ENABLING IGNITION STUDIES AND ADVANCED POWER PLANTS BY DEVELOPMENT OF ULTRA HIGH FLUENCE BEAMS PRODUCED BY PLASMA OPTICS

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EXECUTIVE SUMMARY

Fusion energy production with intense lasers by various approaches is presently a leading candidate for near term power plant demos. These approaches will require lasers with total energies in the range of a megajoule (MJ) or more per pulse to be delivered to the targets. Present concepts require multiple large precision optics that must withstand significant irradiation and are expected to be a critical limit to the plant lifetime and operating costs. Reductions in plant costs are being pursued with the fast ignition (FI) approach [1, 2] which produces the needed hot spot ignition and propagation of burn in the fusion fuel by a rapid and localized deposition of ~ 10 kilojoules of energy in a region that is surrounded by pre-compressed fuel. The needed laser performance and target physics requirements of the different approaches to FI have been established by numerous target modeling efforts [3,4,5], and the experimental validation of these target physics models is the next challenge to this approach to fusion energy. Once target physics of FI and other laser fusion concepts is experimentally confirmed power plant concepts will be developed that further optimize the trade offs of target design, laser size and optic replacement rates to produce the concept with most cost effective design. This work seeks to enable both of these processes by developing the technology of self-generated ion-wave plasma optics that have been used in targets studying hot spot formation and burn in fusion fuel [6], to produce stand alone components that can produce the needed laser beam performance and optic lifetime. The use of plasma as the material for the final optics in a fusion plant is being consider by this and other approaches by numerous researcher groups and is expected to enhance the laser and therefore the target performance, by delivering energy in shorter pulses to smaller focal spots from final optics with substantially reduced area, significantly reducing power plant cost and size [5]. Our approach is to develop ion-wave optical components optimized 1) to be used in presently established fusion power plant concepts and perform demonstrations and experiments to validate models in those specific conditions, and 2) to be fielded at existing and near term facilities to enhance the laser performance available to perform target physics experiments to further optimize and validate such advanced target concepts as FI for fusion power plants. Effort in this area will develop specific components needed for fusion power plant concepts as well as capabilities that can produce a range of plasma optics needed in future fusion power plant concepts, including final optics with reduced area, and higher average power capabilities, than their solid state analogs. Each component created may undergo conceptual development, fabrication and testing in a series of steps designed to meet the requirements established to achieve specific enhanced cost and performance metrics of the relevant power plant concepts, when they are defined.

1. THE POTENTIALS OF ION WAVE PLASMA OPTICS FOR FUSION ENERGY

This work seeks to develop optical components made from plasma that will enable a range of advanced fusion power plant concepts, including those using the FI approach, because plasma is a high power and energy density material that can inherently withstand the high optical fluences that the optics in power plants will be exposed to. These plasma optics also allow increases in laser intensity on target that many other studies have identified as needed to produce smaller and lower cost fusion power plants than are indicated for concepts based on the central hot-spot ignition approach being pursued by the ICF program. The work described here is enabled by recent demonstrations of a more than 6x increase in both fluence and energy in a single beam and a concomitant reduction in focal spot size that has been produced when multiple frequency shifted beams were intersected in a plasma [7,8,9] creating a diffractive optic from stimulated ion waves. Those studies have successfully benchmarked the capability of linear plasma wave models [10,11] to describe the formation of plasma optics and the parameters of the beams created by them, when both beam and plasma conditions were relevant for fusion energy applications. Plasma optics now appear to be a likely avenue to make the next big advances in laser fluence and intensity and would enable low cost fusion applications.

Laser intensity is a critical parameter for cost efficient fusion in these advanced approaches and in the last 10 years has progressed slowly with a saturation of increases from present Chirped Pulse Amplification (CPA) [12, 13]. The limitation to laser intensity now and throughout the history of laser development has been the damage threshold of critical internal components, first amplification crystals and more recently pulse compression gratings. Although the fluence incident on optics can be reduced by increasing beam size at the optic, the requisite expense increase makes new facilities and significant leaps in beam intensity at best focus challenging (see Fig. 1 green data for existing and planned laser facilities at the limits of solid-state optics damage). Further work in this area can develop plasma optics capable of withstanding 5 orders of magnitude more fluence than conventional optics and understanding the plasma processes that create such optics will enable a new period of rapid power and intensity advancement.

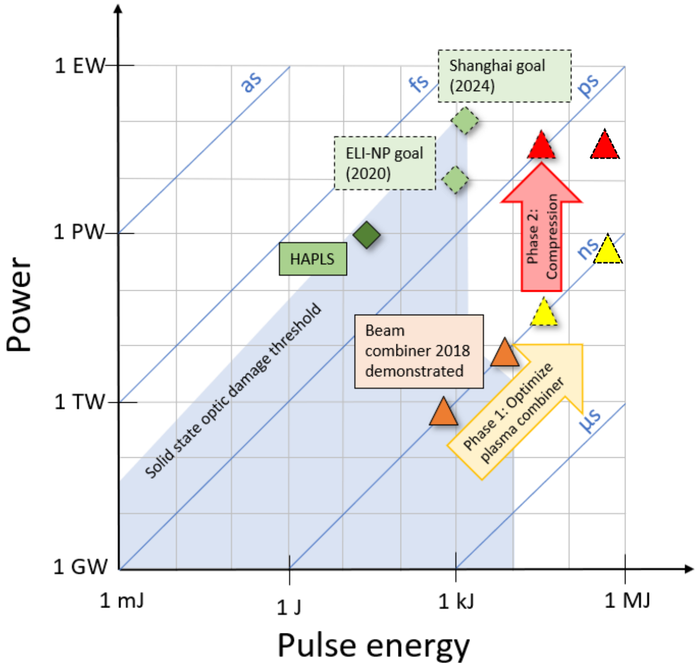

Figure 1: *Power and pulse energy of existing (solid outline diamonds) and planned (dashed diamonds) laser beams, and the limitations of solid-state optics (blue shaded region). The existing beam combiner demonstrated amplification beyond these limits (orange triangles), which this work will extend to higher energy and shorter pulse (dashed yellow and red triangles). Graphic courtesy C. Siders LLNL.*

In particular, the kJ pump energies available at NIF and other lasers have allowed study of Brillouin and other plasma scattering phenomena in a unique regime necessary to fully develop these optics. Plasma amplifiers and optics [14 - 18] have been considered for some time at lower energies and for shorter pulses, but recent progress with plasma beam combination [7, 8] has opened avenues to understanding and controlling plasma optics using existing large laser facilities. Several aspects of plasma optics that can enable advanced fusion power plants can be explored in this type of work, broadly falling into three Phases, achieving 1) record energies in a single high mode quality, 1 ns beam that can serve as a pump for the subsequent stages, 2) extreme powers by amplifying and compressing the beam to a short pulse, and 3) extreme fluence and intensities by focusing this amplified light to the size required to ignite the core of a fusion fuel assembly. In this way it appears possible to leap over the capabilities of even the planned next generation laser facilities. Critically, even modest success in a few of these areas will result in significant improvements to plasma physics understanding and enable whole regimes of new experiments to validate our understanding of hot spot physics and burn propagation on existing laser systems such as NIF.

The dramatically enhanced durability of plasma optics is due to the nature of the plasma material, in which particles have large kinetic energy and do not need to maintain bonds to other individual particles for the material to maintain the needed bulk properties. As such plasma can handle dramatically higher energy fluences and heat loads from optical or nuclear radiation without significantly ‘damaging’ or changing their characteristics than the solids used in conventional optics can. Moreover the precise structure of the plasma optic that is needed to create beams with small focal spots and short pulse durations is provided by the incident laser beams themselves in many important cases, with the precision of those beams being determined by solid state optics that create the plasma optic. With the models and understanding that are emerging, these principles can be applied to a range of optical components needed in different laser fusion power plan concepts including:

1) Plasma pulse compressors to convert the multi-ns pulse produced by existing glass lasers to the >10 ps duration needed for fast ignition concepts using either ion or electron beams, shock ignition and other concepts seeking to ignite burn by applying auxiliary heating to a small hot spot in compressed fusion fuel.
2) Plasma mirrors and beam combiners that can reduce the focal spot size of a beam or transfer energy from large spot size beams to small spot size beams for auxiliary heating of a hot spot or improved energy deposition uniformity in implosions.
3) High average power, high repetition rate plasma optics components of many kinds which will essentially re-create fresh optical material with each pulse of the laser, material that is cooled by radiation at its elevated operating temperature, dramatically reducing the cost of cooling and maintaining the solid state optics of present laser fusion concepts.
4) Plasma beam combiners have been demonstrated transfer of energy from beams with different incidence angles to a beam propagating in a direction that could be selected to optimize target performance in a range of fusion concepts, and allow operation with most of the conventional optics of the laser placed behind radiation shielding [19]. New concepts for plasma optics also promise to protect virtually all conventional optics at a fusion power plant [20].

The above list of applications of our work is by no-means complete as there will likely be more applications of ion-wave plasma optics in fusion power plants than can presently be envisioned, and the models this work provides will serve future fusion concept teams in expanding on the above list. To guide future work so as to ensure the greatest impact on future fusion power plants we highlight a few specific applications that appear to be the highest leverage for present fusion power plant concepts and are presently under study at LLNL as shown in Fig. 2 and described in the next section.

2. STATUS OF PLASMA OPTICS DEVELOPMENT AT LLNL AND NEXT STEPS

An on-going program is developing the technology of plasma optics for fusion power applications by developing a specific combined platform which by its self is directly applicable to both A) enabling studies of hot spot physics that are relevant to ignition and burn on existing and near term laser facilities (such as NIF and LMJ), and B) dramatically reducing the cost of a fusion power plant based on advanced concepts of FI approach to fusion. The baseline configuration that will be developed by three phases of this work, is a series of plasma optics components that will produce the short, intense pulse of light needed for FI and hot spot heating studies as shown conceptually in Fig. 2. Each component shown is being optimized so the system can deliver ~100 kJ to 500 kJ of energy, in pulse durations of 10 ps to 30 ps in spot sizes in the range of 10 microns to 30 microns (as has been identified in Ref.s [3-5] as needed for both ion [21] and electron beam FI). However, producing such a laser pulse would also likely enable a wider range of laser driven fusion power concepts, and the development of models of this system and their experimental verification will enable plasma based optical components to be designed and used in most any fusion scale laser.

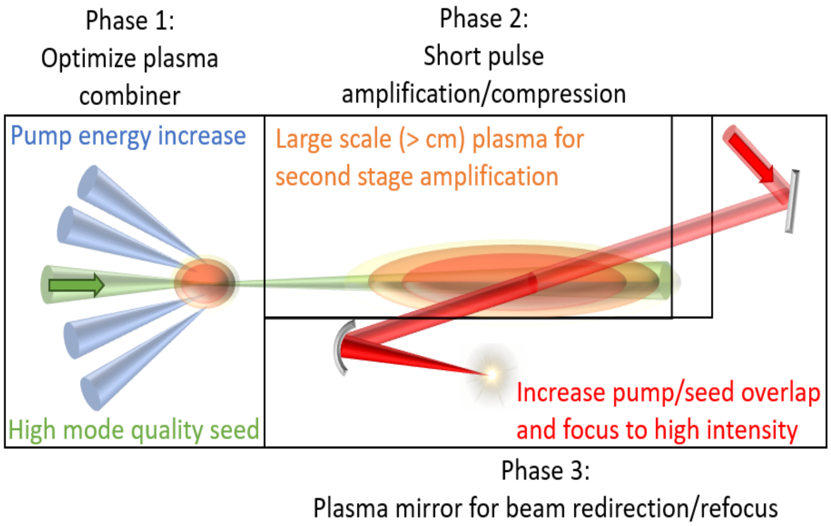

***Figure 2**: The three phases of on-going work at LLNL include 1) optimizing a beam combiner to deliver >~ 100 kJ 1ns, 2) using this output to pump a second stage short pulse amplifier/compressor producing <30 ps duration, and 3) redirecting and refocusing the short pulse beam to reduce spot size to < 30 microns and protect conventional optics from potential plasma scatter.*

As an example of what present understanding suggests may be achievable optimization of a plasma pulse compressor to produce the energy, pulse duration and spot size needed for a power plant using the fast ignition approach to fusion [1,4, 5] has begun [19]. In this example a plasma optics beam combiner and pulse compressor combination, that, as shown conceptually using the models describe here, promises to generate the > 100 kJ, 10's ps duration pulse in a 10's of micron 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 demonstrated in Ref. [7-9] (and shown schematically on the left of Fig. 2) but with a larger plasma and beam volume, thereby enabling the transfer still 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 figure 3 the energy can potentially be 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 present beam combiner can be extended to this higher energy while maintaining the similar fluence in the plasma and the same intensity x density produce. The output pulse could then be compressed by interaction with a second focusing short pulse seed beam in the susbsequent 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 further ensures that the transverse area of the seed beam when it interacts with the pump in the plasma is increased relative to the pump so that a shorter pulse seed can receive all the pump energy without producing higher intensity in the plasma that could drive secondary instabilities. Further the seed can continue focusing after the interaction and come to a reduced size best focus in the fusion target. If the present models of linear plasma wave response can be confirmed to describe the 2nd stage shown Figure 3, it could enable cost effective fusion energy with fast ignition. Our community is now well poised to do similar work for plasma optics optimize for a range of other fusion energy applications.

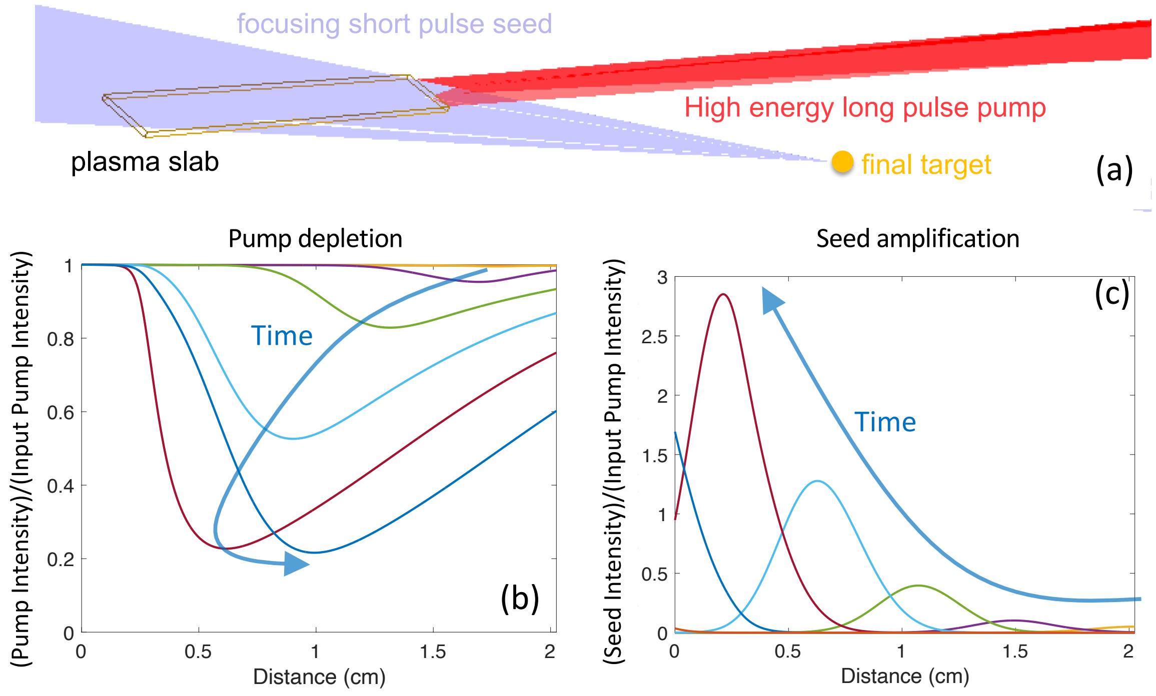

Figure 3 *a) Schematic layout for a second stage of pulse compression with a plasma optic to produce high energy and power on targets producing fusion energy by fast ignition or related techniques. 1D simulation results using the linear wave response described in Ref. [19] show b) the time dependence of the efficient depletion pump and c) the time dependent amplification of a seed of the same intensity with 20 ps duration in counterpropagating geometry that enhances of seed output power by both amplification and compression as needed for F.I. fusion energy.*

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