# Advantages of KrF Lasers for Inertial Confinement Fusion Energy

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**Abstract.** Advanced concepts for direct drive inertial confinement fusion (ICF) have emerged that may lead to sufficient gain for the energy application (g>140) at laser driver energies as low as 1 megajoule. For example, recent “shock ignition” designs compress low aspect ratio pellets then apply a final high intensity spike pulse ($10^{16}$ W/cm$^2$) to ignite the fuel via a converging shock wave. These analyses were based on an excimer laser with a Krypton-Fluoride lasing (KrF) medium. KrF systems are particularly well suited to these new ideas as they operate in the deep ultraviolet ($\lambda$=248 nm), provide highly uniform illumination, possess large bandwidth (1-3 THz), and can easily exploit beam zooming to improve laser-target coupling for the final spike pulse. While this driver option is strongly supported by a multitude of attractive technological features, decisive factors for any candidate technology must assess target physics for high gain operation. This presentation will examine advantages of KrF lasers in relation to the new implosion designs. Supporting experimental and theoretical studies of hydrodynamic instabilities and laser plasma instabilities (LPI) conducted by the Nike laser group at the U. S. Naval Research Laboratory will be discussed. Recent studies of the two plasmon decay instability have made the first determination of the threshold intensity for this instability in an ICF-relevant plasma driven by a KrF laser. This instability is a major concern due to its ability to generate hot electrons that may preheat the compressed fuel prior to ignition. The observed threshold intensities are higher than that reported for longer wavelength lasers. An expanded range of allowed intensities would help KrF lasers meet the requirements of advanced ICF designs. Recent experimental work has also shown that the high ablation pressures and smooth profiles obtained with the Nike laser can be used to accelerate planar targets to velocities consistent with the requirements of impact ignition.

## 1. Introduction

An implosion directly driven by a laser was one of the earliest concepts proposed to achieve inertial confinement fusion (ICF) and remains the most straightforward.[1] The Krypton-Fluoride (KrF) laser with an operating wavelength of 248 nm has the deepest ultraviolet (UV) wavelength of all current candidates for laser drivers and it has demonstrated the most uniform illumination. These qualities provide fundamental advantages to obtaining robust high gain implosions by means of direct drive. Recent target design innovations can further mitigate the challenge posed

[1] BODNER, S.E., et al., “Overview of new high gain target design for a laser fusion power plant”, Fusion Eng. Des. **60** 1 (2002) 93.

by hydrodynamic instability. A particularly promising new approach to direct drive is shock ignition.[2] Simulations indicate that shock ignition can obtain the very high gains projected for fast ignition but with a simpler laser and target configuration.[3-4] NRL simulations indicate gains greater than 100 are feasible with a 500 kJ laser and gains potentially above 200 are possible at energies of 1 MJ when utilizing a KrF driver.[4]

Advantages of KrF for the achievement of high gain target implosions have been recognized for many years.[1] However, it was viewed as a challenging laser technology to implement compared to the ubiquitous flash lamp-pumped Nd:glass lasers that are currently used throughout the world for ICF research. Large KrF systems use high power electron beams to excite a gaseous lasing medium. Obtaining good performance from such amplifiers poses both physics and technological challenges. Nevertheless, the laser fusion program at NRL has made significant progress in advancing the state of the art in efficiency, performance and durability of large electron beam pumped KrF lasers by the development of two large scale systems. The original system, the Nike laser, is an integrated laser-target facility and is the world's largest KrF laser.[5] It has produced up to 5 kJ of laser light in 56 angularly multiplexed beams. The beam smoothing by induced spatial incoherence (ISI) that was implemented on Nike has also allowed an ability to zoom the focal diameter of the laser beams during a pulse.[6-7] This unique feature would be used to match the drive laser focal spot to the diameter of an imploding pellet to increase the overall laser-target coupling efficiency. The newer facility at NRL, the Electra laser, was designed to develop technologies that can meet the fusion energy requirements for rep-rate, efficiency, durability, and cost.[8] The 30 cm aperture main amplifier of Electra provides up to 700 J of laser energy and has demonstrated high transport efficiency (>70%) of the electron beam into the laser gas. The Electra laser has also demonstrated 50,000 shots continuous at 5 Hz and 90,000 shots at 2.5 Hz with technologies that are scalable to a full scale ($\geq$ 16 kJ) amplifier. The overall system efficiency is predicted to be greater than 7% based on advances in the electron beam transport into the gas and the KrF kinetics. This level is adequate for inertial confinement fusion systems based on the high gains predicted for the advanced KrF driven implosion designs cited above.

The combination of good target and driver performance makes direct drive with KrF lasers an attractive choice for inertial confinement fusion energy. The ongoing laser fusion program at NRL has four major objectives: (i) understanding and quantifying the benefits of KrF drivers,

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[2] BETTI, R., et al., "Shock ignition of thermonuclear fuel with high areal density", Phys. Rev. Lett. **98** 15 (2007) 155001.

[3] PERKINS, L. J. , et al., "Shock ignition: a new approach to high gain inertial confinement fusion on the National Ignition Facility", Phys. Rev. Lett. **103** 4 (2009) 045004.

[4] SCHMITT, A. J., et al., "Direct drive fusion energy shock ignition designs for sub-MJ lasers", Fusion Sci. Tech. **56** 1 (2009) 377.

[5] OBENSCHAIN, S. P., et al., "The Nike KrF laser facility: performance and initial target results", Phys. Plasmas **3** 5 (1996) 2098.

[6] LEHMBERG, R. H., OBENSCHAIN, S. P., "Use of induced spatial incoherence for uniform illumination of laser fusion targets", Optics Commun. **46** 1 (1983) 27.

[7] LEHMBERG, R. H., GOLDHAR, J., "Use of incoherence produce smooth and controllable irradiation profiles with KrF fusion lasers", Fusion Tech. **11** 3 (1987) 532.

[8] SETHIAN, J. D., et al., "Electron beam pumped KrF lasers for fusion energy", Phys. Plasmas **10** 5 (2003) 2142.

(ii) developing the high performance ICF target designs through theoretical analysis and computer simulations, (iii) conducting experimental studies of hydrodynamics and laser-plasma instabilities in targets driven by a KrF laser, and (iv) addressing the basic scientific and technological issues in the production and operation of advanced electron-beam pumped KrF lasers for the longer term energy application. This paper will briefly describe the first three goals related to the continued advances in target physics being made at NRL through theory and experiment.

## 2. Theoretical Modeling and Direct Drive Target Designs for KrF Lasers

The main scientific consideration for any fusion concept is achieving enough performance (gain) for economically viable energy production. The required gain is determined by the typical metric for an inertial fusion power plant: $\eta G > 10$, where $\eta$ is the laser efficiency and G is the target gain. A projected efficiency (wall plug to light on target) of 7% for KrF lasers means the target gain must be at least 140. The highest possible gain is desired not only because it decreases recirculating power and produces more energy for a given laser size, but also allows robust enough operation to overcome the inevitable degradations in performance that are inherent in a real system.

There are three main target physics requirements for high gain: efficient laser/target coupling, mitigation of hydrodynamic instabilities, and control of laser plasma instabilities. These problems must be addressed simultaneously to produce a high performance design. KrF lasers have several key advantages. The smooth laser beam and high bandwidth minimize laser induced perturbations, or 'imprinting", on the target which can seed hydrodynamic instabilities. The short laser wavelength maximizes coupling efficiency and has been demonstrated to increase the threshold for deleterious laser plasma instabilities. This allows the target to be driven to higher implosion velocities for higher gain, or alternatively with higher pressures for better hydrodynamic stability. Finally, the zooming capability of KrF lasers can further increase the laser-target coupling efficiency thereby reducing the total energy required in the driver.

The NRL laser fusion program has developed a Eulerian hydrocode, FASTRAD3D, that has been optimized for simulating direct drive targets. It is capable of routine high resolution 1-dimensional and 2-dimensional simulations of Nike planar target experiments as well as pellet implosions. Examples of the high gain designs that demonstrate a progression towards higher performance are shown in Fig. 1. Conventional direct drive designs with implosion velocities of 300 km/sec are shown for a KrF system ($\lambda$=248 nm).[9] These designs reach power plant class gains (G>140) for total laser energies around 1.5 MJ. Higher velocity (350-400 km/sec) direct drive designs (labeled 'FTF') take advantage of the deeper UV of a KrF laser to achieve higher yields with less total laser energy - G>50 at 500 kJ and G $\geq$140 around 1 MJ.[10] The advantages of KrF relative to Nd:glass are illustrated in Fig. 1 with a comparison of theoretical scaling for

[9] SCHMITT, A. J., et al., "Large-scale high-resolution simulations of high gain direct-drive inertial confinement fusion targets", Phys. Plasmas **11** 5 (2004) 2716.
[10] COLOMBANT, D. G., et al.," Direct-drive laser target designs for sub-megajoule energies", Phys. Plasmas **14** 6 (2007) 05631.

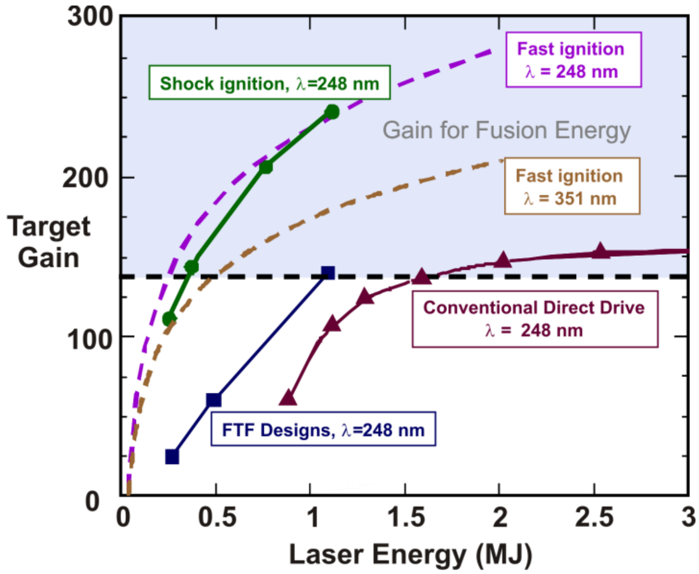


*Figure 1: Gain curves from 1D simulations of various high performance direct drive target designs comparing KrF performance to third harmonic Nd:glass systems. Shaded region shows sufficient gain for pure fusion power plant. Dashed lines represent an analytical prediction for fast ignition. 'FTF' designs refer to a particular set of conventional direct drive designs that use high implosion velocity without a shock ignition pulse.*

gains from fast ignition implosions.[11] Compared to a third harmonic Nd:glass system (λ=351 nm), a KrF-based design (λ=248 nm) can reduce the total energy needed to achieve ignition and significant gain by up to a factor ~2 due to increased absorption and higher hydrodynamic efficiency.

More recently, "shock ignition" designs have also shown promise of requiring only ~ 1 MJ (KrF) lasers for a power plant.[2] In this scheme, a short, high intensity laser pulse applied near the time of peak compression drives a high intensity shock to ignite the core. While its yields are at least as high as for fast ignition (see Fig. 1), shock ignition has an edge over fast ignition because it naturally leads to less complicated targets (e.g. no gold 'guiding' cone) and it eliminates the need for an additional, specialized laser system for the ignition pulse. Simulations of shock ignited targets at NRL predict both high gains and robust resistance to hydrodynamic instabilities like Rayleigh-Taylor and Richtmyer-Meshkov. The hydrodynamic stability is in large part due to the low implosion velocity (i.e. 200-250 km/s rather than the 300-400 km/s in conventional direct drive implosions) and the correspondingly low aspect ratio pellets (~2.5 in initial designs). Pellet aspect ratios and hydrodynamic instabilities are also reduced by the relatively high laser compression intensities in these designs ($1.5\text{-}2\times10^{15}$ W/cm$^2$). The curves in Fig. 1 are a compilation of 1D target simulations. Full 2D simulations have been carried out for many of these designs. For example, 2D simulations of shock ignition targets that incorporate realistic non-uniformities in the target surfaces and laser imprint, have shown about 70% of the gain predicted in 1D.

[11] BETTI, R., et al., "Gain curves for direct-drive fast ignition at densities around 300 g/cc", Phys. Plasmas **13** 10 (2006) 100703.

While there is a large amount of theory and experiment to support the hydrodynamics used in the above simulations, one area that is difficult to assess is the effect that laser plasma instabilities (LPI) will have on the predicted gains. Target designs try to avoid LPI that occur in the ablated plasma surrounding the pellet, primarily because they can excite fast electrons that might preheat the compressed fuel. These effects are less of a concern with shorter wavelength lasers because the intensity threshold for their onset is higher. Experiments with the Nike KrF laser indicate that the thresholds occur at higher intensities than are reported for Nd:glass systems operating at longer wavelengths ($\lambda \geq 351$ nm), see Section 4, and at levels that are similar to the highest compression intensities used in the current target designs. The intensity of the final spike in the shock ignition designs (typically around $10^{16}$ W/cm$^2$), however, is expected to be well above thresholds for LPI. Consequent reductions in gain at later times may be limited because the imploding capsule wall becomes thicker and denser. Simulations suggest that "late" hot electrons below 100 keV will be stopped by the outer surface of the compressed core and may even result in a more efficient heating mechanism that enhances ignition.[3]

## 3. Hydrodynamic Experiments at the Nike KrF Laser

Experiments at the Nike laser facility have studied the effects of KrF drive on laser-driven hydrodynamics. To begin, this laser typically produces 2-3 kJ divided between 44 main beams used to drive targets and 12 diagnostic beams in a separate array for x-ray backlighting. The main beam pulse duration can be varied from 0.3 to 8.0 ns and the spot size can be varied from 180 to 1200 μm in diameter (full-width at half maximum, FWHM). Nike's chosen method of beam smoothing by echelon-free induced spatial incoherence (ISI) provides flat-top uniformity ($\delta I/I$) at a level better than 0.2% when the 44 main beams are overlapped on target.[12] For hydrodynamic studies of the seeding of instability growth by laser imprint, the amount of smoothing can be controlled by selecting either a single beam or multibeam foot pulse. The single beam case has approximately 6x more nonuniformity than the multibeam case. Smoothing can also be controlled through variation of the bandwidth produced in the initial stages of the laser chain. The laser's coherence time has been varied from 0.5 ps to 1.6 ps to vary the laser nonuniformity from 0.2% to 0.5% for imprint studies. Finally, the short wavelength of Nike (248 nm) implies greater absorption of the laser light, leading to higher ablation pressures. This property, combined with the high spatial uniformity has been crucial to many of the hydrodynamics experiments performed at the facility at intensities relevant to direct drive schemes (up to $I{\sim}5\times10^{14}$ W/cm$^2$). The ISI technique has enabled a more recent addition of a zooming capability that allows the main beam spot size to be altered during a laser pulse. This capability may be used for future experiments exploring target acceleration to high velocities and for future studies of LPI with long scale length plasmas.

The planar target geometry allows precise high resolution studies with time–resolved monochromatic x-ray imaging[13]. VISAR and a streaked optical shock breakout diagnostic are also routinely available. The x-ray diagnostic has made it possible to

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[12] DENIZ, A. V., et al., "Comparison between measured and calculated nonuniformities of Nike laser beams smoothed by induced spatial incoherence", Optics Commun. **147** (1998) 402.

[13] AGLITSKIY, Y., et al., "High-resolution monochromatic x-ray imaging system based on spherically bent crystals", Appl. Optics **337** 22 (1998) 5253.

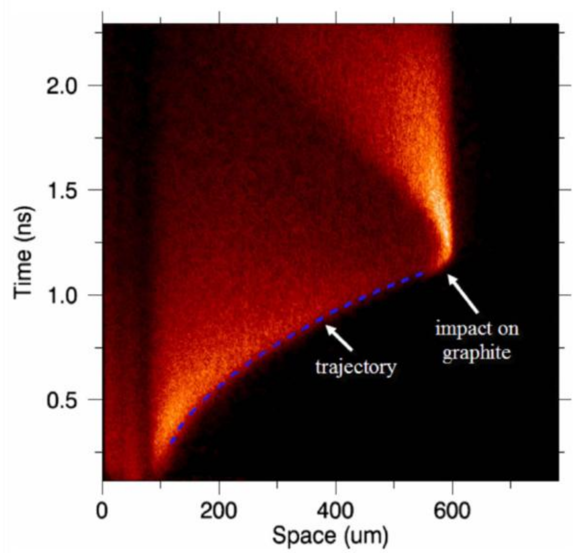


*Figure 2: Side-on streaked image of x-ray self-emission from highly accelerated CH foil. Laser from the left side of image drives the foil into a stationary graphite target on right. Velocity before impact is 1040±60 km/s.*

obtain detailed measurements of a wide range of hydrodynamic phenomena. Initial experimental campaigns investigated 1-D and 2-D Rayleigh-Taylor growth of modulated plastic[14] and cryogenic deuterium targets[15], and the ability of thin high Z overcoats to mitigate laser imprinting.[16] The first observations of the ablative Richtmyer-Meshkov instability (the process that forms the RT perturbation seeding from the roughness of the outer target surface) as well as the full cycle of areal mass oscillations due to feedout (a mechanism forming the RT perturbation seeding from the inner target surface) were performed on the Nike laser.[17] Recent experiments demonstrated for the first time that the stability of a non-accelerated ablation front is an intrinsic property that holds even when target acceleration abruptly stops due to collision with a stationary foil.[18] The x-ray diagnostic capabilities at NRL made it possible to see not just the shock motion, as permitted by the VISAR technique, but the entire post-shock flow extending to the ablation front.

A critical application requiring the high uniformity and high ablation pressure created by a KrF laser was demonstrated in a 2009 campaign performed in collaboration with researchers from Osaka University.[19] These experiments accelerated thin targets to achieve record high

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[14] PAWLEY, C., et al., “Measurements of laser-imprinted perturbations and Rayleigh-Taylor growth with the Nike KrF laser”, Phys. Plasmas **4** 5 (1997) 1969.

[15] SETHIAN, J., et al., “Direct drive acceleration of planar liquid deuterium targets”, Phys. Plasmas **6** 5 (1999) 2089.

[16] OBENSCHAIN, S. P., et al., “Effects of thin high-Z layers on the hydrodynamics of laser-accelerated plastic targets”, Phys. Plasmas **9** 5 (2002) 2234.

[17] AGLITSKIY, Y., et al., “Direct observation of mass oscillations due to ablative Richtmyer-Meshkov instability in plastic targets”, Phys. Rev. Lett. **87** 26 (2001) 265001.

[18 ] AGLITSKIY, Y., et al., “Stability of a shock-decelerated ablation front”, Phys. Rev. Lett, **103** 8 (2009) 085002.

[19] KARASIK, M., et al., “Acceleration to high velocities and heating by impact using Nike KrF laser”, Phys. Plasmas **17** 5 (2010) 056317.

velocities (v~1000 km/s) for bulk material. The motivation for this effort arises from the impact ignition concept for ICF wherein a small foil is accelerated to high speed and collided into a compressed pellet.[20] If sufficiently high density and velocity of this impactor are achieved, then the collision will ignite and burn the assembled core in a manner similar to the fast ignition concept – while easing requirements for the secondary drive laser (e.g. longer pulse, lower total energy). Figure 2 shows an example of a side-on x-ray image from this experiment where a 10.5 μm thick CH foil was driven by a 2 ns pulse across a 600 μm wide gap into a stationary graphite foil. In this image, the laser drives the impactor foil from the left side of the page. The emission from the foil as it accelerates to the right has been imaged onto a streak camera slit by the x-ray optics. The sharp intensity contrast across the foil's thickness indicates integrity of the foil until impact with the second foil. The final velocity of the impactor foil just prior to impact is >1000 km/s. In contrast, the previous record for a glass laser was ~700 km/s achieved with the Gekko/HIPER Nd: glass laser (λ=351 nm) at Osaka University.[21] Interpretation of the NRL experiments, in particular the target integrity and bulk velocities, has been accurately predicted by simulations performed with FASTRAD3D and analytical models.

## 4. Laser Plasma Interaction Experiments at the Nike Laser

Laser-plasma instabilities were identified as a major obstacle to success in laser driven inertial confinement fusion at the earliest stages of development. The coupling between the incoming light and plasma corona surrounding the pellet can lead to several significant problems: a reduction in drive intensity due to absorption or scatter, an increase in illumination nonuniformities (e.g. self-focusing, filamentation, beam cross-talk), and creation of energetic electrons that deposit energy in the compressed fuel thereby preventing high density and ignition. These problems are not strictly limited to either direct drive or indirect drive concepts, although the relative importance of the various processes can be strongly influenced by the configuration of the target and laser. Advances in laser driven ICF have been achieved mainly by the adoption of shorter wavelength, which raises the threshold for LPI, and the development of the various methods of beam smoothing (ISI, smoothing by spectral dispersion (SSD), random phase plates (RPP), polarization smoothing). Shorter wavelengths have a higher rate for collisional absorption rates in the plasma and reduce the magnitude of the ponderomotive force that drives many of the coupling processes. Beam smoothing reduces the occurrence of localized high-intensity laser speckles or 'hot spots' that can serve to initiate instabilities even when the average intensity is below the threshold for onset of growth. The dominance of the Nd:glass systems in ICF has created a large knowledge base for such systems operating up to the third harmonic (typically $\lambda \geq 351$ nm). The regime defined by the shorter wavelength and unique beam smoothing of KrF lasers has not been well explored in experiments.

The three major instabilities in ICF plasmas are stimulated Brillouin scattering (SBS), stimulated Raman scattering (SRS), and the two plasmon decay instability (TPD). While SBS can play an important role in many situations, the current work at NRL has emphasized observation of SRS

[20] MURAKAMI, M., et al., "Innovative ignition scheme for ICF – impact fast ignition", Nucl. Fusion **46** 1 (2006) 99.
[21] AZECHI, H., et al., "Experimental evidence of impact ignition: 100-fold increase of neutron yield by impactor collision", Phys. Rev. Lett, **102** 23 (2009) 235002.

and TPD which directly couple laser light to electron plasma waves. If sufficiently strong, these driven waves can, in turn, generate enough energetic (hot) electrons to spoil an implosion by preheating the fuel. Of these two instabilities, theory predicts that TPD will have the lowest intensity threshold, hence the greatest threat to implosion designs. The experimental program at the Nike laser has begun to investigate LPI by exploring the excitation of parametric instabilities at intensities of up to $\sim 5\times 10^{15}$ W/cm$^2$. These intensities are higher than the ‘standard’ Nike operation used for the hydrodynamics experiments and have been accessed by utilizing smaller spot diameters ($D_{FWHM}$ as low as 180 μm) and shorter pulses ($T_{FWHM} \sim 0.4$ to 1.0 ns). The dominant observed instability has been TPD which has an onset at intensities between 1-2$\times 10^{15}$ W/cm$^2$. Expected emission signatures of SRS have not been observed to date. These results are generally consistent with expectations from idealized theoretical results that treat the laser as a homogeneous planar beam propagating through a plasma with a linear density gradient. As the threshold formulae typically scale as $I \propto 1/\lambda$ where $\lambda$ is the laser wavelength, measurements at Nike confirm that KrF lasers have a higher intensity threshold than has been reported for experiments that utilized 3rd harmonic light from Nd:glass lasers.

Much experimental work needs to be done to more fully explore LPI driven by KrF lasers. Ongoing efforts will continue to refine these results by characterization of the saturation of TPD, hot electron generation, and the role that the unique features of the KrF laser (e.g. ISI, bandwidth) play in determining the LPI evolution. Cryogenic and foam targets are also available for better simulation of actual pellet structures. The energy limitations for the Nike laser preclude simultaneously reaching the plasma parameters expected for the advanced targets, thus preventing a definitive evaluation of the threat of LPI to the implosion designs. This is especially true for the shock ignition ‘spike’ pulse where the designs use intensities of $\sim 10^{16}$ W/cm$^2$. While it will be valuable to pursue related experiments at the larger facilities to advance knowledge of LPI relevant to NRL target designs, the strongly nonlinear nature of LPI processes and concomitant theoretical challenges warrant further experimental efforts with a KrF laser closer to the scale envisioned for a prototype system.

## 5. Conclusion

The KrF laser system is becoming a mature technology that can fulfill the requirements of laser driven inertial confinement fusion. Recent theoretical innovations, especially shock ignition designs, have indicated the short wavelength, high bandwidth, ISI beam smoothing, and zooming capability of KrF lasers could lead to attractive power plants that are simpler and more economical than systems based on diode-pumped solid state laser (DPPSL) technology. A large body of knowledge has been developed to show a good understanding of the hydrodynamics of targets driven by KrF lasers. Recent results have clearly demonstrated how the short wavelength and high uniformity available from these systems allow access to new regimes where high target velocities may be required. Finally, initial studies show that the characteristics of KrF lasers may reduce the threat that LPI poses for advanced implosion designs. Continued development of this approach to inertial confinement fusion appears highly promising.

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