and experimental validation to date under the conditions of the fusion experimental targets and can be described in its simplest form using models that were historically developed to describe the interaction of scattered light with a single pump beam[68,70] and were then applied to the interaction of a plasma pumped with multiple crossing beams.[36–43] In the simplest form that has been found useful to describe CBET observations, the model is of SBS in the strong damping limit[68] (in which the damping rate of the ion wave is assumed much greater than the SBS growth rate) which, after many inverse growth rates, has reached an equilibrium level of scattering at all points in the plasma, and results in each ray of light in the crossing beams undergoing a spatial rate of gain (or loss) of power as it transits an interaction region shown schematically in Fig. 1.

These spatial growth rates have been alternately described in terms of a fluid plasma model[36] with a Landau damping rate inserted, and in a fully kinetic (or Vlasov) plasma model that self-consistently includes the linear Landau wave damping, which are expected to be correct for small amplitude plasma waves propagating in a mixed ion species plasma in which Landau damping is strong.[41] The power growth rate of an amplified seed beam in this regime is given by

$$\begin{aligned} g &= 1/4\,(v_{osc}/c)^2\, k_{iw}^2\, c/\omega_o\, \mathrm{Im}(\chi_e(k_{iw},\omega_{iw}) \\ &\quad \times (1+\Sigma_i \chi_i(k_{iw},\omega_{iw}))/\epsilon(k_{iw},\omega_{iw})) \qquad (1) \\ \epsilon(k_{iw},\omega_{iw}) &= 1+\chi_e(k_{iw},\omega_{iw})+\Sigma_i \chi_i(k_{iw},\omega_{iw}). \end{aligned}$$

Here, ω_o is the pump laser frequency, and v_{osc} is the oscillatory velocity of the electrons in the component of the electric field of the pump that is aligned to the electric field of the seed [$v_{osc} = e\, E_{pump}/(m_e \omega_o)$]. The wave vector of the driven ion wave (k_{iw}) is the difference of the wave vectors of the pump beam and seed beams ($k_{iw} = k_{pump} - k_{seed}$), the frequency of the driven ion wave (ω_{iw}) is the difference in the wave frequencies ($\omega_{iw} = \omega_{seed}$ - ω_{seed}), and $\chi_{e,i}$ are the electron and ion susceptibilities that depend both on k_{iw} and ω_{iw}, which can be calculated for arbitrary distributions of each species.[71] The spatial gain rate of the power, g, can then be integrated along the path of the beam through the entire length of the region of interaction of the beams (L), resulting in an exponential power gain factor (G) experienced by the beam resulting in a transmission through the optic of exp(G), where in the case of a uniform plasma and beam of length L, the resulting integral is simply G = gL. The linear plasma response shown in Eq. (1) describes the formation of ion waves in the plasma which are k matched to scatter the light from the pump beam so that it constructively interferes with, and amplifies, the seed beam. As such the scattering wave amplitudes are largest, and the amplification rates are largest when the ion wave is driven by the beating of the two light waves close to its resonant value which is normally much lower than the frequencies of the light waves. As a result, the amplification rate of the seed is strongly sensitive to small frequency differences in the two beams and can therefore be sensitively dependent on, and controlled by, the exact wavelength of the lasers. In many situations, it is also useful to specialize the definition of the susceptibilities to that for Maxwellian distribution of particles given by[72] as

$$\chi_{e,i}(k_{iw},\omega_{iw}) = -\frac{1}{2}\,\omega_{pe,i}^2/(k_{iw}\, v_{e,i})^2 Z'(\omega/(2^{1/2}\, k_{iw}\, v_{e,i})), \qquad (2)$$

where $v_{e,i}$ is the electron (ion) thermal velocity [$v_{e,i} = (T_{e,i}/m_{e,i})^{1/2}$], and Z' is the derivative of the plasma dispersion function Z with respect to its argument.[73] As suggested by Fig. 1, these formulas apply to the linear response to beams crossing at almost any angle, with one exception being the case of θ approaching zero (co-propagation of beams) for which more than one value of k_{iw} must be considered to describe the scattering of power. In addition, the presence of multiple crossing beams affecting the transmission of a single beam can also be described by these equations by recognizing that the gain (or attenuation) exponents produced by each crossing beam will add to describe their combined effect on the transmitted beam.[60] While the above models strictly only describe the growth and attenuation of two beams which have their polarizations aligned, they are also useful in describing the transmission of the aligned component of polarization and the amplitude of the scattering wave in situations where there are other components of polarization in multiple interacting beams.[51,74] Despite the many limitations of these linear models of plasma response, their power and utility for producing a range of high fluence plasma optics in the future that can operate for ns durations is now strongly suggested by their success in designing and modeling a few specific plasma optics as discussed in section "Recent Plasma Optic Developments." Moreover, as will be described, the CBET models represent a special case of the models of strongly coupled plasma amplifiers that have recently been validated on sub-ps time scales where the complication of binary collisions was un-necessary in the computations, which should give further confidence in the potential to extend them to longer time scales of CBET in collisional plasmas, potentially by adding appropriate physics.

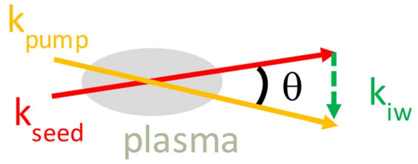

FIG. 1. A simple geometry in which plasma optics can be formed with ion waves having a wave vector (k_{iw}) that is the difference of the wave vectors of two intersecting beams of different wavelengths due to the seeding of SBS that transfers power and energy between the beams.

Recent Plasma Optic Developments

Although the physics of SBS that underlies the CBET process has been studied and tested in the context of a single beam interacting with a plasma for decades (Refs. 42, 68, and 70 and references therein), recent work studying CBET in multibeam systems has, in many respects, demonstrated the closest agreement between models and experimental observations of the SBS process. In particular, there have been a number of experiments that have confirmed the observed increase in beam power that occurs when a seed beam transits a region of plasma with one or more pumping beams is accurately described by gain rate of the beam power defined in Eq. (1) integrated over the laser intensity and plasma profiles. The accurate validation of the predicted growth rate is enabled in multi-beam experiments because the growing electromagnetic wave is introduced as a seed beam with intensity that can be a significant fraction of the pump. This is in contrast to earlier studies[42] of single beam SBS where the growth had to be observed with an electromagnetic seed that was either scattered or reflected from the pump beam, which tended to require many orders of magnitude amplification of the seed power before it could be detected with little control over what the spectral properties and spatial and temporal profiles of the amplified light was. The single beam studies were then further complicated by a rapid change in the fraction of the pump power transferred to the seed beam due to small changes in plasma conditions or pump intensity, causing pump depletion to onset, along with its associated effect on the plasma heating, almost as soon as the conditions evolved that allowed the scattered light to be detected. In multibeam CBET experiments, however, the properties and brightness of the seed are under the experimentalists direct control and its brightness can be set so that amplification factors have exponents of $\lesssim 1$ and are easily measured accurately by the experimental instruments. Moreover, the relative brightness of the two beam can be set so that the pump is the dominant source of heating that determines the plasma conditions in which the interaction takes place, and seed intensity is low enough that variations in its intensity can be studied under essentially constant pump and plasma conditions. Early CBET experiments used to validate CBET models[42,60] measured spatial gain rates integrated across plasma and beam profiles in a plasma in which a flow velocity gradient caused the beams to pass through CBET resonance only near the center of their crossing volume. These experiments validated that the predictions of the integrated gain exponent of beam transmitted power that were based on the integral of Eq. (1) over simulated plasma and beam profiles were in agreement with the experimentally determined gain exponent to within measurement uncertainties that were as large as $\pm 50\%$.[60,75] Still further improvements to the accuracy of the experimental validation of the integrated gain exponent derived from Eq. (1) has now been provided in more recent experiments in which the plasma density and temperature were measured by interferometry and Thompson scattering and the wavelength separation of the seed and pump beam were adjusted to produce a measure of the complete spectrum of gain produced by a single pump beam[49,76] as shown in Fig. 2. The quantities displayed on the vertical axis in the figure are the refractive index perturbations that are calculated both as the amplitude gain exponent G predicted by Eqs. (1) and (2), over the quantity (k_{seed} L) (black line), where G is determined as the integral of the equilibrium value of the spatial gain rate g over the path of the seed beam (which reaches a peak value of $G \sim 0.72$ near resonance in the case shown), as well as the phase shift from the same model (gray line). In evaluating the integral of g from Eq. (1) over the 1.2 mm path length in which the seed interacted with the pump beam to produce the data in Fig. 2, the plasma density

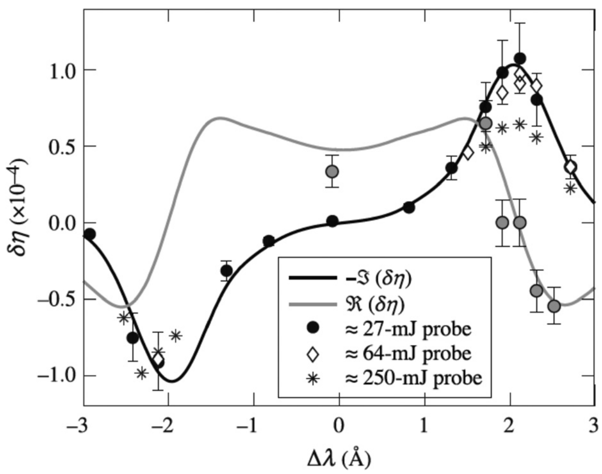

FIG. 2. Experimental measurements of the transmission of a low power probe beam when crossed with a pump beam in plasma with well diagnosed conditions (dots, diamonds, and asterisks with error bars), accurately validate the refractive index perturbation associated with the amplitude gain exponent for the transmitted beam predicted by the models of Eqs. (1) and (2) (black line) as well as that for the phase shift of the beam expected by the same model (gray line) over a range of probe beam wavelengths that encompass the ion wave resonance feature (reproduced with permission from Turnbull *et al.*, Plasma Phys. Controlled Fusion **60**, 054017 (2018). Copyright 2018 IOP Publishing). Measurements shown at higher probe power show reduced (or saturated) gain which further indicates limits to the domain of validity of the linear models.

profile measured by an interferometer and by Thomson scattering was employed, as well as the temperatures and ion species fractions that were taken from HYDRA simulations and confirmed, or in the case of species fraction adjusted, to match the measurements.[49] The work then determines a measured value of both the quantities plotted in the figure from the observed effects of CBET on different components of the beam polarization,[51,74] all of which demonstrate close agreement between the linear models and observations at the lowest levels of incident and transmitted power studied (dot and diamond symbols). The measurements shown in the figure further demonstrate an observed departure from the linear prediction for the power gain exponent at the highest probe powers studied (asterisk symbols) simultaneously demonstrating a limitation to the domain of validity of the linear wave models when the wave amplitudes are the largest of those studied, which is qualitatively similar to what has been seen in earlier measurements of CBET under different conditions.[41,77]

The success of the validation experiments has encouraged the development of simulational tools that evaluate the linear gain rate in more complex situations that may be important in other plasma optic applications. These models include accurate statistical descriptions of the beam intensity profiles when the beams are large and include many diffraction limited maxima and minima in intensity which can locally produce much larger gain rates than the average over the profile[53–57] and enable calculations on time scales comparable to or larger than that of transient effects associated with ion wave growth.[54] The models have also been used to identify the maximum ion wave amplitudes that exist in experiments that probe domains of validity of the linear wave models.[49,59,60,78] These successes in describing CBET in plasmas with approximately Maxwellian particle distributions have also motivated further experimentation with multibeam CBET studying cases where different particle distributions are expected, and the increased control and accuracy of measurements in multi-beam interactions experiments has led to the clearest confirmation yet[79] of the effect of super-Gaussian electron distributions on plasma wave propagation which has been theoretically predicted for decades.[80] Most recently, VPIC simulations[55,81,82] of the effects of both particle trapping and binary collisions have been benchmarked by experiments[83] that show that even when the ion wave amplitudes become large so that ions are trapped in the waves in sufficient number to transfer enough power from the interacting beams to the bulk plasma that they are a significant source of plasma heating and strongly modify the plasma temperatures, the simple linear CBET models of Eq. (1) are still accurate descriptions of the plasma wave amplitude and scattering, provided the linear response is evaluated using particle temperatures that include the non-linearly induced bulk heating.

The combination of the continuing demonstrations of the importance of CBET produced plasma optics cells in controlling the power deposition profiles in ICF experiments[43–48] and the emergence of experimentally validated models of CBET that prove quite accurate under certain conditions[49,53,57,74–76,78] have motivated the first design and test of a stand-alone plasma optic based on CBET[59,60,78] for use in a specific application requiring high fluence in a beam.[58] The device, a beam-combiner, has combined much of the energy of up to 20, f/20 pump beams into a single output beam of 1 ns duration as described in recent publications studying up to eight pump beams[59,60] and a forthcoming publications that describes the results with 20 pump in more detail.[61] The maximum pumping studied so far has resulted in a

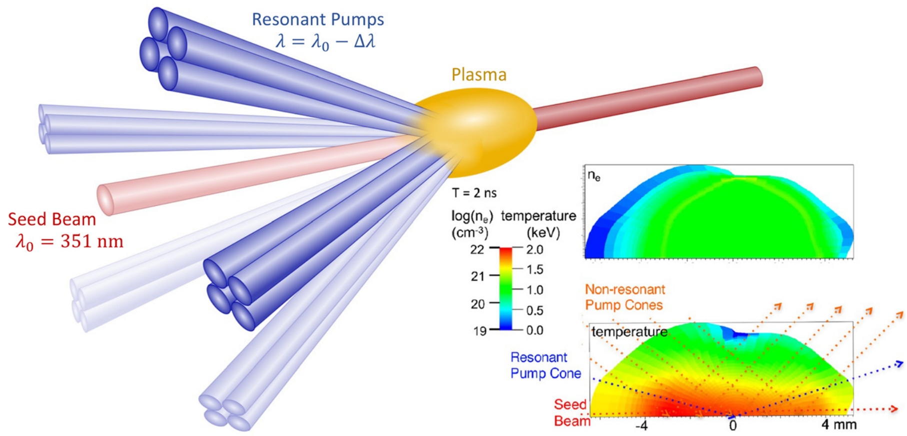

FIG. 3. A plasma beam-combiner has been created at the NIF facility by pre-heating a balloon of CH gas filled uniformly with electrons at 2.5% of the critical density of the 351 nm pump beams. The HYDRA simulated[64] plasma conditions allowed the density and wavelengths of the pump and probe beam to be optimized in the design resulting in transfer of significant pump beam power to the 1 ns duration seed with minimal inverse-bremsstrahlung absorption, filamentation, and backscatter to produce an output beam with more than 10× its incident energy and no observable reduction in its focal quality[61] without need for empirical optimization [reproduced from with permission from Kirkwood *et al.*, Physics of Plasmas **25**, 056701 (2018). Copyright 2018 AIP Publishing].[60]

10× amplification of a low power seed which provides a > 3× increase in single beam power and energy available in a 1 ns pulse at the NIF facility. The plasma optic is created by pre-heating a balloon of CH gas with 40 heater beams incident at angles ≳45° from a seed beam with a red shifted wavelength, as well as with up to 20 beams incident at angles between 15° and 20° with respect to the seed that, once the plasma is formed, provide the energy and power to amplify the seed beam. This illumination creates simulated plasma conditions of $T_e = 1.8$ keV and $n_e = 2.5\%$ of the critical density, as has been optimized under these conditions for minimizing inverse absorption of all beams while efficiently transferring energy from the pump to seed beams with scattering ion wave amplitudes that are known to avoid saturation mechanisms as described in detail in the design of the optic[60] and are shown in Fig. 3. Tests of the 20 pump beam design of the optics[60] were initially carried out with 0.75 kJ incident in a 1 ns square pulse in the seed beam and the number of pump beams increased in steps from 0 to 8,[59,60] and recently have been extended to 16 and 20 pump beams[61] as permitted by the original design[60] with minor changes in the seed and heater timing to eliminate pumping by non-resonant heaters. In all these experiments, the output power, energy, spot size, and pulse shape of the seed beam was determined from measurements of the brightness and size of the spot of x-ray emission it produced when subsequently incident on a witness plate[59–63] and were found to be in good agreement (within measurement uncertainties) with the predictions of the models based on linear wave responses[78] as shown in Fig. 4. The results show that the seed energy is increased in the optic by 7.1 kJ to deliver 7.8 (±1.6) kJ as predicted by the models and provide a robust demonstration that present modeling capability can be applied to accurately design a plasma optic that provides a beam fluence and energy that exceeds that of each of the incident beams that are used to create it, and which meets the specific needs demanded by an application.

As many of the applications that require extreme optical energies and powers also demand the beams can come to focus in small spot sizes, the focal quality of beams produced by plasma optics will also need to be adequate and accurately predicted by models. The ability of the seeded SBS instability that gives rise to CBET to amplify the individual rays in a beam without re-directing them[41] is likely to become a critical enabling property of future plasma optic devices and as such deserves careful experimental validation of its models. This ability is inherent in the three wave model that is used to describe SBS occurring at finite angles to the pumping beam because when plasma

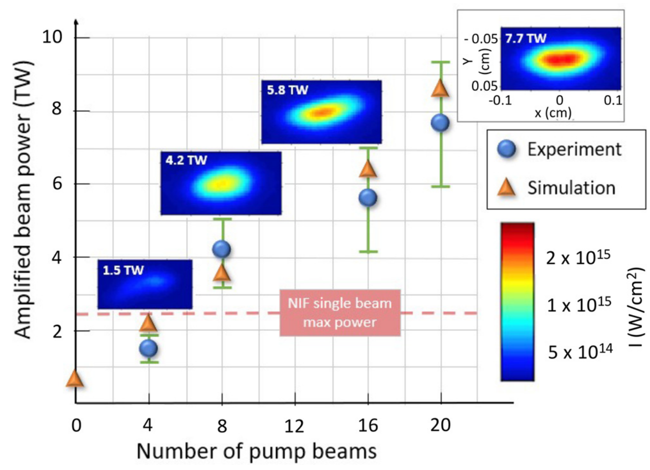

FIG. 4. The time averaged power output in a single beam from the beam combiner optic created at the NIF laser facility is determined from measurements of the x-ray emission spot produced when the 1 ns duration seed is subsequently incident on a witness plate (inset), and is studied as the number of pumping beams is increased in a series of experiments where it reaches a maximum of 7.7 TW in a 1 ns pulse, which is more than 3× the power otherwise available in a 1 ns pulse at NIF. The average power observed in the spots (blue dots) is also compared to predictions of the simulations based on the linear wave response described in the text (orange triangles) and is found to be in agreement (within measurement uncertainty) in all cases.[61]

density is low, the model preserves the wave numbers in the output beam spatial distribution to be only those that exist in the input distribution.[68] As a result, the model predicts that a beam on its way to a small focal spot can be amplified by SBS without affecting the size of the spot at best focus, and if such predictions can be well enough validated by observations under the needed conditions they will enable still more extreme performance from plasma optics. The beam combiner platform undergoing tests at NIF has also begun to provide the critical validation of this focal property of CBET amplified beams in very recent and not previously published experiments in which the incident seed beam is modified to have a smaller spot size at best focus than the pump beams that amplify it.[63] These experiments have been carried out in the same manner as the experiments with eight pump beams described in detail in Refs. 59 and 60. However, now the seed beam is prepared without the continuous phase plate (CPP) that is used by the pump beams and limits the size of their spots to 1.6×1.2 mm at best focus.[59,60] As a result, the un-smoothed incident seed beam now comes to a much smaller best focus of $\sim$0.15 mm dia. Experiments have now been performed with the best focus of the unmodified seed beam placed 24 mm past the plasma optic which allows the seed beam to maintain a spot size in the plasma optic approximately equal to the best focus of CPP smoothed pumps, but prepares the phase front of the seed in the optic so that it continues to focus energy to create a still smaller spot upon exiting the plasma optic. This focusing seed incident with 120 GW of power was amplified in the plasma by interaction with eight resonant pump beams that is expected from previous studies of this system[59–61] to increase its energy by $\sim 7\times$ to deliver 1.1 kJ to the witness plate and which is found to be consistent with the brightness seen in x-ray images of the small seed spot on the plate[62,63] as shown in Fig. 5. However, in this case,[63] the energy is transferred to the seed well before its best focus and is observed to appear on a witness plate 12 mm past the optic with a $\sim 3\times$ reduced spot size (when the spot sizes are determined as the total x-ray signal integrated over the area of each observed spot divided by the peak signals observed in the spot) as also shown in Fig. 5. The observations confirm the preservation of a smaller area at best focus for the amplified seed even when interacting with pumps with larger areas at best focus, as expected.

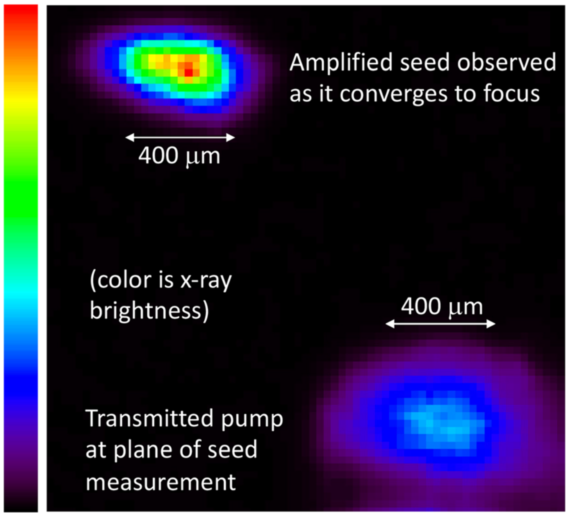

FIG. 5. Recent experiments using the beam combiner have further demonstrated the capability of the plasma optic to transfer power to a seed beam that can be focused to a smaller spot than the pumps that amplify it as this image of the brightness produced with a gated x-ray camera when both beam are incident on a witness plate in the configuration of Refs. 59, 60, and 63 shows as discussed in the text. The experiments with focused seed beams have demonstrated the capability of these plasma optics to transfer power and energy from pump to seed beam while preserving the focal properties of the seed, opening a path to future optics that can deliver beams with extreme intensity and fluence is small spots as well as high power and energy onto targets of interest.

These experiments also demonstrate significant success of the simulations based on linear plasma wave models in predicting the observed performance of the high fluence plasma optics studied. As such, the work constitutes an important step in developing predictive models that can be used to design plasma optics for future applications while encouraging a more complete study of the physics of these processes. In particular, the current experimental database together with the additional experiments that could be carried out in the near term should be used to define the limits of validity of the plasma models that have been used so far. In expanding use of the linear plasma wave model to a wider range of conditions, it will be important to identify the non-linear effects that can arise to in-validate the linear models as well as to determine more precisely the conditions under which the linear models apply. Significant work has already been done to identify non-linearities and other effects on the ion waves produced by single beam SBS interactions that will likely also limit the validity of the present models of CBET and can help identify some of physical processes that should be studied to determine these limits. The physical process identified by these earlier studies were rich and diverse an included fundamental process such as wave-breaking (or strong trapping) of the ion acoustic waves responsible for the scattering as was first identified with 1D ion particle simulations,[84] and the ion wave decay instability which was first recognized in 1D fluid models as potentially important.[85] This led to increasingly more sophisticated models employed to study SBS saturation identifying a range of related phenomenon using various modeling techniques, including the recognition that in 2D both weak trapping effects and ion wave decays can come into play to limit the scattering from SBS.[86] Subsequent experimental observations of the ion wave decay products showed they existed even when the pumping waves had surprisingly low amplitudes.[87,88] This motivated PIC modeling of both electrons and ions which found both species exhibit significant trapping effects that play a role in the development of a broad spectrum of daughter ion waves in the cases studied and require kinetic simulations to adequately capture.[89] Further simulation work has also shown the importance of the addition of multi-wave effects including ion wave harmonics and side bands,[90] and more recent Vlasov simulations have confirmed the broad spectrum of ion waves and demonstrated the potential for ion heating, further expanding the richness and complexity of the phenomena now recognized to affect ion wave growth and saturation of SBS in conditions that may be important for the development of useful plasma optics.[91,92] As a result, it is clear that progress on ion wave plasma optics will be significantly limited by the state of simulation capabilities for many of the same or similar phenomena that have been studied for SBS and which will either need to be understood in sufficient detail to be used in the design of the optics or to allow the choice of conditions for optics to avoid the regime that are the most complex to model. While it is clear that the simplest linear wave models of CBET driven ion waves used in Eqs. (1) and (2) neglect all of the above non-linear effects and that plasma optics models may need to address those as well as still more complex physics for which computational studies have only very recently begun, recent work on CBET driven ion waves has already studied many of them. In particular, CBET studies have already shown that the ponderomotive force of the beams can create fluctuations in the plasma[93] that have been known to locally affect the shape of the ion wave response function and the level of scattering the ion waves produce,[36] and that many effects of particles moving between localized hot spots in the beams as well as competing stimulated scattering instabilities can significantly affect power flow in other situations.[55,56] The next phases of study will likely need to define the region of parameter space where such effects can be avoided in the design of plasma optics, and/or improve models to include them in the design formulas.[83] This work will require further experiments to benchmark the theories that will likely build on the present numerous experimental observations for which non-linear CBET effects were inferred in larger integrated studies of ICF targets[43,46–48] as well as those that study the output of plasma optics produced by CBET more directly[38,49,59–63,75,78,79,83] and should pursue the goal of establishing experimentally validated metrics to define the region of validity of the needed wave models.

The numerous non-linear effects in the plasma wave response of an optic that are illustrated above will certainly need further study; however, it is apparent that even when wave amplitudes are very small, they will modify the distribution of ions due the presences of particles trapped in the driven waves. This could cause both momentum deposition in the plasma[41] and heating and acceleration of ions,[50,83] which both could cause the shape of the resonance profile expressed in Eq. (1) to change over time, as well as affect many of the other non-linear process that will occur as the wave amplitudes further increase.[89–91] Because these trapped particle distributions can evolve over very long time scales and develop fine structure in velocity space, it is likely necessary that the effect of particle collisions on them be modeled as well and such simulations have only become available very recently.[81–83] To illustrate the importance of developing these and other emerging simulation capabilities, we consider two examples of useful metrics for determining some of the limits beyond which the ion wave amplitudes could potentially depart from the linear wave response of Eqs. (1) and (2). The two metrics considered are (i) the comparison of the threshold for collisionless ion trapping to the ion wave amplitudes driven by CBET with narrow band lasers and (ii) the threshold for particle collisions to affect that trapping. The metrics are evaluated in a uniform 1D plasma and applied to cases where experiments have studied CBET directly[49,59,60,75,77] and, as such, do not include other non-linear effects or situationally dependent effects such as spatial non-uniformity, particle transport, or finite laser bandwidth which can affect some cases. In these cases, however, the Landau damping rate was dominated by ion damping, and the necessary condition for non-linear trapping of ions in the waves is that the bounce time is shorter than the duration of the experiment (or the pulse duration) τ_p, or equivalently satisfies the metric

$$1 > \tau_p\omega_{bi} = \tau_p\{(\delta n_e Z_i e^2/M_i)/[\varepsilon_0(1+\chi_i)]\}^{1/2}. \qquad (3)$$

Here, the bounce frequency of the ions in the wave, ω_{bi}, is expressed in terms of the wave perturbation in the electron density δn_e,[71] a lower limit to which can be determined in many cases from the measured fraction of the beam power scattered by the optic, F. When this is done using the coherent power scattering rate of a plane electromagnetic wave interacting with a plane wave density perturbation integrated over an interaction region of size L, the result gives $\delta n_e \sim 4\,F^{1/2}\, n_c/(kL)$ (where n_c is the critical density for the beam, k is the beam wave number). Notably for all the present experiments in which CBET is studied directly and the linear response of Eqs. (1) and (2), when evaluated for plasma conditions that are exist when CBET effects are absent, is observed to describe the CBET measurements at the lowest wave amplitudes studied,[49,59,60,75,77] the metric of Eq. (3) is greater than one, so that trapping would be expected to occur if collisions are un-important. This means that the observation that Eqs. (1) and (2) are an accurate description of scattering is suggesting there is a process suppressing the effects of trapping, allowing the linear wave model to apply. The comparison of these experimental results to the collisionless trapping metric makes it clear that simulation based models of these plasma optics will need to include processes that occur on the much longer time scales associated with particle trapping rather than simply including those that occur on the linear wave damping and growth times, and one such effect that has already been confirmed to be important in Ref. 83, is particle collisions. A useful metric for the importance of particle collisions in modeling will likely be the comparison of the time needed for the particles that produce the linear Landau damping of the wave, to trap in the wave ($1/\omega_{bi}$), to the time needed for coulomb collisions to relax the distribution of trapped particles to back to a Maxwellian. While a complete description of the distribution of particles present in all these plasma optics awaits detailed simulational studies,[55,81–83] the simplest form of this metric that will likely be relevant considers the distribution of the ions responsible for Landau damping driven by the potential of a uniform plane wave with the average wave amplitude needed for the optic to efficiently deplete the pumps and compares the rate at which it under-goes collisional relaxation. A formulation of the distribution of trapped particles that would form in the extreme case of an applied, spatially sinusoidal, potential that is an impulse in time, ϕ_o, is described in the absence of collisions in Ref. 71 as

$$\delta f(x,v,t) \sim 2\, q_i\phi_o k/(m_i\omega_{pi})\,\mathrm{Im}\,\{f_o'(v)/\varepsilon(k_{iw},k_{iw}v)\,\exp(ik_{iw}(x-vt))\}. \qquad (4)$$

The rate of relaxation of such a distribution by ion–ion collisions in a Maxwellian background plasma can be estimated by a heuristic collision operator[71]

$$\partial/\partial t\,\delta f(x,v,t) = \nu_{ii}\partial/\partial v\,[v\delta f + T_i/m_i\partial\delta f/\partial v], \qquad (5)$$

yielding the minimum time dependent distortion of the trapped particle population due to collisions as

$$\delta f_c(x,v,t) \sim \delta f(x,v,t)\,\exp(-\nu_{ii}t\,\{ikvt/2 + T_i k^2 t^2/(3m_i)\}). \quad (6)$$

These comparisons suggest a metric for a plasma optic to be affected by ion–ion collisions, in a regime where ion trapping is occurring, is when the exponent in Eq. (6) evaluated at the trapping time and at the ion velocity that is equal to the wave phase velocity, has a magnitude greater than 1, which defines the region below the black line in Fig. 6. The conditions of each of the existing experiments that directly study CBET[49,59,60,75,77] are evaluated using measured or simulated plasma

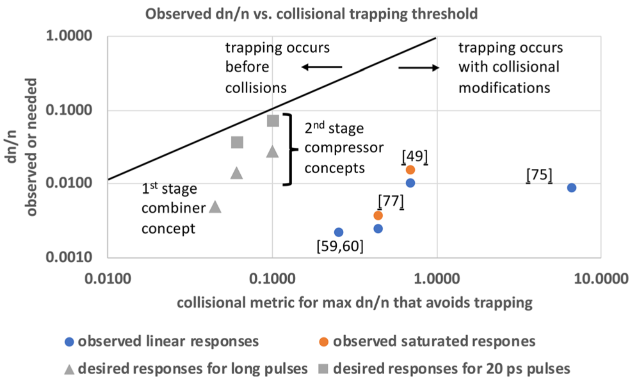

FIG. 6. Comparison of existing experiments that validate Eqs. (2) and (3) for describing plasma optics with the metric defined in Eq. (6) for ion–ion collisions to affect trapping of ions in the plasma wave (region below the black line) shows the importance of future simulations that include collisional effects and experiments to validate them to make progress on plasma optic designs. The colored points represent experiments with both saturated and linear responses taken from the references indicated next to the points, and the gray points indicate desired conditions for the plasma pulse compressor concepts discussed in section "Future Directions."

conditions taken from the original papers in each case (with the recognition that parameters such as simulated values of T_i may still be rather uncertain), and are represented by the colored points in the figure. The fact at all experimental points, including those exhibiting non-linear saturation effects, are below the black line indicates it will be critical for understanding the ion wave response and scattering observed in these experiments to recognize that they all are not only well within the domain of ion trapping defined by the metric of Eq. (3), but are also well within the domain in which ion–ion collisions can significantly affect the ion trapping process defined by the exponential factor in Eq. (6). The fact that these most detailed experimental studies of plasma optics created by CBET driven ion waves have observed both linear ion wave responses [in agreement with Eqs. (1) and (2) scattering estimates], and saturated ion wave responses [with scattering below the levels of Eqs. (1) and (2)] with all cases being in the regime in which ion trapping can be significantly affected by collisions is seen by comparing the ion wave perturbation observed, δn_e (colored points), with the minimum value of δn_e needed to avoid collisional effects on ion trapping by keeping the exponential factor in Eq. (6) small (black line), as shown in Fig. 6. The difficulties inherent in simulating the $\sim$ cm scale plasmas and $>$ 10's of ps duration pulse lengths needed for many future applications of these optics, on the relevant trapped particle and collision time scales, highlight the likely importance of validating the ion wave response models used to design the optics with experimental observations in the conditions needed, especially if such observations can be done in reduced scale tests accessible at existing laser facilities. Such experimentation, done in concert with modeling and design of plasma optics, may be one of the most important steps for developing this technology in the near term.

FUTURE DIRECTIONS

The opportunities and challenges for developing engineering models of ion wave plasma optics described here will likely be addressed by the development and testing of specific plasma optics components in the near future. In particular, the regime of high fluence and energy per pulse, in beams made with plasma optics, is promising to advance numerous applications.[16] Some examples of this are as follows: (1) fusion energy produced by lasers, which needs focusable beams with 10's ps duration, in the fast ignition approach,[19] or multi-ns duration in the central hot spot approach,[17,20] and where the optics will need to withstand substantial radiation by both UV light and nuclear reaction products for the life of a power plant; (2) bright sources of high energy photons for radiography of dense, thick objects on fast time scales,[21–23] in which high optical fluence is needed as well as intensity; and (3) next generation particle accelerators[24] and photon sources that need to operate at high peak and average fluence to test the physics of matter in extreme conditions. These and other applications will likely each require distinctly different plasma optical components with their performance optimized in a range of different plasma and beam conditions, which will all demand predictive models and proto-type tests prior to the construction of the laser facilities that use them. The recent developments with ion wave plasma optics described above suggests there may be many ways to enable these applications, and further that the linear models can already provide the first indication of what such components can achieve for many of the potential applications, as well as direct further development of attractive options using more sophisticated models and experimental validation tests. As a result, it appears that progress will occur most quickly when specific applications provide support for these developments, and the community of plasma researchers will need to connect with the communities demanding the applications to outline the plan in each case.

To motivate the next steps, two specific examples of concepts of plasma optics for specific applications are provided that have not been considered previously. The first example of such an application, which directly builds on recent demonstrations,[59–63] is a final optic for a fusion energy power plant based on the central hot spot approach using ns duration beams,[20,44,45] which uses a plasma to bend the path of the incident photons at a long enough distance from the target that enough material can be placed between the radiation emitting target and the conventional optics forming the beams so as to prevent damage or activation of those optics. As such, these or very similar plasma optics may significantly improve power plant operating costs, reliability, and safety. A second example of an application which could be developed in the near term is a plasma optics beam combiner and pulse compressor combination, that, as shown conceptually using the models described here, promises to generate the $>$ 100 kJ, 10's ps duration pulse in a 10's of micrometer size spot that could directly provide the localized source of energy needed to ignite fusion fuel for producing energy. Conceptually, such a light pulse could be produced with a conventional laser, with the needed energy in ns duration pulses in multiple pumps beams, that illuminate a beam combiner with intrinsic physical parameters (fluence, density, and temperature) similar to the optic shown in Figs. 3 and 4 but with a larger plasma and beam volume, thereby transferring much greater energy to a single collimated output beam. When the output of this first stage is brought to a highly elliptical focus and incident on a second stage of a plasma in the geometry shown in Fig. 7, the energy can potentially be further transferred to a counterpropagating pulse with as little as 10's of ps duration. While there are many possible optimizations for such a concept, it is clear that the beam combiner of Figs. 3 and 4 can be extended to this higher energy while maintaining the similar fluence in the plasma and

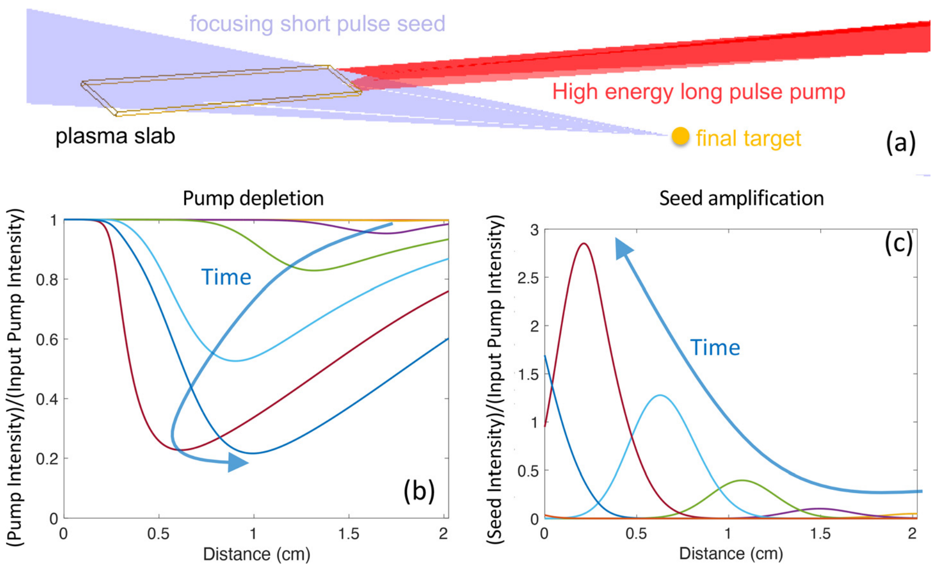

FIG. 7. (a) Schematic layout for a high fluence plasma combined beam to undergo a second stage of pulse compression with a plasma optic to produce high energy and power on targets producing fusion energy by fast ignition or related techniques. 1D simulation results using the linear wave response described in the text show (b) the time dependence of the efficient depletion of the 170 TW/cm^2 pump and (c) the time dependent amplification of a seed of the same intensity with 20 ps duration in counterpropagating geometry that shows enhancement of seed output power by both amplification and compression.

CBET gain in at least two steps. First, our linear gain and threshold models show that the energy in the output seed spot in the configuration of Figs. 3 and 4 could be increased further to > 20 kJ by a reduction in the gas density and an increase in the total pump power by a factor of 2.5× (so that the density × intensity product, as well as the CBET, SBS, and SRS backscatter gains remain the same as that of the demonstrations of Figs. 3 and 4). Second, a further 10× increase in energy in the seed (to > 200 kJ) can be produced using the same fluence and plasma conditions by a 10× elongation of the interaction region in one dimension (to ∼1 mm × ≳10 mm in transverse dimension) and the use of heater beams with highly elliptical spots that have 10× more energy at the same fluence and an elliptical defocused seed beam to produce an output beam of the same fluence but with 10× more energy available to pump the second stage of plasma that is shown in Fig. 7. That pulse could then be compressed by interaction with a second focusing short pulse seed beam in the subsequent region of plasma shown in the figure, in which the pumping beam propagates for a distance of at least 15 cm per ns of its pulse duration allowing interaction with the much shorter counter-propagating pulse seed to potentially deplete the entire pump pulse, similar to what has been proposed for Raman compression in the past.[1,4] The 174° crossing angle shown in this example ensures that the transverse area of the seed beam when it interacts with the pump in the plasma is ∼10× larger than that of the pump, so that a 10× shorter pulse seed can receive all the pump energy without producing higher intensity in the plasma that could drive secondary instabilities, and the seed focal properties first demonstrated in the data of Fig. 5 in the plasma conditions of the first stage may allow an even smaller best focus spot of the short pulse seed due to the lower density plasma in the second stage, potentially allowing the energy to be delivered to a much smaller spot on a target placed near best focus. Optimizing the concept and confirming the plasma physics needed to create the density perturbations required in this second region of plasma are the critical next step for developing such an optic for fusion energy; however, the expectations of basic linear models described above and HYDRA simulations of plasma creation by the pump beam are promising. The HfYDRA simulations with classical particle heat transport show that if a He/H gas is heated by 1 ns beam with a 350 nm wavelength in a narrow spectrum and a fluence of ∼3 × 10^{15} W/cm^2 a uniform plasma is created in the second stage with an electron density of 0.5–1.0 × 10^{19} cm^{-3}, and T_e∼ 500–700 eV, which the models of Eqs. (1) and (2) predict can produce a several fold resonant amplification of the power of a seed that has a few Å longer wavelength, while depleting most of the energy in the long pulse pump. This is illustrated by a 1D simulation of the second stage amplifier that solves the standard time- and space-dependent coupled three-wave equations for the light and plasma waves and the HYDRA predicted plasma conditions near the point where the pump is incident on the second stage plasma. Here, the pump is seen to be depleted while the seed is amplified > 60× as shown in Figs. 7(b) and 7(c). In this simulation, the ion temperature is elevated above the HYDRA predicted values for classical heat transport to give a more conservative estimate of the seed amplification as may be more correct when effects such as non-local ion heat transport and the effects of particle trapping on ion-heating[83] are fully understood. In this case, there is also minimal inverse bremsstrahlung absorption of either beam, the average beam intensity is kept below the thresholds for filamentation and backscattering by SBS or SRS, suggesting that a bright seed with duration of 100 ps could collect a large fraction of the energy in the pump, and a further reduction of seed pulse duration may be possible due to non-linear pulse shortening (as studied in other contexts[1]). As a result, if further work can show non-linear saturation and other deleterious effects are benign (such as Raman forward scatter which is known to be suppressed by non-linear saturation in some cases[69]), it appears possible that hundreds of kJ of energy can be delivered in 10's of ps in a beam that comes to best focus on a final target where it could accelerate particles, such as ions[94] into an assembled high density of fusion fuel.[19,95] The energy delivered to the hot spot would be similar to what is presently produced in ignition studies that are driven kinetically by implosions[20,45] as well as to what has been identified as needed for other approaches to ignition such as fast ignition[19,95] and other fusion energy applications. Next steps in this plan would be studies of non-linear effects such as ion trapping which would occur at a higher rate relative to the collisional relaxation rate than occurred in existing experiments where trapping did not degrade optic performance. This concept is represented by the gray points in Fig. 6, which are closer to the collisionless trapping regime than the colored points that show wave amplitudes and plasma conditions that have been studied by experiments and in some cases described by the linear wave response of Eqs. (1) and (2). While simulations may be able to address the more complex phenomenon, much of the non-linear physics may also be tested in smaller scale experiments, with the needed plasma conditions, beam intensities, and wave amplitudes at existing laser facilities.

High fluence plasma based optics, when fully developed, may have many advantages over those made of conventional materials that are more susceptible to damage from optical and nuclear radiation and could be used both in laser fusion test facilities and in fusion power plants themselves, as well as drivers for sources of high energy particles and photons. The development of applications such as this can use the presently existing models to guide both the optic design as well as the next steps in model development and experimental tests to confirm the expectations.

AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

REFERENCES

[1]Malkin, V. M., Shvets, G., and Fisch, N. J, "Fast compression laser beams to highly overcritical powers," Phys. Rev. Lett. **82**, 4448–4451 (1999).
[2]Y. Ping, W. Cheng, S. Suckewer, D. S. Clark, and N. J. Fisch, Phys. Rev. Lett. **92**, 175007 (2004).
[3]J. Ren, W. Cheng, S. Li, and S. Suckewer, Nat. Phys. **3**, 732–736 (2007).
[4]G. A. Mourou, N. J. Fisch, V. M. Malkin, Z. Toroker, E. A. Khazanov, A. M. Sergeev, T. Tajima, and B. L. Garrec, Opt. Commun. **285**, 720–724 (2012).
[5]W. Cheng, Y. Avitzour, Y. Ping, S. Suckewer, N. J. Fisch, M. S. Hur, and J. S. Wurtele, "Reaching the nonlinear regime of Raman amplification of ultrashort laser pulses," Phys. Rev. Lett. **94**, 045003 (2005).
[6]J. Ren, S. Li, A. Morozov, S. Suckewer, N. A. Yampolsky, V. M. Malkin, and N. J. Fisch, "A compact double-pass Raman backscattering amplifier/compressor," Phys. Plasmas **15**, 056702 (2008).
[7]N. A. Yampolsky and N. J. Fisch, "Limiting effects on laser compression by resonant backward Raman scattering in modern experiments," Phys. Plasmas **18**, 056711 (2011).
[8]G. Vieux, S. Cipiccia, D. Grant, N. Lemos, P. Grant *et al.*, "An ultra-high gain and efficient amplifier based on Raman amplification in plasma," Sci. Rep. **7**, 2399 (2017).
[9]R. G. M. Trines, E. P. Alves, E. Webb, J. Vieira, F. Fiuza, R. A. Fonseca, L. O. Silva, R. A. Carins, and R. Bingham, Sci. Rep. **10**, 19875 (2020).
[10]A. A. Andreev, C. Riconda, V. T. Tikhonchuk, and S. Weber, Phys. Plasmas **13**, 053110 (2006).
[11]L. Lancia, J.-R. Marquès, M. Nakatsutsumi, C. Riconda, S. Weber, S. Hüller, A. Mančić, P. Antici, V. T. Tikhonchuk, A. Héron, P. Audebert, and J. Fuchs, "Experimental evidence of short light pulse amplification using strong-coupling stimulated Brillouin scattering in the pump depletion regime," Phys. Rev. Lett. **104**, 025001 (2010).
[12]S. Weber, C. Riconda, L. Lancia, J.-R. Marques, G. A. Mourou, and J. Fuchs, "Amplification of ultrashort laser pulses by Brillouin backscattering in plasmas," Phys. Rev. Lett. **111**, 055004 (2013).
[13]G. Lehmann and K. Spatschek, "Nonlinear Brillouin amplification of finite-duration seeds in the strong coupling regime," Phys. Plasmas **20**, 073112 (2013).
[14]M. R. Edwards, Q. Jia, J. M. Mikhailova, and N. J. Fisch, "Short-pulse amplification by strongly coupled stimulated Brillouin scattering," Phys. Plasmas **23**, 083122 (2016).
[15]M. Chiaramello, F. Amiranoff, C. Riconda, and S. Weber, "Role of frequency chirp and energy flow directionality in the strong coupling regime of Brillouin-based plasma amplification," Phys. Rev. Lett. **117**, 235003 (2016).
[16]C. N. Danson, C. Haefner, J. Bromage *et al.*, High Power Laser Sci. Eng. **7**, e54 (2019).
[17]C. A. Haynam, P. J. Wegner, J. M. Auerbach *et al.*, Appl. Opt. **46**, 3276–3303 (2007).
[18]J. Bude, P. Miller, S. Baxamusa *et al.*, Opt. Express **22**, 5839–5851 (2014).
[19]T. Norimatsu, Y. Kozaki, H. Shiraga, H. Fujita, K. Okano, and Members of LIFT Design Team, Nucl. Fusion **57**, 116040 (2017).
[20]E. Moses, T. Diaz, D. L. Rubia, J. F. Latkowski *et al.*, Fusion Sci. Technol. **56**(2), 547–572 (2009).
[21]C. Courtois, R. Edwards, A. Compant La Fontaine, C. Aedy, S. Bazzoli, J. L. Bourgade, J. Gazave, J. M. Lagrange, O. Landoas, L. Le Dain, D. Mastrosimone, N. Pichoff, G. Pien, and C. Stoeckl, Phys. Plasmas **20**, 083114 (2013); Using MeV photon sources made with 10 ps pulses. (what about present Mackinnon project?).
[22]A. C. L. Fontaine, C. Courtois, F. Gobet, F. Hannachi, J. R. Marquès, M. Tarisien, M. Versteegen, and T. Bonnet, Phys. Plasmas **26**, 113109 (2019).
[23]R. D. Edwards, M. A. Sinclair, T. J. Goldsack, K. Krushelnick, F. N. Beg, E. L. Clark, A. E. Dangor, Z. Najmudin, M. Tatarakis, B. Walton, M. Zepf, K. W. D. Ledingham, I. Spencer, P. A. Norreys, R. J. Clarke, R. Kodama, Y. Toyama, and M. Tampo, Appl. Phys. Lett. **80**, 2129 (2002).
[24]W. Leemans, Phys. Today **72**(2), 40 (2019).
[25]D. S. Clark and N. J. Fisch, "Operating regime for a backward Raman laser amplifier in preformed plasma," Phys. Plasmas **10**, 3363 (2003).
[26]Z. Toroker, V. M. Malkin, and N. J. Fisch, "Backward Raman amplification in the Langmuir wavebreaking regime," Phys. Plasmas **21**, 113110 (2014).
[27]D. S. Clark and N. J. Fisch, "Particle-in-cell simulations of Raman laser amplification in preformed plasmas," Phys. Plasmas **10**, 4848 (2003).
[28]J. D. Sadler, R. M. G. M. Trines, M. Tabak, D. Haberberger, D. H. Froula, A. S. Davies, S. Bucht, L. O. Silva, E. P. Alves, F. Fiúza, L. Ceurvorst, N. Ratan, M. F. Kasim, R. Bingham, and P. A. Norreys, Phys. Rev. E **95**, 053211 (2017).
[29]R. M. G. M. Trines, F. Fiúza, R. Bingham, R. A. Fonseca, L. O. Silva, R. A. Cairns, and P. A. Norreys, Nat. Phys. **7**, 87 (2011).
[30]M. R. Edwards, Z. Toroker, J. M. Mikhailova, and N. J. Fisch, "The efficiency of Raman amplification in the wavebreaking regime," Phys. Plasmas **22**, 074501 (2015).
[31]L. Lancia, A. Giribono, L. Vassura, M. Chiaramello, C. Riconda, S. Weber, A. A. Castan, A. Chatelain, A. Frank, T. T. Gangolf, M. N. M. N Quinn, J. J. Fuchs, and J.-R. Marquès, Phys. Rev. Lett. **116**, 075001 (2016).
[32]J.-R. Marques, L.Lancia, T. Gangolf, M.Blecher, S.Bolaños, J. Fuchs, O. Willi, F. Amiranoff, R. L. Berger, M. Chiaramello, S. Weber, and C. Riconda, Phys. Rev. X **9**, 021008 (2019).
[33]H. Peng, C. Riconda, M. Grech, J.-Q. Su, and S. Weber, Phys. Rev. E **100**, 061201 (2019).
[34]H. Peng, J.-R. Marques, L. Lancia, F. Amiranoff, R. L. Berger, S. Weber, and C. Riconda, Matter Radiat. Extremes **4**, 065401 (2019).
[35]J. Lindl, O. Landen, J. Edwards, E. Moses, and NIC Team, Phys. Plasmas **21**, 020501 (2014).
[36]W. L. Kruer, S. C. Wilks, B. B. Afeyan, and R. K. Kirkwood, Phys. Plasmas **3**, 382 (1996).
[37]R. K. Kirkwood, B. J. MacGowan, D. S. Montgomery, B. B. Afeyan, W. L. Kruer, D. M. Pennington, S. C. Wilks, J. D. Moody, K. Wharton, C. A. Back, K. G. Estabrook, S. H. Glenzer, M. A. Blain, R. L. Berger, D. E. Hinkel, B. F. Lasinski, E. A. Williams, D. Munro, B. H. Wilde, and C. Rousseaux, Phys. Plasmas **4**, 1800 (1997).
[38]R. K. Kirkwood, B. B. Afeyan, W. L. Kruer, B. J. MacGowan, J. D. Moody, D. S. Montgomery, D. M. Pennington, T. L. Weiland, and S. C. Wilks, Phys. Rev. Lett. **76**, 2065 (1996).

[39]H. A. Baldis, C. Labaune, E. Schifano, N. Renard, and A. Michard, Phys. Rev. Lett. **77**, 2957 (1996).
[40]C. Labaune, H. A. Baldis, B. Cohen, W. Rozmus, S. Depierreux, E. Schifano, B. S. Bauer, and A. Michard, Phys. Plasmas **6**, 2048 (1999).
[41]E. Williams, B. I. Cohen, L. Divol, M. R. Dorr, J. A. Hittinger, D. E. Hinkel, A. B. Langdon, R. K. Kirkwood, D. H. Froula, and S. H. Glenzer, Phys. Plasmas **11**, 231–244 (2004).
[42]R. K. Kirkwood, J. D. Moody, J. Kline, E. Dewald, S. Glenzer, L. Divol, P. Michel, D. Hinkel, R. Berger, E. Williams, J. Milovich, L. Yin, H. Rose, B. MacGowan, O. Landen, M. Rosen, and J. Lindl, Plasma Phys. Controlled Fusion **55**, 103001 (2013).
[43]P. Michel, S. H. Glenzer, L. Divol, D. K. Bradley, D. Callahan, S. Dixit, S. Glenn, D. Hinkel, R. K. Kirkwood, J. L. Kline, W. L. Kruer, G. A. Kyrala, S. Le Pape, N. B. Meezan, R. Town, K. Widmann, E. A. Williams, B. J. MacGowan, J. Lindl, and L. J. Suter, Phys. Plasmas **17**, 056305 (2010).
[44]O. A. Hurricane, D. A. Callahan, D. T. Casey, E. L. Dewald, T. R. Dittrich, T. Döppner, S. Haan, D. E. Hinkel, L. F. Berzak Hopkins, O. Jones, A. L. Kritcher, S. L. Pape, T. Ma, A. G. MacPhee, J. L. Milovich, J. Moody, A. Pak, H.-S. Park, P. K. Patel, J. E. Ralph, H. F. Robey, J. S. Ross, J. D. Salmonson, B. K. Spears, P. T. Springer, R. Tommasini, F. Albert, L. R. Benedetti, R. Bionta, E. Bond, D. K. Bradley, J. Caggiano, P. M. Celliers, C. Cerjan, J. A. Church, R. Dylla-Spears, D. Edgell, M. J. Edwards, D. Fittinghof, M. A. Barrios Garcia, A. Hamza, R. Hatarik, H. Herrmann, M. Hohenberger, D. Hoover, J. L. Kline, G. Kyrala, B. Kozioziemski, G. Grim, J. E. Field, J. Frenje, N. Izumi, M. Gatu Johnson, S. F. Khan, J. Knauer, T. Kohut, O. Landen, F. Merrill, P. Michel, A. Moore, S. R. Nagel, A. Nikroo, T. Parham, R. R. Rygg, D. Sayre, M. Schneider, D. Shaughnessy, D. Strozzi, R. P. J. Town, D. Turnbull, P. Volegov, A. Wan, K. Widmann, C. Wilde, and C. Yeamans, Nat. Phys. **12**, 800 (2016).
[45]A. B. Zylstra, A. L. Kritcher, O. A. Hurricane, D. A. Callahan, K. Baker, T. Braun, D. T. Casey, D. Clark, K. Clark, T. Döppner, L. Divol, D. E. Hinkel, M. Hohenberger, C. Kong, O. L. Landen, A. Nikroo, A. Pak, P. Patel, J. E. Ralph, N. Rice, R. Tommasini, M. Schoff, M. Stadermann, D. Strozzi, C. Weber, C. Young, C. Wild, R. P. J. Town, and M. J. Edwards, Phys. Rev. Lett. **126**, 025001 (2021).
[46]E. Dewald, J. L. Milovich, P. Michel, O. L. Landen, J. L. Kline, S. Glenn, O. Jones, D. H. Kalantar, A. Pak, H. F. Robey, G. A. Kyrala, L. Divol, L. R. Benedetti, J. Holder, K. Widmann, A. Moore, M. B. Schneider, T. Döppner, R. Tommasini, D. K. Bradley, P. Bell, B. Ehrlich, C. A. Thomas, M. Shaw, C. Widmayer, D. A. Callahan, N. B. Meezan, R. P. J. Town, A. Hamza, B. Dzenitis, A. Nikroo, K. Moreno, B. Van Wonterghem, A. J. Mackinnon, S. H. Glenzer, B. J. MacGowan, J. D. Kilkenny, M. J. Edwards, L. J. Atherton, and E. I. Moses, "Early-time symmetry tuning in the presence of cross-beam energy transfer in ICF Experiments on the National Ignition Facility," Phys. Rev. Lett. **111**, 235001 (2013).
[47]L. A. Pickworth, T. Doppner, D. E. Hinkel, J. E. Ralph, B. Bachmann, L. P. Masse, L. Divol, L. R. Benedetti, P. M. Celliers, H. Chen, M. Hohenberger, S. F. Khan, O. L. Landen, N. Lemos, B. J. MacGowan, D. A. Mariscal, P. A. Michel, M. Millot, A. S. Moore, J. Park, M. B. Schneider, D. A. Callahan, and O. A. Hurricane, Phys. Plasmas **27**, 102702 (2020).
[48]R. P. J. Town, M. D. Rosen, P. A. Michel, L. Divol, J. D. Moody, G. A. Kyrala, M. B. Schneider, J. L. Kline, C. A. Thomas, J. L. Milovich, D. A. Callahan, N. B. Meezan, D. E. Hinkel, E. A. Williams, R. L. Berger, M. J. Edwards, L. J. Suter, S. W. Haan, J. D. Lindl, E. L. Dewald, S. Dixit, S. H. Glenzer, O. L. Landen, E. I. Moses, H. A. Scott, J. A. Harte, and G. B. Zimmerman, Phys. Plasmas **18**, 056302 (2011).
[49]D. Turnbull, A. Colaïtis, R. K. Follett, J. P. Palastro, D. H. Froula, P. Michel, C. Goyon, T. Chapman, L. Divol, G. E. Kemp, D. Mariscal, S. Patankar, B. B. Pollock, J. S. Ross, J. D. Moody, E. R. Tubman, and N. C. Woolsey, Plasma Phys. Controlled Fusion **60**, 054017 (2018).
[50]P. Michel, W. Rozmus, E. A. Williams, L. Divol, R. L. Berger, S. H. Glenzer, and D. A. Callahan, Phys. Plasmas **20**, 056308 (2013).
[51]P. Michel, L. Divol, D. Turnbull, and J. D. Moody, Phys. Rev. Lett. **113**, 205001 (2014).
[52]J. F. Myatt, J. G. Shaw, R. K. Follett, D. H. Edgell, D. H. Froula, J. P. Palastro, and V. N. Goncharov, J. Comput. Phys. **399**, 108916 (2019).
[53]A. Colaitis, T. Chapman, D. Strozzi, L. Divol, and P. Michel, Phys. Plasmas **23**, 032118 (2016).
[54]L. Divol, D. P. Turnbull, T. Chapman, C. Goyon, and P. Michel, Phys. Plasmas **26**, 043101 (2019).
[55]L. Yin, B. J. Albright, D. J. Stark, W. D. Nystrom, R. F. Bird, and K. J. Bowers, Phys. Plasmas **26**, 082708 (2019).
[56]D. J. Stark, L. Yin, B. J. Albright, A. Seaton, and R. F. Bird, Phys. Plasmas **28**, 022702 (2021).
[57]T. Chapman (unpublished).
[58]K. B. Fournier, C. G. Brown, Jr., M. J. May, S. Compton, O. R. Walton, N. Shingleton, J. O. Kane, G. Holtmeier, H. Loey, P. B. Mirkarimi, W. H. Dunlop, R. L. Guyton, and E. Huffman, Rev. Sci. Inst. **85**, 095119 (2014).
[59]R. K. Kirkwood, D. P. Turnbull, T. Chapman, S. C. Wilks, M. D. Rosen, R. A. London, L. A. Pickworth, W. H. Dunlop, J. D. Moody, D. J. Strozzi, P. A. Michel, L. Divol, O. L. Landen, B. J. MacGowan, B. M. VanWonterghem, K. B. Fournier, and B. E. Blue, Nat. Phys. **14**, 80 (2018).
[60]R. K. Kirkwood, D. P. Turnbull, T. Chapman, S. C. Wilks, M. D. Rosen, R. A. London, L. A. Pickworth, A. Colaitis, W. H. Dunlop, P. Poole, J. D. Moody, D. J. Strozzi, P. A. Michel, L. Divol, O. L. Landen, B. J. MacGowan, B. M. Van Wonterghem, K. B. Fournier, and B. E. Blue, Phys. Plasmas **25**, 056701 (2018).
[61]P. Poole, R. K. Kirkwood, T. D. Chapman, S. C. Wilks, M. D. Rosen, L. Pickworth, W. H. Dunlop, B. J. MacGowan, K. B. Fournier, B. M. Van Wonterghem, and B. E. Blue, "Time-resolved measurement of power transfer in plasma amplifier optic," Phys. Rev E (submitted).
[62]L. A. Pickworth, M. D. Rosen, M. B. Schneider, D. E. Hinkel, L. R. Benedetti, R. L. Kauffman, and S. S. Wu, High Energy Density Phys. **23**, 159 (2017).
[63]P. Poole, R. K. Kirkwood, T. D. Chapman, S. C. Wilks, M. D. Rosen, L. Pickworth, W. H. Dunlop, B. J. MacGowan, K. B. Fournier, B. M. Van Wonterghem, and B. E. Blue (unpublished).
[64]M. M. Marinak, G. D. Kerbel, N. A. Gentile, O. Jones, D. Munro, S. Pollaine, T. R. Dittrich, and S. W. Haan, Phys. Plasmas **8**, 2275 (2001).
[65]T. W. Johnston and J. M. Dawson, Phys. Fluids **16**, 722 (1973).
[66]E. A. Williams, Phys. Plasmas **13**, 056310 (2006).
[67]D. H. Froula, L. Divol, N. B. Meezan, S. Dixit, J. D. Moody, P. Neumayer, B. B. Pollock, J. S. Ross, and S. H. Glenzer, Phys. Rev. Lett. **98**, 085001 (2007).
[68]J. F. Drake, P. K. Kaw, Y. C. Lee, G. Schmid, C. S. Liu, and M. N. Rosenbluth, Phys. Fluids **17**, 778 (1974).
[69]C. Niemann, R. L. Berger, L. Divol, R. K. Kirkwood, J. D. Moody, C. M. Sorce, and S. H. Glenzer, J. Instrum. **6**, P10008 (2011).
[70]B. I. Cohen and C. E. Max, Phys. Fluids **22**, 1115 (1979).
[71]S. Ichimaru, *Statistical Plasma Physics* (Addison-Wesley, Redwood, CA, 1992), Vol. 1.
[72]E. Williams, R. L. Berger, R. P. Drake, A. M. Rubenchik, B. S. Bauer, D. D. Meyerhofer, A. C. Gaeris, and T. W. Johnston, Phys. Plasmas **2**, 129 (1995).
[73]B. D. Fried and S. D. Conte, *The Plasma Dispersion Function* (Academic Press, New York, 1961).
[74]D. Turnbull, P. Michel, T. Chapman, E. Tubman, B. B. Pollock, C. Y. Chen, C. Goyon, J. S. Ross, L. Divol, N. Woolsey, and J. D. Moody, Phys. Rev. Lett. **116**, 205001 (2016).
[75]R. K. Kirkwood, P. Michel, R. A. London, D. Callahan, N. Meezan, E. A. Williams, W. Seka, L. Suter, C. Haynam, and O. L. Landen, Phys. Rev. E **84**, 026402 (2011).
[76]D. Turnbull, C. Goyon, G. E. Kemp, B. B. Pollock, D. Mariscal, L. Divol, J. S. Ross, S. Patankar, J. D. Moody, and P. Michel, Phys. Rev. Lett. **118**, 015001 (2017).
[77]R. K. Kirkwood, J. D. Moody, A. B. Langdon, B. I. Cohen, E. A. Williams, M. R. Dorr, J. A. Hittinger, R. Berger, P. E. Young, L. J. Suter, L. Divol, S. H. Glenzer, and O. L. Landen, Phys. Rev. Lett. **89**, 215003 (2002).
[78]A. Colaitis, T. Chapman, D. Strozzi, L. Divol, and P. Michel, Phys. Plasmas **25**, 033114 (2018).
[79]D. Turnbull, A. Colaitis, A. M. Hansen, A. L. Milder, J. P. Palastro, J. Katz, C. Dorrer, B. E. Kruschwitz, D. J. Strozzi, and D. H. Froula, Nat. Phys. **16**, 181–185 (2020).
[80]B. B. Afeyan, A. E. Chou, and W. L. Kruer, Phys. Rev. Lett. **80**, 2322 (1998).
[81]K. J. Bowers, B. J. Albright, L. Yin, B. Bergen, and T. J. Kwan, Phys. Plasmas **15**, 055703 (2008).
[82]K. J. Bowers, B. J. Albright, L. Yin, W. Daughton, V. Roytershteyn, B. Bergen, and T. J. Kwan, J. Phys. **180**, 012055 (2009).
[83]A. M. Hansen, K. L. Nguyen, D. Turnbull, B. J. Albright, R. K. Follett, R. Huff, J. Katz, D. Mastrosimone, A. L. Milder, L. Yin, J. P. Palastro, and D. H. Froula, Phys. Rev. Lett. **126**, 075002 (2021).

[84]W. L. Kruer, E. J. Valeo, and K. G. Estabrook, Phys. Rev. Lett. **35**, 1076 (1975).
[85]S. J. Karttunen, J. N. McMullin, and A. A. Offenberger, Phys. Fluids **24**, 447 (1981).
[86]B. I. Cohen, B. F. Lasinskii, and A. B. Langdon, Phys. Plasmas **4**, 956 (1997).
[87]H. C. Bandulet, C. Labaune, K. Lewis, and S. Depierreux, Phys. Rev. Lett. **93**, 035002 (2004).
[88]C. Niemann, S. H. Glenzer, J. Knight, L. Divol, E. A. Williams, G. Gregori, B. I. Cohen, C. Constantin, D. H. Froula, D. A. Montgomery, and R. P. Johnson, Phys. Rev. Lett. **93**, 045004 (2004).
[89]C. Riconda, A. Heron, D. Pesme, S. Huller, V. T. Tikhonchuk, and F. Detering, Phys. Rev. Lett. **94**, 05503 (2005).
[90]B. I. Cohen, E. A. Williams, R. L. Berger, D. Pesme, and C. Riconda, Phys. Plasmas **16**, 032701 (2009).
[91]T. Chapman, S. Brunner, J. W. Banks, R. L. Berger, B. I. Cohen, and E. A. Williams, Phys. Plasmas **21**, 042107 (2014).
[92]T. Chapman, R. L. Berger, B. I. Cohen, J. W. Banks, and S. Brunner, Phys. Rev. Lett. **119**, 055002 (2017).
[93]C. Neuville, K. Glize, P. Loiseau, P.-E. Masson-Laborde, A. Debayle, M. Casanova, C. Baccou, C. Labaune, and S. Depierreux, Plasma Phys. Controlled Fusion **60**, 044006 (2018).
[94]S. Palaniyappan, C. Huang, D. C. Gautier, C. E. Hamilton, M. A. Santiago, C. Kreuzer, A. B. Sefkow, R. C. Shah, and J. C. Fernandez, Nat. Commun. **6**, 10170 (2015).
[95]J. C. Fernandez, B. J. Albright, F. N. Beg, M. E. Foord, B. M. Hegelich, J. J. Honrubia, M. Roth, R. B. Stephens, and L. Yin, Nucl. Fusion **54**, 054006 (2014).