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The LLNL ICF Program: Progress Toward Ignition and Gain in the Laboratory

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THE LLNL ICF PROGRAM: PROGRESS TOWARD IGNITION IN THE LABORATORY

ABSTRACT

The Inertial Confinement Fusion (ICF) Program at the Lawrence Livermore National Laboratory (LLNL) has made substantial progress in target physics, target diagnostics, and laser science and technology. In each area, progress required the development of experimental techniques and computational modeling. The objectives of the target physics experiments in the Nova laser facility are to address and understand critical physics issues that determine the conditions required to achieve ignition and gain in an ICF capsule. The LLNL experimental program primarily addresses indirect-drive implosions, in which the capsule is driven by x rays produced by the interaction of the laser light with a high-Z plasma. Experiments address both the physics of generating the radiation environment in a laser-driven hohlraum and the physics associated with imploding ICF capsules to ignition and high-gain conditions in the absence of alpha deposition. Recent experiments and modeling have established much of the physics necessary to validate the basic concept of ignition and ICF target gain (fusion energy released by ICF capsule/ driver energy delivered to target-capsule assembly) in the laboratory. The rapid progress made in the past several years, and in particular, recent results showing higher radiation drive temperatures and implosion velocities than previously obtained and assumed for high-gain target designs, has led LLNL to propose an upgrade of the Nova laser to 1.5 to 2 MJ (at 0.35 μm) to demonstrate ignition and energy gains of 10 to 20—the Nova Upgrade.

An upgrade to the Omega laser is supported by progress in the direct-drive approach to ICF, particularly in the production of extremely smooth beams and in the Omega implosion results. A direct-drive addition to the Nova Upgrade would be justified by positive results from the Omega Upgrade campaign of hydrodynamically equivalent implosions and from the LLNL–University of Rochester direct-drive planar hydrodynamic experiments in the Nova two-beam facility. If this addition were begun by about 1996, it should be possible to demonstrate ignition and gain by the direct-drive approach by about the year 2000.

1. INTRODUCTION

The LLNL ICF Program is addressing the critical physics and technology issues directed toward demonstrating and exploiting ignition and propagating burn to high gain with ICF targets for both civilian and military applications. Nova is the primary U.S. facility employed in the study of the x-ray-driven ("indirect-drive") approach to ICF. In this concept, laser energy is converted to x-radiation in a hohlraum (a centimeter-scale, high-Z chamber that traps electromagnetic radiation); this x-radiation then implodes and heats the fusion fuel in an ICF capsule. Nova's principal objective is to demonstrate that laser-driven hohlraums can achieve the conditions of driver-target coupling efficiency, driver irradiation symmetry, driver pulse-shaping, target preheat, and hydrodynamic stability required by hot-spot ignition and by fuel compression to realize a fusion gain (fusion energy released/driver energy delivered) of 2 to 10. The Nova experimental program also addresses and elucidates many of the plasma physics and fluid dynamics issues important to both indirect- and direct-drive ICF.

The primary focus of the LLNL Program is indirect-drive ICF. The LLNL Target Physics program, as described in Sec. 2, has two principal elements: (1) hohlraum laser-plasma (HLP) physics, which addresses driver-plasma coupling, generation and transport of x rays, and the development of energy-efficient hohlraums; and (2) hydrodynamically equivalent physics (HEP), which addresses the capsule physics associated with ignition and gain. The Precision Nova project, as described in Sec. 3, encompasses the upgrades to the Nova experimental facility (laser, laser diagnostics, target diagnostics, and target fabrication) required to conduct the experiments that constitute the HLP and HEP target-physics programs. Significant progress has recently been made in this project.

The primary scientific requirement for realizing the full military and civilian applications of ICF is achieving target gain (the ratio of fusion energy produced to driver energy beamed at the target) of about 50 to 100 or greater. Once an ICF capsule ignites, the propagation of the fusion burn to produce high gain is relatively straightforward. A laboratory demonstration of ignition and propagating burn would be the final step in establishing the scientific feasibility of ICF. An ignition/low yield laboratory facility will provide the data needed to bridge the gap between the Halite/Centurion and Nova data and will thereby document the scientific feasibility of ICF.

Lawrence Livermore National Laboratory therefore believes that the next major step in the national ICF Program is the demonstration of ignition and moderate gain ($G \lesssim 10$). Recent theoretical and experimental results show that the ignition drive energy threshold can be reduced significantly by operating indirectly driven targets at radiation temperatures ~1.3 to 1.6 times higher (thereby achieving higher implosion velocity) than originally proposed for the Laboratory Microfusion Facility (LMF). (Temperatures of ~1.3× have already been demonstrated on Nova.) Specifically, it should be possible to demonstrate ignition and propagating burn with about 1.5 to 2 MJ of laser energy as against the 5 to 10 MJ that is necessary for the high-yield LMF. LLNL proposes to upgrade the existing Nova facility to 1.5 to 2 MJ (3- to 5-ns pulses) and to demonstrate ignition and propagating burn to low gain appropriately scaled hydrodynamic equivalents of high-yield targets. The rapid progress made in the last several years in target physics and in laser and target-fabrication technologies gives us confidence that this Nova Upgrade, described in Sec. 4, can be built and operated as designed and that ignition and gain will be experimentally demonstrated by the end of this decade.

2. TARGET PHYSICS

Figure 1 schematically illustrates the target physics requirements for ignition and propagating burn to a new energy gain. The target-physics investigations with Nova and Precision Nova required to verify the predictions of ignition and energy gain fall under two major headings: (1) hohlraum laser-plasma (HLP) physics issues associated with driver-target coupling, symmetry, and long-scalelength laser-plasma instabilities in hohlraums; and (2) hydrodynamically equivalent physics (HEP) implosion issues associated with hydrodynamic stability, mix, and symmetry conditions relevant to capsule ignition and gain in the absence of alpha deposition.

2.1 Hohlraum laser-plasma physics

To achieve the efficient coupling of laser energy to the plasma required to achieve high gain for acceptable driver energy (≲5 to 10 MJ), the laser-plasma coupling must be dominated by inverse bremsstrahlung absorption. Parametric instabilities that reduce the absorption of the laser light by the target plasma or that generate suprathermal electrons, which can preheat the fuel, must be minimized or eliminated [1]. For example, instabilities such as stimulated Brillouin scattering (SBS) linearly increase the required driver energy for a fixed gain, whereas processes such as stimulated Raman scattering (SRS), which generate suprathermal electrons, increase the required driver energy approximately as f_{hot}^3 for a fixed gain (f_{hot} is the fraction of the driver energy that is contained in the suprathermal electron population with a mean energy of $3/2\, kT_{hot}$).

Recent LLNL experiments have concentrated on studying such processes in the long-scalelength plasmas ($L/\lambda > 10^3$, where L is the plasma scalelength and λ is the vacuum wavelength) associated with high-gain targets. Experiments on Nova that have studied SRS in such large plasmas have been reported [2]. In addition to the research on SRS, over the past several years we have extensively investigated ponderomotive filamentation [3]. A quantitative understanding of filamentation, including its threshold, stability, and nonlinear evolution, is necessary to evaluate the various beam-smoothing techniques that have been developed or proposed to reduce the intensity modulation that can act as the seed for filamentation and to understand its ramifications in determining the mix of laser-plasma coupling processes that occur in the corona. To complement Ref. 2 on SRS, we summarize our research in ponderomotive filamentation below.

The quantitative characterization of filamentation has been difficult because no direct emission process is associated with it. Measurements to infer filamentation have generally included imaging and spectroscopy of secondary optical emission and x-ray imaging [3]. To perform more quantitative measurements, we have developed techniques that employ laser beams having a well-defined intensity perturbation with a given spatial frequency, and we have used phase-sensitive techniques with optical probes to directly measure the intensity-driven density depression within the plasma.

The results of such an experiment using 1-μm light, a preformed exploding-foil plasma, and a 0.26-μm probe are shown in Fig. 2(a). Interferometry is used to observe the phase shifts due to the density depressions caused by filamentation. In these experiments the wave number k_r was systematically varied from 750 to 3000 cm^{-1}. Density depressions are clearly visible with k_r = 750 and 1500 cm^{-1}. Little or no growth of filamentation with k_r = 3000 cm^{-1} is observed, as expected with the known plasma conditions. Figure 2(b) shows the inferred spatial-growth wave numbers $k_i(\lambda)$ and corresponding values from the simple homogeneous theory. The agreement is very good.

2.2 Hydrodynamically equivalent physics

Inertial confinement fusion requires a quantitative understanding of hydrodynamic instabilities so that the energy threshold for ignition and the achievable gain (for a given energy) can be predicted. Such understanding is also necessary to specify the fabrication quality (and characterization) of high-gain targets. In high-gain ICF, where the target acceleration is designed to minimize entropy addition to the fuel, the Rayleigh-Taylor instability is of most concern [4].

A generalized dispersion relation relates the modal growth rate γ to the various parameters characterizing the ablation-driven acceleration a, i.e., $\gamma = \gamma(a, k, L, V_a)$, where V_a is the ablation velocity. Recent theoretical/computational work addressing the Rayleigh-Taylor instability in accelerating plasmas driven by laser-driven ablation have obtained dispersion relations of the form [5]

$$\gamma = \alpha \sqrt{\frac{ka}{1 + kL}} - \beta k V_a \equiv \varepsilon \gamma_{\text{class}} = \varepsilon \sqrt{ka}. \tag{1}$$

By fitting this analytic form to numerical simulations, Takabe and Morse [5] obtained $\alpha = 0.9$ and $\beta = 3$ with $kL \ll 1$ (because L in electron-driven ablation is of the order of the electron mean free path at the ablation surface and is typically $\lesssim$1 to 2 μm).

Present theoretical and experimental research on hydrodynamic stability is directed towards three areas: (1) the determination of the effective single-mode growth rate in the linear regime; (2) the early nonlinear evolution, including the generation of harmonics; and (3) the effect of a spectrum of modes in determining the onset of nonlinear behavior and the net perturbation at the relevant interface. The Nova experimental program is directed to all three areas and involves both planar foil and integrated implosion experiments.

To create an independent x-ray backlighting source, one Nova beam (2 ns, 2 kJ, 0.35 μm, defocused to a spot size of 500 μm) was fired onto a planar foil target. This source was placed ~7 mm behind the focus of a 22× magnification Wölter x-ray microscope. The x-ray image was recorded with either an x-ray streak camera, allowing for continuous, 50-ps time resolution of a one-dimensional slice through the image, or with an x-ray framing camera that yielded as many as four two-dimensional images with gate times of 100 ps. The diagnostic and experimental techniques, including the x-ray backlighter, were well characterized to permit quantitative comparison with detailed hydrodynamic simulations [6]. At each instant the measured transmission contrast (corrected for the instrument modulation transfer function) between the peak and valley of the areal density modulation is spatially Fourier analyzed. The logarithm of this contrast for each Fourier component is then plotted against time.

Figure 3 shows the behavior of the observed amplitude of the fundamental initial modulation frequency from the Fourier transform for small and intermediate initial modulation. In both cases, opacity contrast was not observed at $t = 0$. The best we can do is infer its value, knowing the amplitude of the initial perturbation and the foil thickness and scaling the initial contrast observed in the case of large initial amplitude. Doing this gives growth factors of 20 for the intermediate and 60 for the small initial-perturbation cases.

The smooth curves shown in Fig. 3 represent the results of a two-dimensional, Lagrangian hydrodynamics calculation. To obtain results that can be compared with the observed opacity contrast, the hydrodynamic calculation outputs are post-processed by transporting the measured backlighter x-ray spectrum through the calculated foil as a function of time. The measured instrumental response is folded into this calculation. The agreement between observation and calculation is quite striking. The fact that the calculations tend to disagree late in time during the nonlinear phase may reflect a shortcoming of a Lagrangian code for situations exhibiting large mass flow.

3. PRECISION NOVA

The broad-based effort in laser, target, and diagnostic capabilities to enhance the Nova facility's experimental capabilities is known as the Precision Nova project. The upgrades will enable us to irradiate targets with 0.35-μm light in pulses having complex shape, a high degree of power balance, and high pointing accuracy, enabling us to implode capsules to a radial convergence of at least 15 to 20. The imploded capsules will attain very high densities and will experience hydrodynamic growth factors similar to those expected in ignition-and-gain implosions. It will also be necessary to improve target-fabrication capabilities to perform the noncryogenic HEP implosions, as well as upgrades to target diagnostics to accurately diagnose the implosions. Progress in all three areas has been significant:

- We have demonstrated a four-level continuous pulse at 0.35 μm with a maximum contrast of 125:1.
- New, absolutely calibrated, full-aperture 0.35-μm laser diagnostics have been installed on two of the 10 beams of the Nova laser.
- We have demonstrated 0.35-μm power balance of 4% on two beams throughout a 10:1-contrast shaped pulse.
- We have demonstrated an x-ray framing-camera gate time of <35 ps, a factor of 3 improvement over existing instruments.
- We have made substantial progress in constructing the advanced, high-resolution, sensitive neutron spectrometer. Activation is scheduled by October 1991.
- We have fabricated and irradiated advanced hohlraums on Nova.
- We have developed techniques for doping ablator materials of intermediate atomic number. Such ablators are required to control preheat and hydrodynamic stability.
- A differential optical profilometer for determining surface roughness (0.1-μm resolution) and thickness of fusion capsules (0.01-μm resolution) is operational.

The improved performance of Nova at 1.05 μm has allowed us to increase the 0.35-μm energy for target experiments. The 0.35-μm energies at which Nova had previously been operated were due to both reduced 1.05-μm energy (deliberately reduced to avoid damage to the laser glass; the damage limit was ~ 60 kJ for $t > 1$ ns), and reduced 0.35-μm frequency conversion with the Type II/II KDP arrays because of the slight depolarization (4% of the 1.05-μm energy) arising from stress birefringence in the amplifier glass and spatial filter lenses [7]. In addition to solving the damage problem, the new amplifiers have essentially eliminated birefringence in the laser glass. The depolarized output energy in a laser chain is now typically 2% and is principally due to the spatial-filter lenses. These improvements have resulted in on-target 0.35-μm energies exceeding 45 kJ in a 2-ns pulse (energies at the output of the KDP crystals are typically 15% greater) [8].

4. NOVA UPGRADE

LLNL proposes the Nova Upgrade path as an alternative to the earlier LMF path for pursuing the defense and energy applications of ICF. The impetus for the Nova Upgrade comes from the recent demonstration that significantly higher radiation-drive temperatures and implosion velocities are possible. Operating at higher drive temperatures allows an increase in capsule implosion velocity without the otherwise deleterious effects of reduced hydrodynamic stability that results from increasing implosion velocities at fixed drive conditions. As shown in Fig. 4, the increase in implosion velocity has a significant effect on the ignition cliff, or the threshold drive energy for initiating propagating burn. The energy delivered by the proposed Nova Upgrade (1.5 to 2 MJ at ~600 TW) has a margin of safety of a factor of ~2 for ignition and propagating burn to low gain.

The proposed Nova Upgrade is an 18-beamline Nd:glass laser. The laser has a compact multipass design, fully relayed, with 4 × 4 segmented optical components. Each beamline is thus composed of 16 "beamlets," giving a total of 288 beamlets in the system. The beamlets are optically independent and individually pointed at the target for maximum control of illumination uniformity. Specifications for the laser are determined by the ignition target requirements, which are shown in Table 1.

The most important sources of our confidence in meeting the energy and power goals lie in the fact that demonstrated damage thresholds (at both 1.05 and 0.35 μm) and frequency-conversion efficiencies exceed the values used in the Nova Upgrade baseline design. The extraction efficiency of a Nd:glass amplifier operating in a multipass configuration is directly proportional to the average 1.05-μm fluence that can be safely handled by the optical elements. As shown in Table 2, we have operated Nova at average and peak fluences that exceed those of the Nova Upgrade design. Demonstrated damage thresholds of all other optical components meet or exceed the requirements at both 1.05 and 0.35 μm. Conversion efficiencies of 84% from 1.05 to 0.35 μm have been measured with KDP crystals at the full 30-cm Nova Upgrade aperture, well in excess of the 70% assumed for the baseline design.

Computer codes have been written to model laser performance, including energy storage, extraction, propagation, and frequency conversion. These codes have been validated by comparison with data from Nova. Combining these codes with cost models and the new, high-damage-threshold materials allows a cost/performance optimization of the Nova Upgrade design. The Nova Upgrade performance resulting from the optimization process is shown in Fig. 5. Each point in the figure represents a design optimized for the pulse duration indicated. The curve shows the performance of the Nova Upgrade design over the entire range of pulse durations. The figure shows that the Nova Upgrade design performs as well as the best possible design for pulse durations of 2 to 8 ns, and is only ~10% below the best design for shorter pulse durations.

5. SUMMARY AND CONCLUSIONS

The LLNL ICF Program is addressing the critical physics and technology issues directed towards demonstrating and exploiting high-gain ICF for both civilian and military applications.

Substantial progress in a number of areas critical for high-gain ICF has been made during the past several years. Recent improvements in Nova have resulted in a demonstration of output energies in excess of the original design goals. Continued refinement and improvement of our pulse-shaping capability has led to experimental demonstrations of high-density implosions. Basic physics studies exploring both hydrodynamic stability and ponderomotive filamentation have been successfully completed. These experiments have been very encouraging in that our ability to model such diverse phenomena has been quantitatively demonstrated.

We believe that the next major step in the national ICF Program is the demonstration of ignition and moderate gain (G ≲ 10) before the turn of the century utilizing an upgrade to the Nova laser from its present 40- to 50-kJ, 50-TW (0.35 μm) output to 1.5 to 2 MJ, 300 to 600 TW (0.35 μm). The rapid progress made in the last several years in target physics and appropriate laser and target fabrication technologies and the recent demonstration of significantly increased hohlraum drive temperatures and implosion velocities, give us confidence that the Nova Upgrade can be built and operated as designed and that ignition and gain will be experimentally demonstrated.

An upgrade to the Omega laser is supported by progress in the direct-drive approach to ICF, particularly in the production of extremely smooth beams and in the implosion results obtained in the Omega laser facility. The linkage of the direct-drive program on the Omega Upgrade and the indirect-drive program on the Nova Upgrade should be noted: A direct-drive addition to the Nova Upgrade would be justified by positive results from the Omega Upgrade campaign of hydrodynamically equivalent implosions and from the joint LLNL–University of Rochester direct-drive planar hydrodynamic experiments on the Nova two-beam facility. If this addition were begun by about 1996, it should be possible to demonstrate ignition and gain by the direct-drive approach by about the year 2000.

With the initiation of an Inertial Fusion Energy (IFE) technology development program in the next few years, as recommended in the final report of the Fusion Policy Advisory Committee [9], and demonstration of ignition and gain by about 2000, an IFE Engineering Test Facility (ETF) and an IFE prototype reactor could be available in about 2015 and 2025, respectively, as indicated in Fig. 6.

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Figure Captions

Fig. 1. The requirements for ignition and energy gain targets for ICF fall into four major categories: (1) driver-target coupling, (2) symmetry, (3) stability, and (4) pulse shaping.

Fig. 2. (a) Interferograms of preformed plasmas irradiated with a beam with a controlled one-dimensional intensity perturbation of varying spatial wave number. (b) Spatial growth rate k_i vs perturbation wavelength $\lambda = 2\pi/k_r$ for preformed plasma conditions of (a). Reduced data from (a) is also plotted in the figure.

Fig. 3 Rayleigh-Taylor growth of perturbations on slabs driven with pulse-shaped drive. The smooth curves are LASNEX simulations, and the jagged curves represent the data. The small-amplitude cases show growth by factors of about 20 and 60. Perturbations had wavelength 50 μm.

Fig. 4 Calculated target gains vs laser driver energy at fixed hohlraum coupling efficiency as a function of drive temperature.

Fig. 5 Nova Upgrade laser designs for optimization of laser power with pulse length.

Fig. 6 Inertial confinement fusion energy development path.

Table 1. Requirements for target ignition.

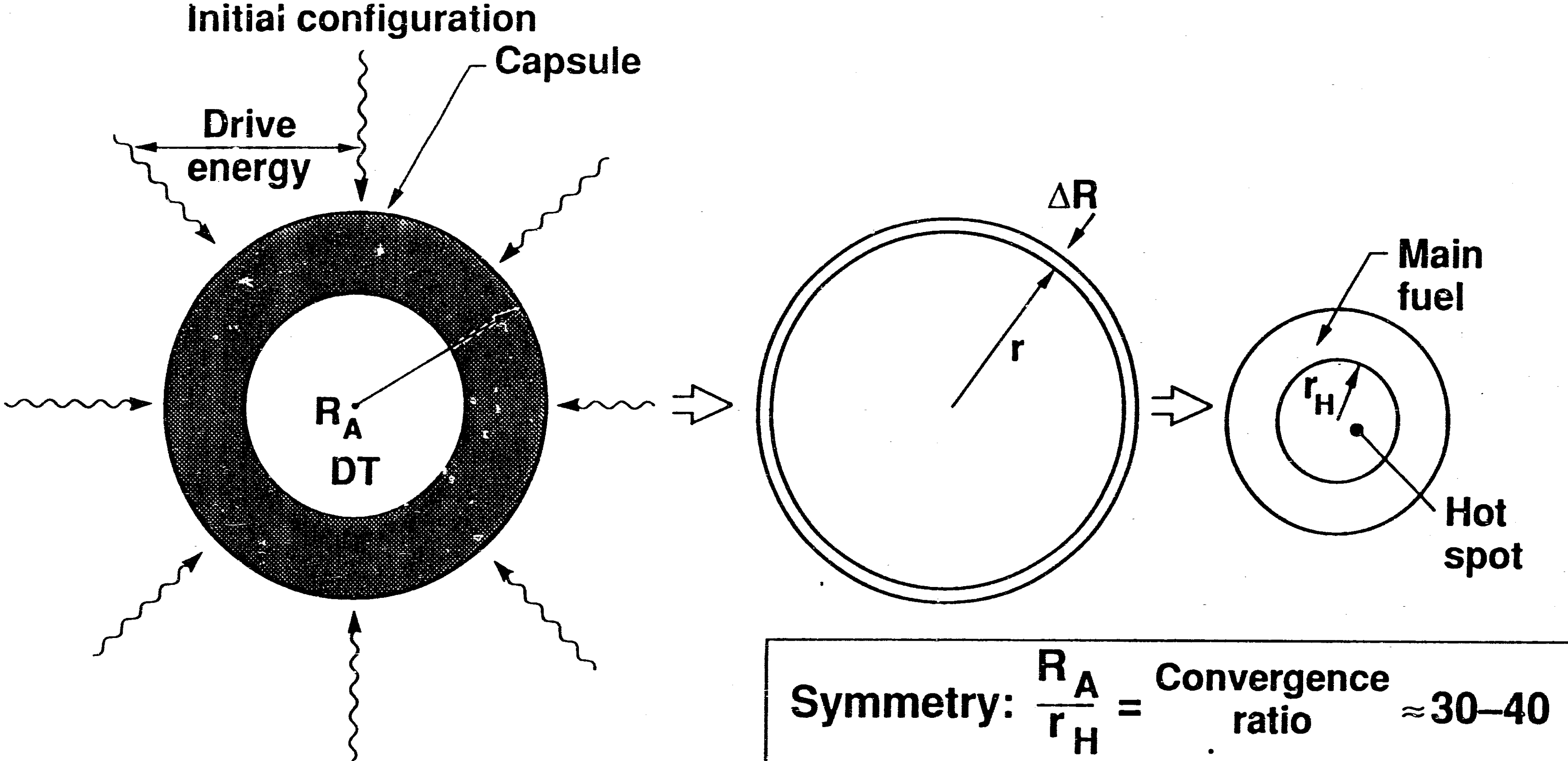
Energy at 0.35 μm	1.5–2 MJ
Pulse duration	3–5 ns
Peak power	300–600 TW
Pulse shape	Continuous or picket fence
Dynamic range	>100:1 (continuous)
	10–40:1 (picket fence)
Power balance	5–10% rms
Pointing accuracy	10–30 μrad

Table 2. Average and peak fluences demonstrated in existing Nova operations and corresponding specifications for Nova Upgrade. Peak-to-average fluence ratio is 1.5 in both cases.

	Nova demonstrated (Beamline 7, 2.5-ns pulse)	Nova Upgrade design (2.5-ns operation)
1.05-μm area-weighted average fluence (J/cm^2)	12.3	11.2
1.05-μm peak fluence (J/cm^2)	18.5	16.8

Ignition and Gain

Many high gain ICF targets have common features



Driver-target coupling

- Absorption
- Transport
- Preheat

Symmetry: $\frac{R_A}{r_H}$ = Convergence ratio ≈30–40

Stability: $\frac{r}{\Delta R}$ = In-flight aspect ratio ~ 25–35

Pulse shaping

50-00-0390-1696G

9/28/90

Figure 1

HLP

Experimentally measured ponderomotive filamentation growth lengths agree with theoretical predictions

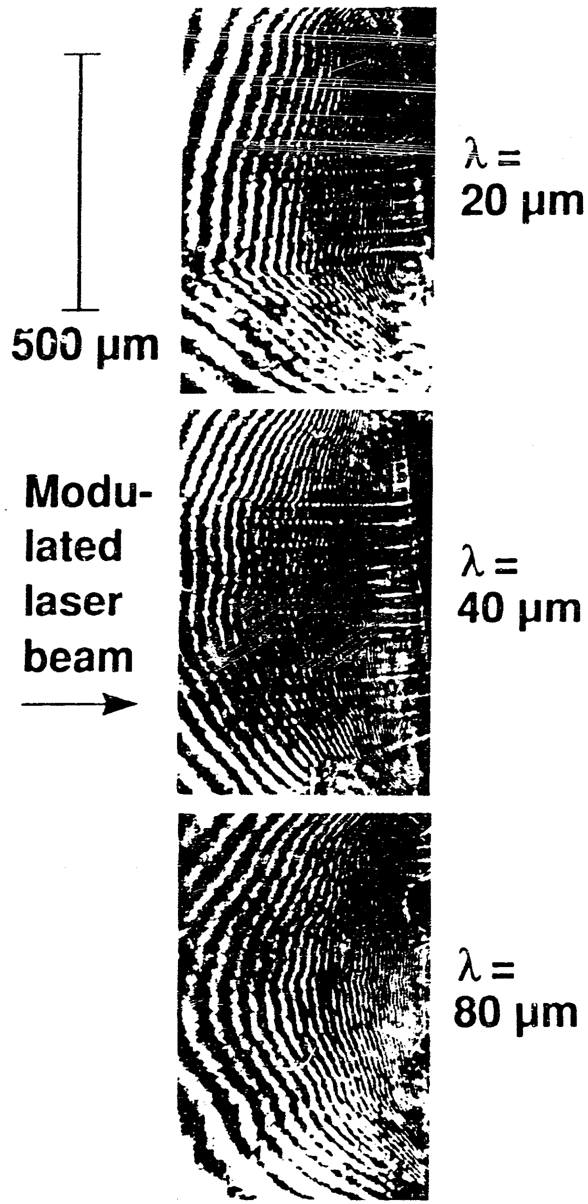


Figure 2a

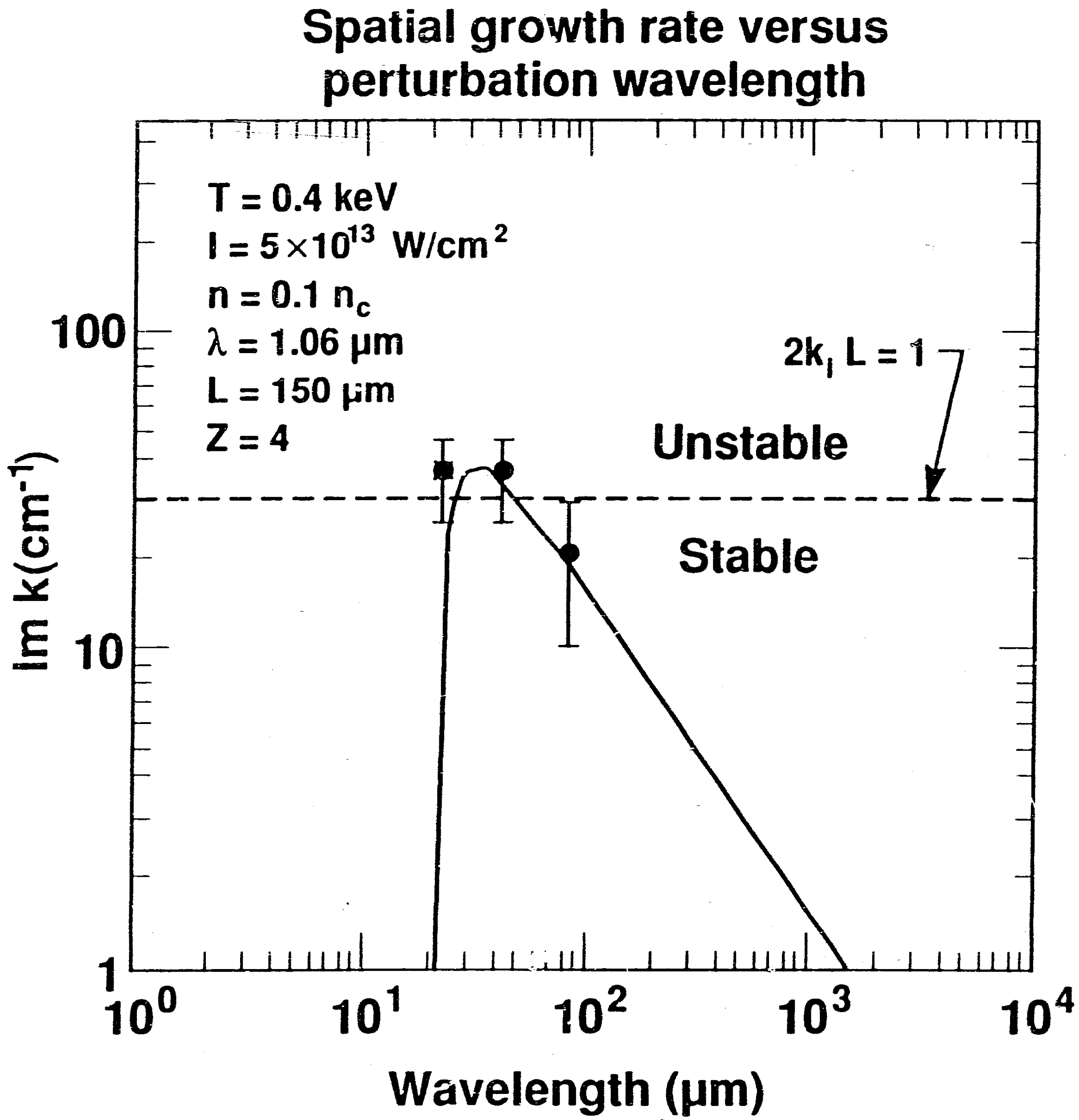


Figure 2b

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HEP

Experimental R-T growth rates are reduced by ablation and density scale length and are in good agreement with theoretical prediction

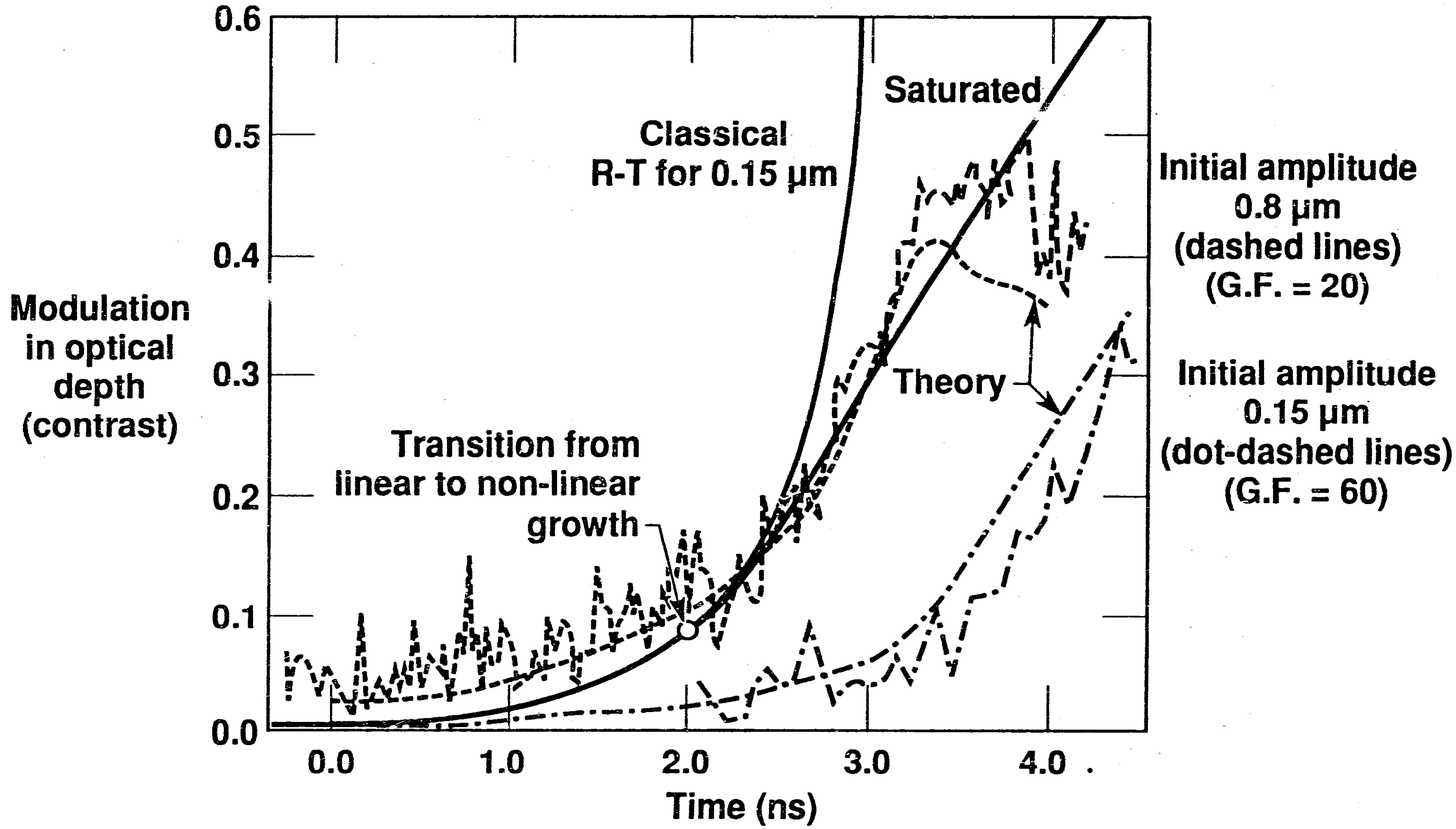

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Figure 3

Nova Upgrade

Increasing implosion velocity for a fixed hydro stability criteria allows ignition and propagating burn at lower drive energy

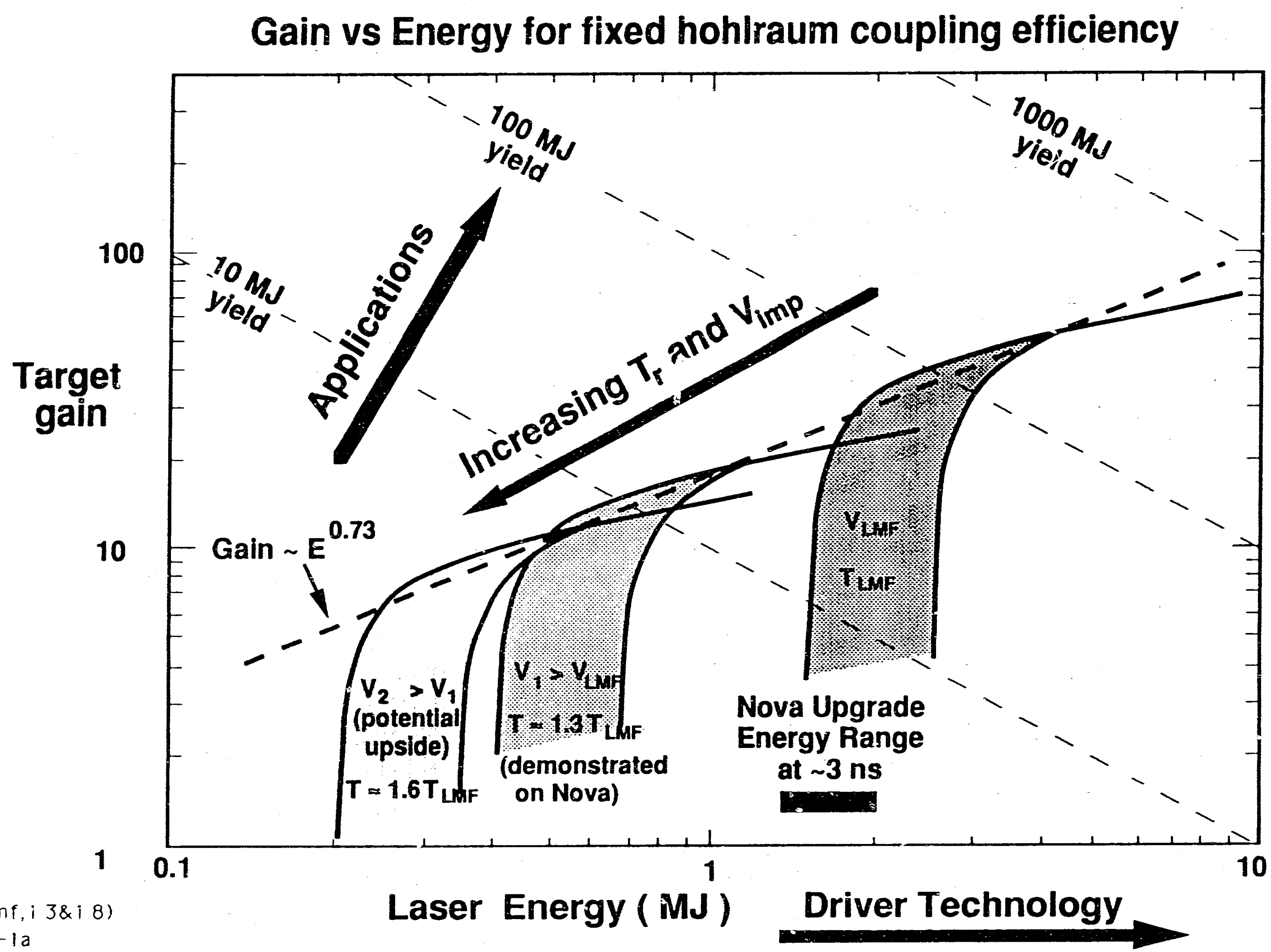

Figure 4

GvsE Tr/(lmf,i 3&i 8)
179-8-7-es-1a

Optimized laser has broad flexibility in performance

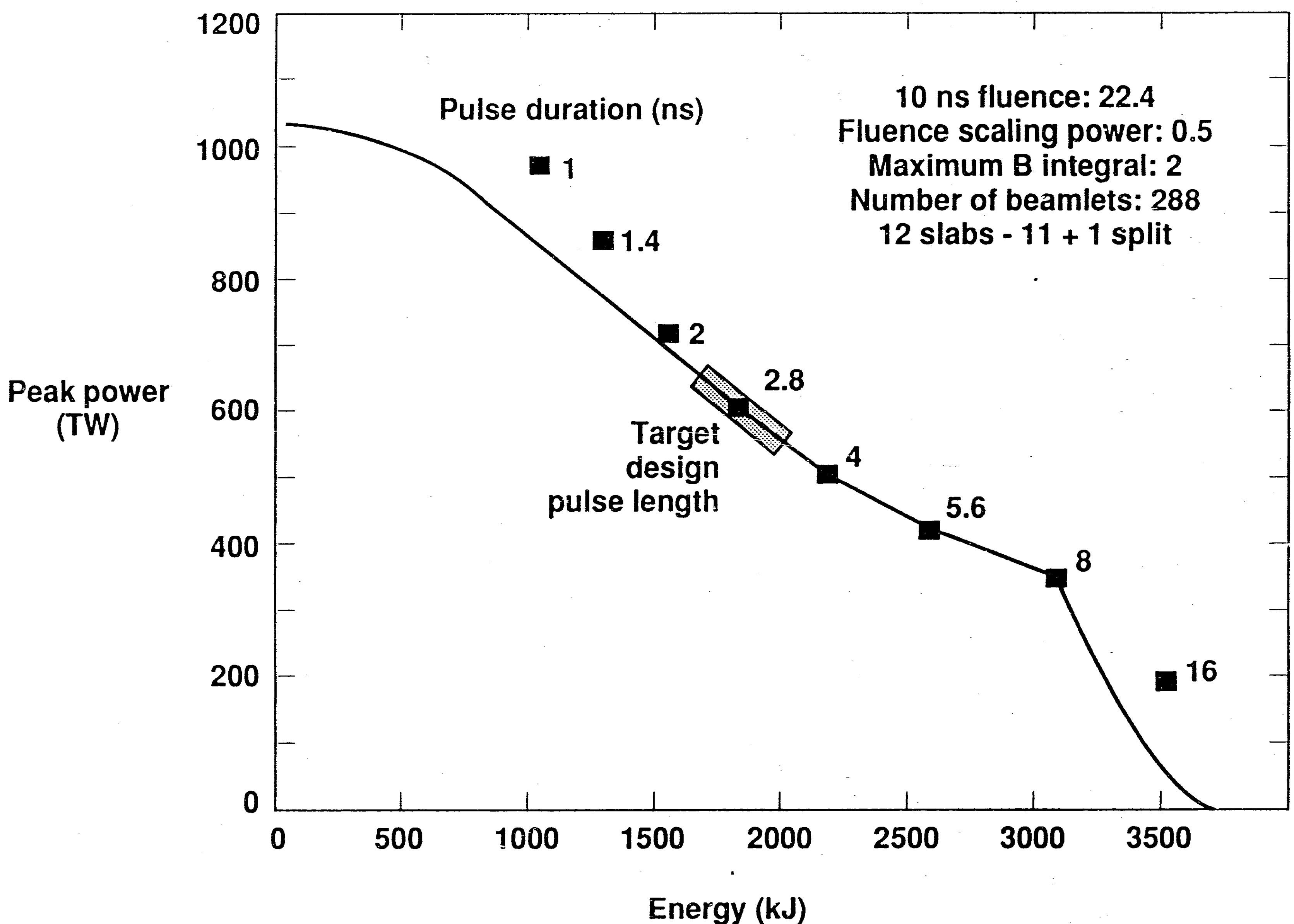

Figure 5

Summary

Demonstration of ignition and gain on Nova Upgrade would allow an IFE deployment decision by ~ 2000

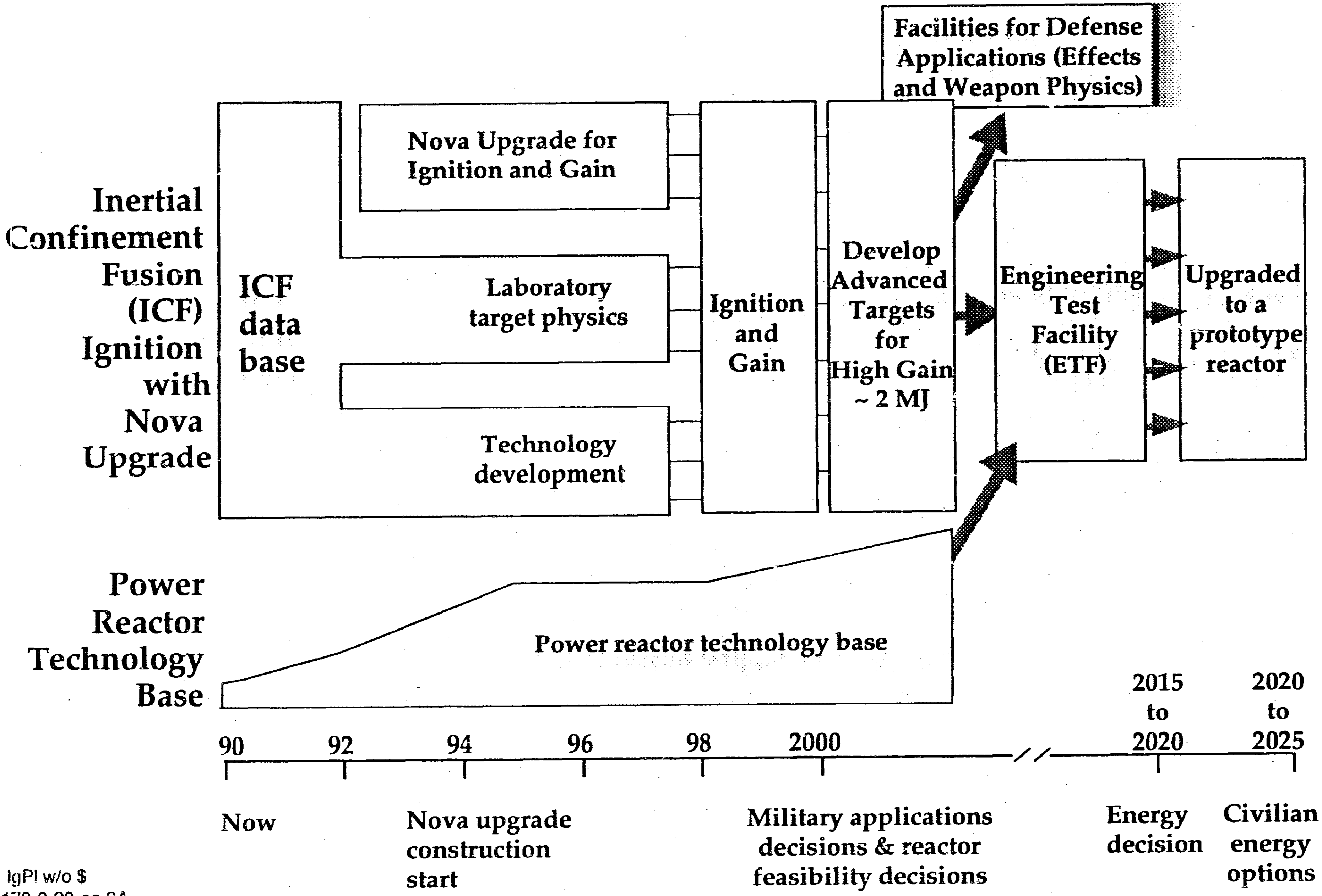

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Figure 6

END

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