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Research Article
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StarDriver: Recent Results on Beam Smoothing and $2\omega_{pe}$ Mitigation

Eimerl D*

EIMEX Software and Consulting, 107 Siebe Dr, Fairfield CA 94534, USA

Abstract

StarDriver was recently proposed as a highly flexible laser driver for inertial confinement fusion and high energy density physics. It envisions a laser drive consisting of very many beams at an aperture and energy where the optical technology is well-developed, used in concert to create a large scale laser driver system. In this paper we describe a StarDriver–class laser with 5120 physical beamlets disposed about the target chamber in 80 evenly spaced ports, each port containing 64 beamlets, each beamlet having about ~1.5 THz of 2D SSD bandwidth and suitable phase plates, an aperture of ~65 mm, an energy of 80 J, and frequency-converted to ~351 nm. StarDriver has many beamlets at an aperture where optical technology is well-developed, and each beamlet has energy ~100 J in a several times diffraction limited beam. The ensemble of beamlets has frequency bandwidth 2%-10%, thereby providing significant control of both hydrodynamic and laser-plasma instabilities The drive at the target is ~400 kJ, has a well-behaved low L-mode spectrum, and smooth's very rapidly, reaching an asymptotic smoothness of <1% in less than 1 ns. We also review recent results showing that the $2\omega_{pe}$ instability can be significantly reduced by 20 THz bandwidth.

Keywords: StarDriver; Laser; Physics

Background

To achieve the plasma conditions required for Inertial Confinement Fusion (ICF) and High Energy Density Physics (HEDP) drivers that effectively compress energy in space and time and whose energy can be effectively delivered to an appropriate target are required. The top-level requirements for ICF are currently under investigation at NIF (Lawrence Livermore National Laboratory) [1,2] and Omega (University of Rochester, NY) [3,4]. One of the challenges for ICF is obtaining the necessary uniformity to drive the fusion fuel capsule. For laser driven ICF with direct drive target concepts, modeling and the world-wide data base suggest the required pulse energy (1-3 MJ), and peak power (~400-500 TW) in a temporally shaped pulse for fusion ignition and gain. For civilian energy applications, namely Inertial Fusion Energy (IFE), lasers with average power of nominally 10-20 MW at repetition rates of ~10 Hz with driver efficiencies >10% are required. It is expected over the next decade that experiments on NIF will explore the physics of a variety of target concepts with MJ-sized plasmas representative of attractive "high gain" target configurations, further develop quantitative predictive simulation tools and hopefully demonstrate fusion ignition and modest fusion gain (G>10). These experiments and the development of quantitative and predictive modeling tools will be essential for the development of laser driven IFE.

In addition to these top-level laser energy and power requirements, experiments, theory, and computer simulations have conclusively demonstrated the importance of laser wavelength and "beam smoothing" [5,6] for ICF/IFE. To achieve the required convergence ratios (20-35) the ablative pressure on the capsule must be better than 1-2% *rms* for the low spatial frequencies (L mode ~10-20), and in addition to fabrication imperfection, hydrodynamic instabilities during target implosion are seeded by high spatial frequency non-uniformities in the laser drive. Laser-plasma instabilities in the plasma around the target can reduce the laser-target energy coupling efficiency, generate "suprathermal" electrons which "preheat" the target preventing efficient compression, and redistribute the light both reducing the coupling efficiency and degrading the symmetry in the ablative pressure.

To obtain the required ablation pressures and hydrodynamic efficiency while minimizing laser plasma instabilities, UV lasers have become the baseline for all ICF concepts. Experimental data have shown that beam smoothing technologies, or more accurately technologies that reduce spatial and temporal coherence, are also essential for controlling and minimizing laser-plasma instabilities and preventing the seeding of hydrodynamic instabilities for direct drive. Techniques for beam smoothing have been developed by NRL [5] (Induced Spatial Incoherence (ISI)) and LLE [6] (Smoothing by Spectral Dispersion (SSD)) To date the former approach has only been applied to KrF lasers while the latter technique is applicable to solid state lasers including those up-converted to higher harmonics using non-linear frequency conversion techniques. Variations of SSD are found in essentially every solid state laser employed in fusion and high energy density physics research today.

Beam smoothing technologies incorporate bandwidth in a laser beam that is multi-spatial mode at the target. Regardless of the optical technology involved, it is essential that the coherence time of the radiation field at the target be short enough for the laser drive to control hydrodynamic and laser-plasma instabilities. In presently envisioned IFE laser drivers (KrF or up-converted solid state lasers) all of the apertures utilize the same gain media and therefore operate only over the limited bandwidth of that medium (~0.2% for KrF at 0.248 μm and 0.02% at 0.35 μm only over the limited bandwidth of that medium m for tripled Nd:glass). Theory and modeling have long suggested that a much larger bandwidth would be most effective in minimizing or eliminating the deleterious effects described above [7]. This limitation motivates a key attribute of the StarDriver approach. StarDriver employs a frequency-diverse collection of many apertures that enables much larger system bandwidth and combines this with a large angular spread of the beamlets irradiating any region of the corona.

StarDriver [8] is motivated by the need to irradiate mm-scale

***Corresponding author:** Eimerl D, EIMEX Software and Consulting, 107 Siebe Dr, Fairfield CA, USA, Tel: 011-925-413-0777; E-mail: deimerl@eimexinc.com

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targets at intensities of 10^{15} Watts/cm^2 at a standoff of >10 meters with a source that is essentially incoherent, in order to control hydrodynamic and laser-plasma instabilities. StarDriver envisions very many beams (~10,000), at an aperture where the optical technology is well-developed, used in concert to create a large scale laser driver system. The complete set of very many StarDriver beamlets provides both a much shorter laser coherence time for the laser field in the target (individual beam quality), as well as a much denser k-spectrum of the drive in the target corona, than any competing laser driver concept. The large number of beams also relaxes the tolerances on individual beamlet parameters compared to legacy ICF drivers, and enhances independent control of the mid-spatial frequencies and the high spatial frequencies in the drive. As mentioned above, StarDriver also offers unprecedented opportunity to optimize the laser drive including time-dependent focusing at the target in almost any parameter a laser beam may have. Such focal "zooming" is one strategy important to reducing cross-beam energy transfer in the corona and to maximize driver target coupling. The small laser aperture also reduces transverse ASE enabling the near full use of the gain media bandwidth.

We have simulated [9] the on-target time-dependent intensity profile of a StarDriver-class IFE driver with 5120 physical beamlets disposed about the target chamber in 80 evenly spaced ports, each port containing 64 beamlets, each beamlet having about ~1.5 THz of 2D SSD bandwidth and suitable phase plates, an aperture of ~65 mm, an energy of 80 J, and frequency-converted to ~351 nm. With less than 10,000 beamlets, each with 2D SSD, spanning 2% bandwidth, the laser drive on target is asymptotically less than 1% and is reached in less than 1 ns. This performance is a very significant improvement over legacy ICF laser drivers and will ease, significantly, the constraints on target concepts arising from hydrodynamic instabilities. Figure 1 summarizes the smoothing performance.

We have also estimated the growth rates for the LPI process of CBET and two-plasmon decay (TPD) using a dispersion relation approach. We found that 2% bandwidth is adequate to suppress CBET. In the larger IFE-scale targets, it may also be adequate to suppress TPD, but in general, this may require as much as 5% bandwidth. Our LPI results must be taken as highly preliminary; much further work remains.

The most significant conclusions from this study are: (1) It appears that to reach 1% smoothness about 150,000 monochromatic beamlets are required. (2) The time development of the drive asymmetry is as expected and is very similar to ISI. (3) With SSD, significant improvement in the asymptotic smoothness is achieved. With 2D SSD, the number of beamlets is reduced to about 5000 beamlets.

The $2\omega_{pe}$ instability

The $2\omega_{pe}$ instability is a nonlinear laser-plasma interaction where intense electron plasma waves are generated, creating very energetic electrons that pre-heat the ICF fuel thereby reducing its density below that required for ignition and burn. It occurs in the corona surrounding the target where the electron density is ¼ ciritical. The distribution of rays at the ¼ critical surface of the corona is quite different from the distribution of rays approaching the target from the chamber wall. All rays entering the corona are reflected. If a ray penetrates to the ¼ critical surfaces it must pass through it twice, with a direction and intensity quite different from those it had prior to entering the corona. In order to represent a more realistic picture of the laser drive we calculated the distribution of rays in a corona that is typical for IFE-scale direct drive targets.

The corona profiles we used were taken from a full 1D hydrodynamic simulation, using the NRL FASTRAD3D code, of a target designed to be directly driven by a symmetrical laser the size of NIF. The cryogenic spherical target consists of a 128-µm thick ablator shell (1.31 mm outer radius) surrounding a 223 µm- thick layer of DT-ice shell. The ablator shell (0.33 g/cm^2) is made of low-density (100 mg/cm^3) plastic (CH) foam into which liquid DT is wicked, and then frozen. This target is driven by a 13.6 ns laser pulse at 2.7 TW initially, which rises after 8.3 ns to a steady 260 TW, delivering about 1 MJ of light onto the target. The pulse is preceded about 2 ns beforehand by a short 50 ps, 8 kJ spike that shapes the adiabat in the target and reduces hydrodynamic instability growth.

At the ¼ critical surfaces the laser modes form a dense k-space where the modes span a large bandwidth. It is shown in Figure 2.

The growth rate of the instability depends on the local direction of the electron plasma waves involved. In Figure 3 we show the growth rate of the instability as a function of the total StarDriver bandwidth, where each line corresponds to a particular electron plasma wave. This graph corresponds to a time in the pulse where the instability is expected to be most virulent. Clearly a bandwidth of 20 THz would significantly reduce the instability and a bandwidth OD 35 THz migh suppress it completely.

IFE driver

A StarDriver-class IFE driver with 5120 beamlets in a ported configuration with 80 ports of 64 beamlets, each delivering 80 J in a 65 mm beam, and having 2% bandwidth would deliver 400 kJ to a direct drive target and provide both extreme flexibility in the laser drive and a high level of control of all known instabilities. The energy on target

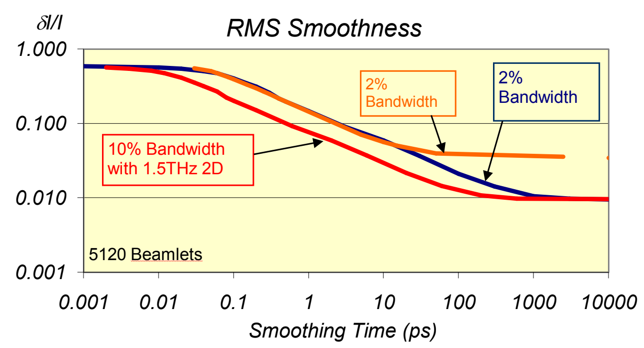

Figure 1: RMS Smoothness of a Star Driver-Class driver.

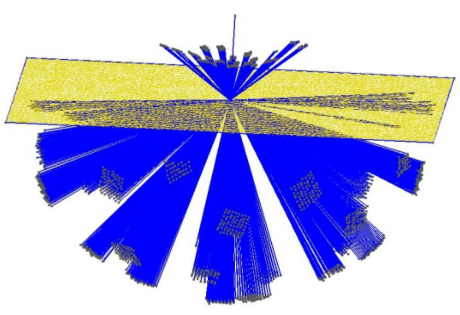

Figure 2: The k-space: direction and field strength of the laser modes. The weaker modes have turned back from the more dense plasma.

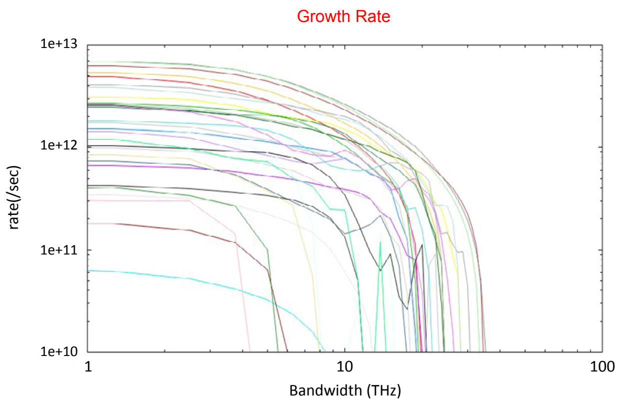

Figure 3: Absolute instability growth rates in MJ-class IFE targets.

could be increased to ~1.6 MJ without compromising the smoothing performance by increasing the number of ports to 180, increasing the number of beamlets per port to 100, and/or increasing the energy of each beamlet. Although significant research remains, 5-10% bandwidth would likely control all the known instabilities in direct drive ICF, enabling R&D to focus on the hydrodynamics of fuel compression and ignition.

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