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Pre-Amplifier Module for Laser Inertial Confinement Fusion: Stable, uniform, precise, high-gain interchangeable module

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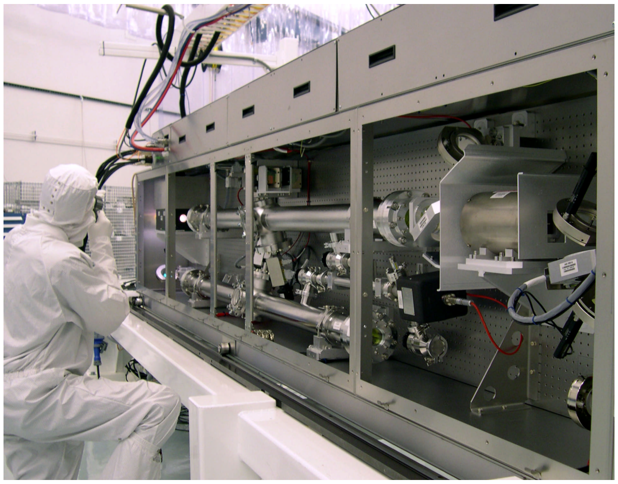
Pre-Amplifier Module for Laser Inertial Confinement Fusion:
Stable, uniform, precise, high-gain interchangeable module

Lawrence Livermore National Laboratory



The Pre-Amplifier Modules (PAMs) are the heart of the National Ignition Facility (NIF), providing most of the energy gain for the most energetic laser in the world. Upon completion, NIF will be the only laboratory in which scientists can examine the fusion processes that occur inside stars, supernovae, and exploding nuclear weapons and that may someday serve as a virtually inexhaustible energy source for electricity. Consider that in a fusion power plant, 50 cups of water could provide the energy comparable to two tons of coal.

The National Ignition Facility requires 48 interchangeable PAMs.

Each PAM provides 100 decibels (dBs) of optical gain—equivalent in audio terms to the difference between a whisper and a jet engine on takeoff.

Energy output of each PAM is up to 10 joules.

Shot-to-shot energy stability is < 1%.

A fully programmable beamshape eliminates the laser-induced growth of defects in the costly downstream optics.

Of paramount importance for achieving laser-driven fusion ignition with the least energy input is the synchronous and symmetric compression of the target fuel—a condition known as laser power balance. NIF's 48 PAMs thus must provide energy gain in an exquisitely stable and consistent manner. While building one module that meets performance requirements is challenging enough, our design has already enabled the construction and fielding of 48 PAMs that are stable, uniform, and interchangeable.

PAM systems are being tested at the University of Rochester's Laboratory for Laser Energetics, and the Atomic Weapons Enterprise of Great Britain has purchased the PAM power system.

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AFFIRMATION: I affirm that all information submitted as a part of, or supplemental to, this entry is a fair and accurate representation of this product.

Submitter's signature: ___________________________

2. **Joint entry with:**

N.A.

3. **Product name:**

Pre-Amplifier Module (PAM) for Laser Inertial Confinement Fusion

4. **Brief description:**

Ultra-stable, uniform, and interchangeable multi-Joule, 100-dB laser amplifiers provide optical gain for the world's most energetic laser in the study of inertial confinement fusion.

5. **When was this product first marketed or available for order?**

The Pre-Amplifier Module (PAM) technology in its current configuration was first available for order in December, 2008. We entered the PAM technology in the R&D 100 competition in 2008. Since then, we have upgraded the capabilities of the PAM by adding a Programmable Spatial Shaper (PSS) device. With this upgrade, we are now able to dynamically adjust the beam shape to compensate for (1) higher-order nonuniformities of the downstream amplifiers and (2) shadow-mask flaws in the downstream optics that are susceptible to laser-induced damage growth. We expect that this upgrade will save NIF $5 million per year in operational costs: refurbishing damaged optics was anticipated to cost approximately $5 million per year. The upgraded PAM eliminates these costs.

6. **Inventor or Principal Developer**

Lawrence Livermore National Laboratory

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7. **Product price**

There are no current plans to bring the PAM to market; however, its overall value was demonstrated by the decision of the Laboratory for Laser Energetics (LLE) at the University of Rochester and the Atomic Weapons Establishment (AWE) of the United Kingdom to purchase NIF Preamplifier hardware rather than design and build their own systems or procure commercial products. LLE purchased a complete PAM/Power Supply system, and AWE bought several NIF Preamplifier Power Supplies to support their experimental programs.

8. **Do you hold any patents or patents pending on this product?**

Yes for subcomponents, but not on the PAM as a whole.

9. **Describe your product's primary function as clearly as possible.**

Lawrence Livermore National Laboratory's (LLNL's) Pre-Amplifier Modules (PAMs) are modular and interchangeable subsystems that provide most of the energy for the National Ignition Facility (NIF). Each of the 48 PAMs amplifies a seed pulse from less than a nanojoule to as much as 10 joules, or a factor of 10 billion. The pulse is then split four ways to feed four Main Amplifiers, where the energy of each is increased again, this time by a factor of a few thousand. All 192 beamlines combine at the target chamber for a total energy that exceeds a megajoule. This enormous energy is essential for achieving fusion ignition.

Significance of the National Ignition Facility

Since the late 1940s, researchers have used magnetic fields to confine hot, turbulent mixtures of ions and free electrons called *plasmas* so that they can be heated to temperatures of 100 to 300 million Kelvins (180 million to 540 million degrees Fahrenheit). Under those conditions, positively charged deuterium nuclei (containing one neutron and one proton) and tritium nuclei (two neutrons and one proton) can overcome the repulsive electrostatic force that keeps them apart and fuse into a new, heavier helium nucleus with two neutrons and two protons. The helium nucleus has a slightly smaller mass than the sum of the masses of the two hydrogen nuclei, and the difference in mass is released as kinetic energy, according to Albert Einstein's famous formula $E = mc^2$. The energy is converted to heat as the helium nucleus, also called an alpha particle, and the extra neutrons interact with the material around them.

In the 1970s, scientists began experimenting with powerful laser beams to compress and heat the hydrogen isotopes in capsules to the point of fusion. The fusion reaction propagates outward through the cooler, outer regions of the capsule much more rapidly than the capsule can expand. Magnetic fields are unnecessary as the plasma is confined by the inertia of its own mass. The technique is called inertial confinement fusion, or ICF.

NIF is designed to produce fusion burn and energy gain using a novel indirect approach to ICF on a heretofore-unprecedented scale. NIF's intense laser beams, focused into a tiny gold cylinder called a *hohlraum*, will generate a surrounding bath of soft x rays that will compress a tiny hollow shell filled with deuterium and tritium to 100 times the density of lead. As a result, a temperature of more than 100 million degrees Celsius and pressures 100 billion times the Earth's atmosphere will be achieved. Under these extreme conditions, the fuel core will undergo a self-sustaining thermonuclear burn or *ignition*, releasing 10 to 100 times more energy than the amount deposited by the laser beams.

Experiments on NIF beginning in 2010 will be the first using ICF to generate more energy released from the fusion fuel than the laser energy used to produce the fusion reaction. Creating ICF and energy gain in the NIF target chamber will be a significant step toward making fusion energy viable in commercial power plants. Determining the minimum energy needed to start the fusion process is critical to determining the viability of inertial fusion energy, thus NIF can provide the basis for evaluating future decisions about inertial fusion energy development facilities and programs.

In a fusion power plant, the heat from the fusion reaction would be used to drive a steam-turbine generator to produce electricity. The simplest fusion fuels, the heavy isotopes of hydrogen (deuterium and tritium), are derived from water and the metal lithium, a relatively abundant resource. The fuels are virtually inexhaustible—one in every 6,500 atoms on Earth is a deuterium atom—and they are available worldwide. One gallon of seawater would provide the equivalent energy of 300 gallons of gasoline; fuel from 50 cups of water contains the energy equivalent of two tons of coal. A fusion power plant would produce no pollutants or climate-changing gases, as well as considerably fewer and less environmentally harmful radioactive byproducts than current nuclear power plants. NIF will not be used to generate electricity. However, by demonstrating fusion ignition and energy gain in the laboratory, NIF experiments should bring fusion energy a giant step closer to being a viable source of virtually limitless energy.

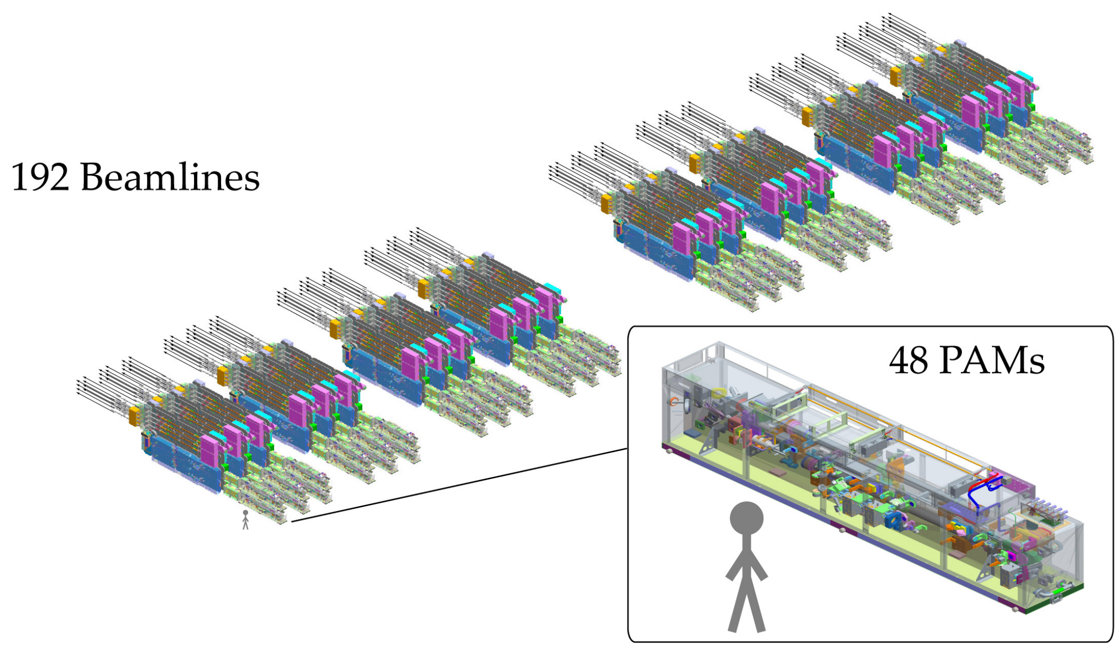


Figure 1. CAD rendering of the system of 48 PAMs and four-way branching optics feeding 192 main beamlines (arranged in 24 bundles of 8 in upper left). The insert shows a blowup of a PAM, with a human figure for scale.

NIF Amplification

NIF will rely on 192 pulsed laser beams (Figure 1) to compress targets, resulting in pressures and densities required to initiate thermonuclear burn. The laser amplifiers provide optical gain of over 13 orders of magnitude from nanojoules to tens of kilojoules per beamline. Inside NIF's stadium-size building, laser components shape and smooth a seed pulse, amplify it more than a quadrillion times, and direct it at a tiny target precisely centered in the target chamber. This process is replicated simultaneously 192 times, with all beamlines converging on the target chamber. The combined action of gain (>13 orders) and multiplexing of beamlines (>2 orders) results in an energy rampup across 15 orders of magnitude. Figure 2 illustrates the critical role that the 48 PAMs play in delivering most of this amplification with its two internal stages: the Regenerative amplifier (Regen) and Multi-Pass Amplifier (MPA).

Appendix C includes two short Quicktime videos: a tour of the PAM factory, and a PAM being installed into the NIF system.

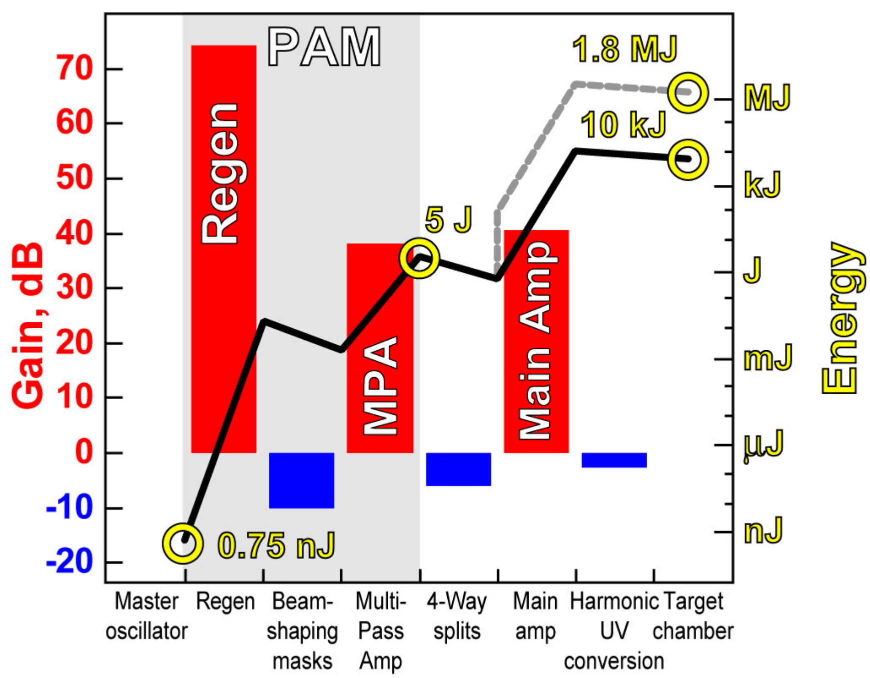


Figure 2. An overview of the NIF gains and energies by subsystem. The red bars represent laser amplifier gain, and the blue bars represent losses due to beam-shaping, beamline splitting, and harmonic-conversion elements. The solid black line denotes the accumulated energy per beamline. The dashed line represents the combined energy of 192 beamlines. Fifteen orders of magnitude are traversed in the rampup of energy delivered to the fusion target. More than ten of these orders of magnitude are delivered by the PAMs.

The PAMs at Work

Each PAM is a precision, two-stage, high-gain laser amplifier with a gain of over 10 billion. PAMs have been designed to enable the construction of the largest and most energetic laser ever built. Of paramount importance for achieving ignition on NIF with the lowest possible input energy is the synchronous and symmetric compression of the target fuel, a condition known as laser power balance. This in turn demands that the 48 PAMs provide their gains in an exquisitely stable and consistent manner. All PAMs have met a demanding set of requirements, including energy and pointing stability and beam and pulse-shape flexibility.

In addition, interchangeability was a significant requirement.Laser amplifier systems at the joule level are not common, though commercially available systems do exist. Typically, these are custom systems designed to be used individually in research labs, not in concert as part of a larger, synchronized system of amplifiers. Each tends to have idiosyncrasies resulting in inconsistencies that preclude interchangeability. To build 48 such systems (plus spares) that conform to precision standards enabling them to be fully interchangeable was at one time deemed impossible, but was nonetheless a requirement due to NIF's need to maintain constant operational status.

Production, installation, and qualification of the 48 PAMs required for NIF concluded in November 2007. Extra PAMs have been produced both for ready-to-swap spares on NIF and for external customers.

The two stages of the PAM are built up on opposite sides of a vertically oriented optical breadboard as shown in the CAD rendering in Figure 3. The first-stage Regens in each of the 48 PAMs are designed to operate at 1 Hz in a highly stable regime for energy, spatial pulse shape, temporal shape, and optical prepulse noise. The design of the Regen allows it to reduce fluctuations in the injected pulse energy (deviating from a nominal setpoint of 0.75 nJ from the master oscillator) by a factor of 80 at the 25-mJ Regen output, meaning even very "noisy" input is converted to stable, flat output. Following the Regen, the Gaussian beam is reformatted into a square beam with a pre-compensated shape tailored for the Main Amplifiers. The beam then transits through the second stage MPA system in each PAM, where it is amplified by a factor of 10,000 up to 10 J. The MPA is designed to minimize the possibility of parasitics (unwanted self-oscillations due to inadverdent feedback above the 0.01% level) and pencil beams (undesired amplification of reflections from transmitting surfaces). The PAM outputs have highly stable beam pointing characteristics and excellent beam quality.

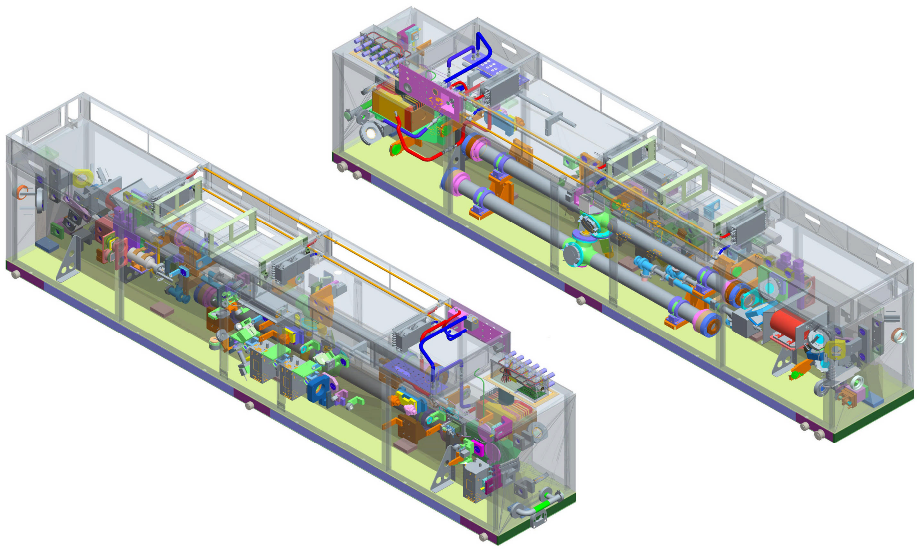
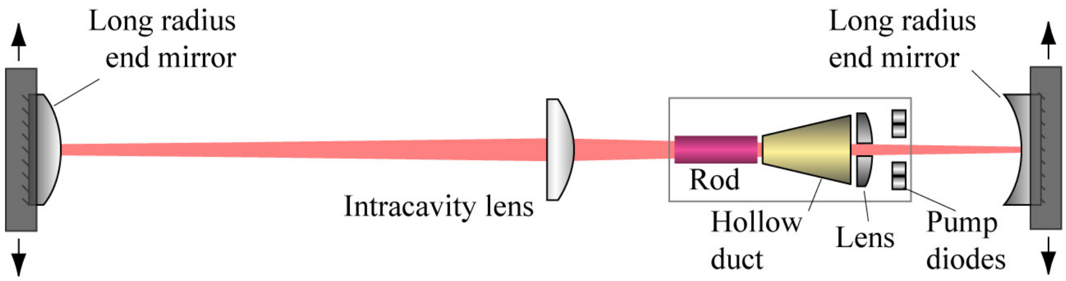


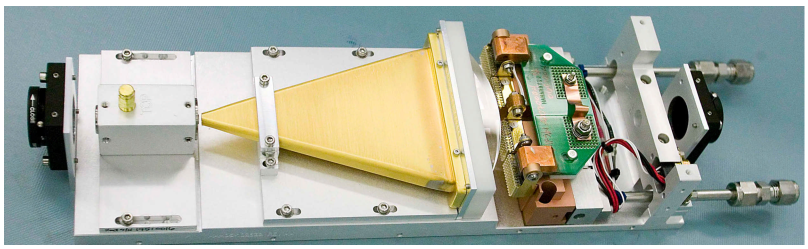
Figure 3. CAD rendering of both sides of the PAM. A view from the Regenerative Amplifier side is illustrated on the left, and from the Multi-Pass Amplifier on the right. PAM dimensions are 15 x 2 x 3 ft.

The Regen

The Regen consists of a laser-diode-pumped nedodymium-glass amplifier in a cavity defined by end mirrors. The amplifier head contains pump diodes and a hollow duct concentrator that enables positioning of the rod at a dynamically stable location, where the mode size is insensitive to surface-figure perturbations on the rod facets and thermal lensing in its bulk. The cavity is folded with mirrors to condense the 45-ft-long cavity within a manageable volume. Figure 4 displays a schematic of the unfolded resonant cavity along with photographs of the amplifier head assembly and rod.



(a)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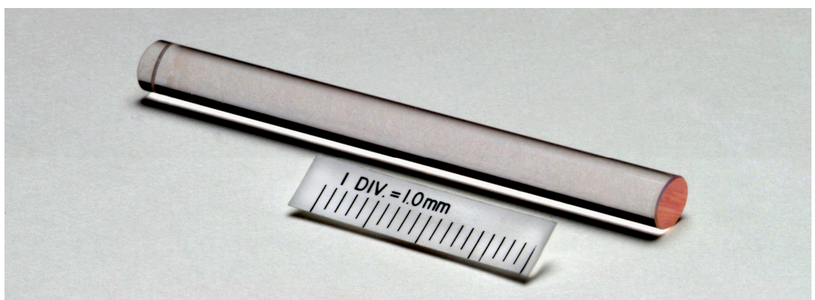

(c)

Figure 4. (a) Unfolded Regen resonant cavity. A hollow-lens-duct, end-pumped geometry is used to concentrate 800-nm pump light from a 4-kW diode array into the neodymium-doped phosphate glass rod. Translation-mounted curved end mirrors with a long radius of curvature are employed for precise alignment. (b) Photograph of the hollow-lens-duct amplifier head assembly. (c) Photograph of the neodymium-doped phosphate glass rod, 5 mm diameter by 50 mm long.

The Regen resonant cavity was designed with the goals of stability, uniformity, and reliability with minimized hardware complexity. Unfolded, the cavity consists of two curved end mirrors, a rod, and an intra-cavity lens. Numerous cavity configurations were considered and evaluated for the following factors:

- Beam-size stability and consistency (impacted by surface-figure errors).
- Steering alignment insensitivity (in the presence of vibrations and drift).
- Efficient energy extraction (optimally filling the rod with the beam size).
- Robustness against optical damage (ensuring that no focused beam "hotspots" exist).

Due to an imposed constraint of an unusually long cavity to accommodate up to 33-ns pulses, meeting these goals was challenging because even weak focal lensing due to pump-induced thermal gradients and surface-figure errors can contribute to large changes in beam size for unoptimized cavity configurations. For many cavity designs, small changes in rod focal power change the beam area by several percent, in turn changing the output energy proportionally. This sensitivity impacts both the stability of any one PAM and the uniformity across PAMs:

- Shot-to-shot pumping variations lead to beam-size instability that in turn leads to energy instability.
- Surface-figure inconsistencies across manufactured rods can lead to disparities in the mode shape from PAM to PAM.

As a function of rod focal power, there are always two zones supporting geometrically stable light paths. Within these geometrically stable zones, there exists an optimal plateau where the change in beam size in the rod due to changes in the rod focal power is zero. One of these zones is less sensitive to beam decentering perturbations, while the other is less sensitive to beam steering perturbations. Because the optics employed for folding the cavity are mirrors that unavoidably convert mechanical vibrations and drifts into tilts, we chose an optimal configuration in the steering-insensitive zone. The curvatures of the two end mirrors and focal power of the intra-cavity lens then became degrees of freedom that allowed us to remain optimized in this zone while maximizing the energy-extraction efficiency and simultaneously minimizing hotspots due to an overly focused beam. In other words, the Regen remains robust even in the presence of unavoidable manufacturing errors.

Proceeding from an optimized resonant cavity design, numerous iterations were made towards improving the overall stability of the optomechanical mounts. The seed pulse from the master oscillator is injected via an optical fiber that is positioned in a novel actuator-free mount consisting of sliding plates. The fold mirrors are likewise adjusted without actuators but rather by nudge-rotating the base along one axis and rotating wedged mirrors for steering corrections in the other axis. Finally, the cavity is aligned in an unconventional manner—not with tip/tilt mounts but rather by translating the weakly curved end mirrors. These improvements have resulted in highly precise initial alignment, elimination of actuator drift and backlash, and overall “set and forget” operation.

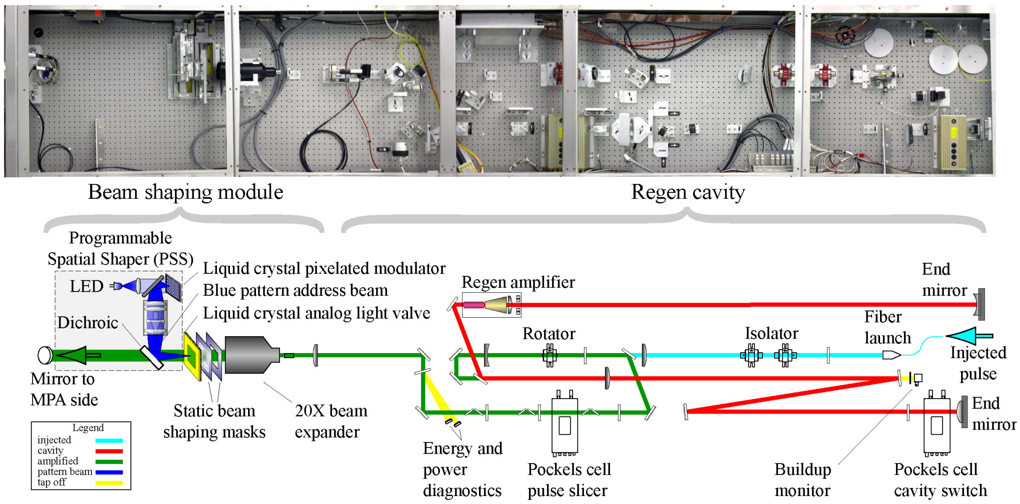

Figure 5. PAM first-stage Regen and Beam Shaping Module layout. A pulse from the master oscillator is injected into the Regen cavity, at which point the laser pulse makes over a hundred passes through the Regen amplifier before being switched out at its maximum energy gain. Not shown in the photo is the new Programmable Spatial Shaping assembly on the far left.

Figure 5 displays a photograph of the Regen resonant cavity along with a parallel schematic identifying key components. A Pockels cell in the cavity is used to Q-switch a tailored seed pulse into and out of the 45-ns cavity. Amplification takes place over 116 passes through the rod, with a single-pass net gain factor of ~1.2. Switching out the pulse at the peak of the energy buildup, where the saturated gain equals the loss, yields 25 mJ. [Operating with a relatively low gain per pass over many passes ensures a very broad buildup peak, which in turn results in exquisite energy stability. The path length in the Regen when taking into account the folds and multiple passes is over half a mile and represents two-thirds of the total path delay on the NIF system.

Flexible Beam Formatting

The Regen output Gaussian beam is then expanded up to 60 mm and shaped into a square profile with a serrated apodizer mask. A square profile was chosen to optimally fill the NIF main laser slabs; although a laser profile would normally be guassian (rounded), NIF manufacturing requirements call for a square beam shape. The slabs are actually rectangular, but they are tilted so that they present a square cross-sectional profile. A static shaping mask is optionally introduced to compensate for nonuniform spatial gain profiles both in the MPA and in the NIF Main Amplifiers. Additionally, a programmable mask was introduced into the design of the PAMs. This Programmable Spatial Shaper provides the capability of dynamically adjusting the beam shape to compensate for (1) higher-order nonuniformities of the downstream amplifiers and (2) shadow-mask flaws in the downstream optics that are susceptible to laser-induced damage growth. Alignment fiducials are optionally introduced to precisely center the beam output. The shaped beam is then passed through a hole in the vertical breadboard onto the second stage of the PAM.

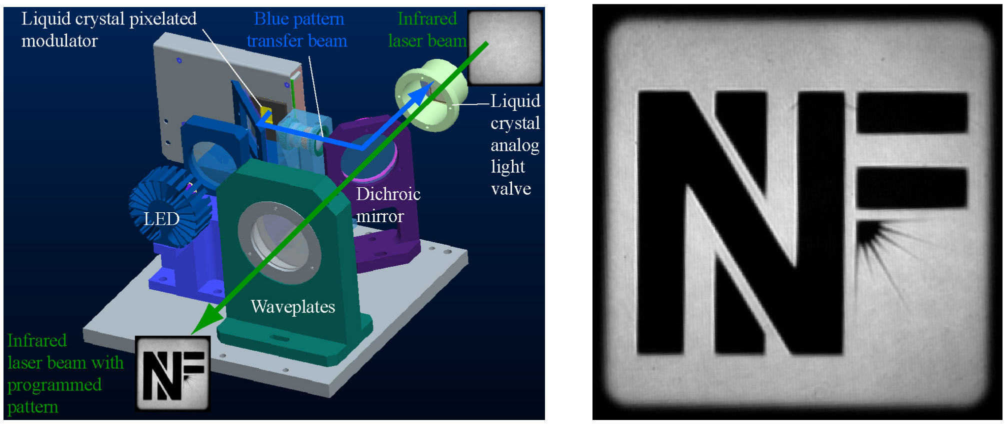

Figure 6. Programmable Spatial Shaper package. The package implements a two-stage liquid crystal spatial light modulator. In the first stage, a pixelated pattern is imprinted onto an incoherent blue light source using a conventional liquid-crystal light modulator, as found in a projection television. In the second stage, that pattern is transferred from the incoherent illumination to the coherent infrared beam using a liquid-crystal analog light valve. The resulting patterned beam is free of spurious pixelization artifacts. The image on the right displays the fidelity of imprinting an arbitrary black pattern on the laser beam, in this case the NIF logo (black portions are masked; lighter portions show laser light proceeding unmasked).

This flexibility is significant. By masking portions of the beam to essentially “steer around” minor defects in downstream optics—defects that, if not refurbished, grow into major damage upon continued exposure to NIF laser light—this element of the PAM allows NIF to save an estimated $5 million per year in refurbishing costs, as well as avoiding operational delays that might be caused by refurbishing.

To maintain alignment of the 48 PAMs for the planned 30-year life of NIF, 10 actuated control points were added with automated software routines for adjusting misalignments in centration of the beam on the 20X expander, pointing and centering into the MPA and pointing and centering out of the MPA.

The MPA

The beam is injected through a pair of pointing and centering mirrors and a Faraday rotator before entry into the MPA. Figure 7 displays a photograph of the MPA along with a schematic identifying key components. The MPA consists of a four-pass arrangement through a flashlamp-pumped neodymium-doped glass rod (32-mm-diameter by 300-mm-long), as shown in Figure 8. The ends of the rod are tapered to stifle unwanted whispering gallery parasitic modes that rob energy and burn o-ring seals. The flashlamp design incorporates 1.5-inch-thick glass walls for increased mechanical durability and cerium doping to reduce UV emission leading to degradation of rubber seals. The voltage supplied to the flashlamps is adjusted near 2.0 kV to target a four-pass optical gain of ~10,000.

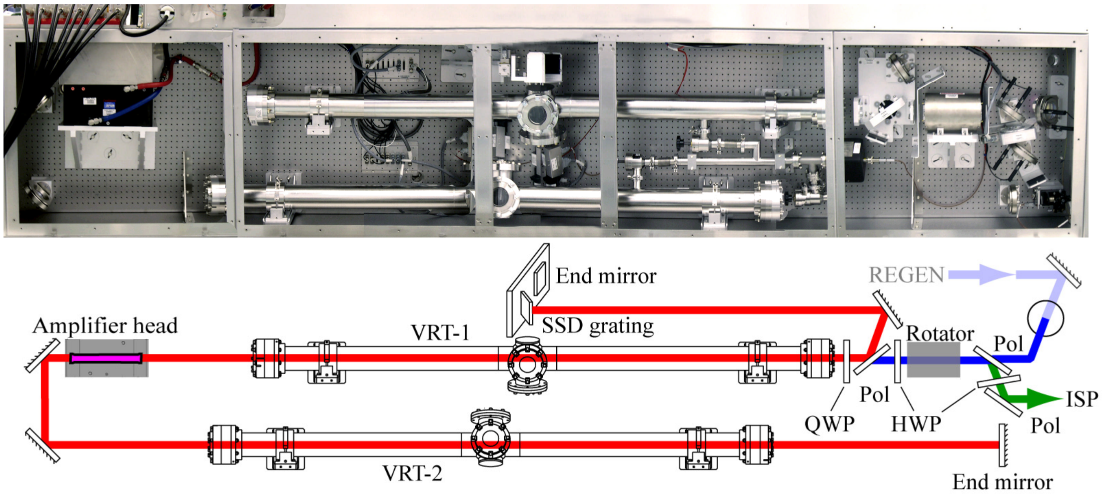

Figure 7. PAM second stage MPA geometry. Following the Regen stage and beam shaping module, the light is injected (blue) through a Faraday rotator into the four-pass amplifier circuit (red). The upper Vacuum Relay Telescope (VRT-1) images the shaped beam onto the flashlamp-pumped neodymium-glass rod. The lower Vacuum Relay Telescope (VRT-2) images the beam onto a displaced end mirror to avoid spatial-hole burning and pulse-shape distortion on the second pass. A quarter waveplate (QWP) and polarizer (Pol) enable two more passes through the rod after reflecting from a choice of end mirror or diffraction grating.

The square beam profile is then relay imaged through a pair of two-lens Vacuum Relay Telescopes (VRTs). The VRTs also spatially filter the serrated edges defined by the beam shaping module, yielding a soft-apodized edge profile that prevents diffraction-induced ripple. The upper telescope (VRT-1) images the shaped beam onto the rod. The lower telescope (VRT-2) images the beam onto a displaced end mirror to avoid spatial-hole burning and pulse-shape distortion on the second pass. A quarter waveplate enables two more passes through the rod after reflecting off an end mirror or diffraction grating.

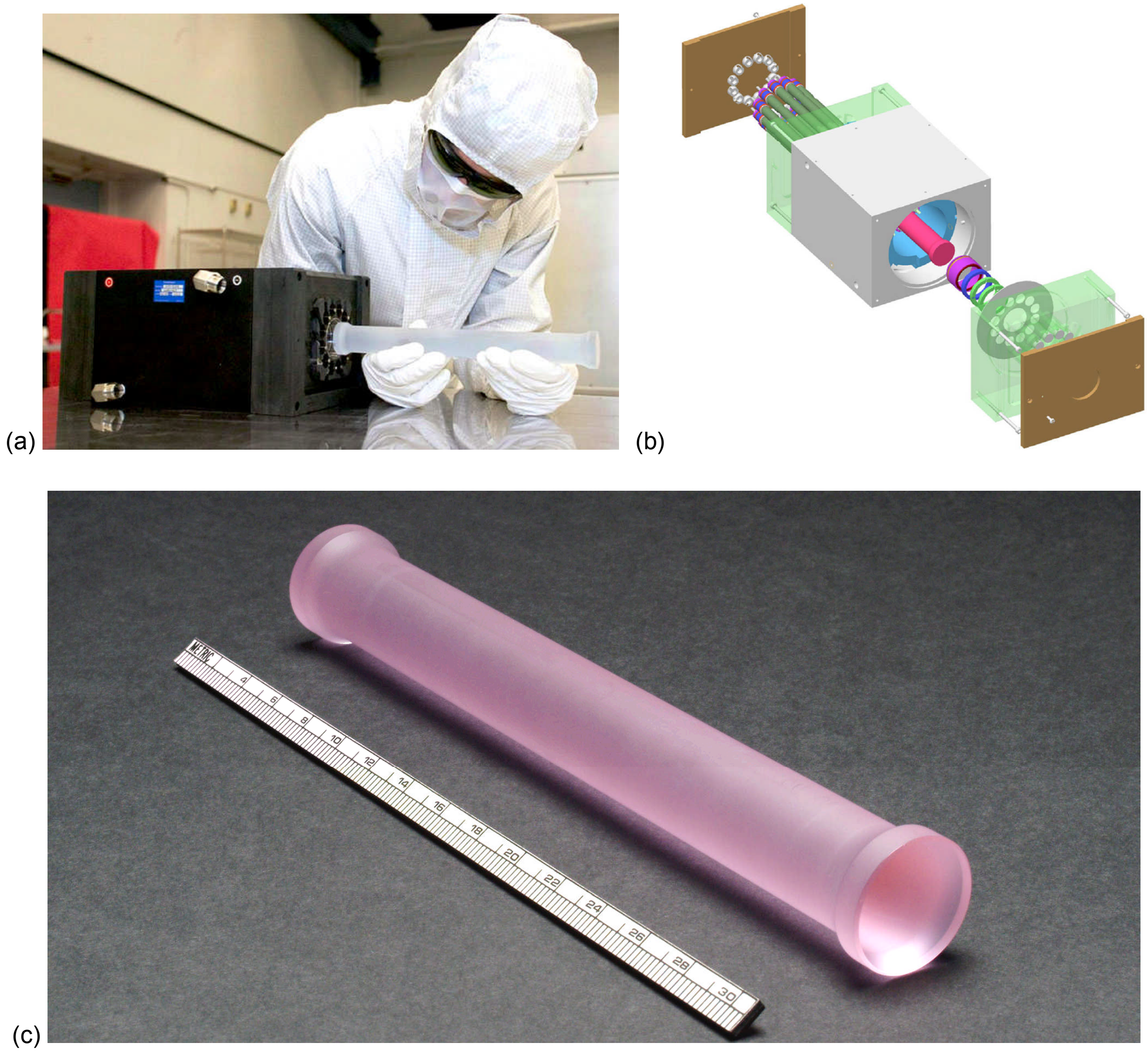

Figure 8. (a) Photograph of the MPA amplifier head assembly and (b) breakaway diagram displaying the arrangement of the neodymium glass rod, 12 flashlamps, pump reflector, light baffles, seals, and endcaps. (c) A photograph of the 3-mm-diameter, 300-mm-long neodymium-doped phosphate glass rod. The rod is manufactured with flared barbell styled ends to minimize whispering gallery parasitic oscillations.

Each VRT contains a four-element pinhole array such that each of the four passes is angularly multiplexed. The lenses are further tilted to suppress unwanted reflections from entering the pinhole array and manifesting themselves as amplified pencil beams. The orientations of the tilts were strategically chosen to minimize net wavefront distortions below 0.5 waves peak-to-valley. The system delivers nearly diffraction-limited performance, as quantified in Figure 9. Further care has been taken to wedge or tilt remaining optical components and baffle mechanical components that give rise to stray reflections that result in parasitic oscillations. The serrated aperture mask implements a “blue chrome” process that includes both chrome and oxide layers for reduced reflectance. It is further tilted to reduce parasitic mechanisms resulting from reflections off the backside of the mask.

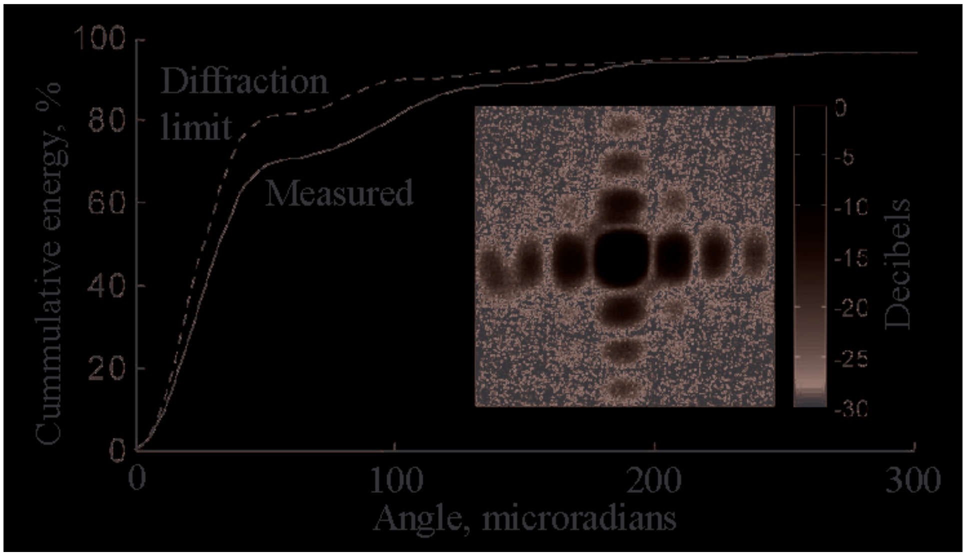

Figure 9. MPA output farfield cumulative angular energy with comparison to the diffraction limit for a perfect square beam. The inset displays the raw farfield spot data displayed on a logarithmic scale. The cross-pattern is essentially the textbook, ideal focused intensity pattern associated with a square laser-beam profile.

After four passes and a net gain of 10,000, the beam is amplified with a quadratic gain nonuniformity that is approximately 2.5:1. The output beam traverses a pair of motorized polarizers that are used to clean up the polarization, attenuate the output in conjunction with a motorized half-waveplate, and make fine corrections to the pointing and centering of the output beam.

The system of 48 PAMs is subject to a stringent set of requirements. A shot-to-shot RMS energy stability of 1% is achieved when operated near maximum energy output in the saturating regime. The nearfield contrast (spatial noise) is around 3.5%, and the overall beamshape is well within the required ±5% deviation from a prescribed shape.

All mounts on the MPA were carefully screened and pretested for optimum pointing stability. Measurements consistently validate a pointing stability below 10 microradians RMS. Accelerated lifetime tests were performed on motorized components expected to be frequently exercised over the projected 30-year NIF lifetime. These consist of the 10 control points for beam pointing and centering, translation stages that toggle beam shaping, and rotation stages for half-waveplates used to fine-adjust beam energetics.

10 A. **List your product's competitors by manufacturer, brand name and model number.**

Livermore's Pre-Amplifier Module (PAM) is a unique system, specifically designed for the National Ignition Facility (NIF), the highest-energy laser in the world. There are similar systems being built at Laser MegaJoule still under construction in France, Atomic Weapons Establishment in Great Britain, and the Laboratory for Laser Energetics in Rochester, NY. The specifications for these systems are unpublished.

Three commercial entities that sell laser systems in nearly the same regime as the PAM are listed in the comparative table in Section 10B.

A quantitative comparison shows the PAM's significant advantages. The Continuum Powerlite Nd:YAG laser system has comparable energy stability, but its energy output and pointing stability are worse by a factor of three, temporal jitter stability by a factor of ten. Likewise, the Ekspla NL310 Nd:YAG matches the PAM in energy stability, but falls even further away than the Continuum Powerlite Nd:YAG regarding energy output, pointing stability, and temporal jitter stability. The Spectra-Physics Quanta-Ray pro Nd:YAG is even more distant, and does not even match the PAM's energy stability.

A qualitiative comparison is even more striking—the other systems are completely incapable of meeting the PAM's vital requirements of beam-shape and pulse-shape adjustability and unit interchangeability.

10 B. **Comparative Matrix**

Laser system	NIF-PAM Nd:Glass	Continuum Powerlite Nd:YAG	Spectra-physics Quanta-Ray pro Nd:YAG	Ekspla NL310 Nd:YAG
Energy output	10 J	3 J	2.5 J	1.6 J
Energy stability	< 1% RMS	< 1% RMS	< 2% RMS	< 1% RMS
Pointing stability	< 10 microrad	< 30 microrad	< 25 microrad	< 100 microrad
Beam shape	fully adjustable with 100:1 contrast	non-adjustable	non-adjustable	non-adjustable
Temporal jitter stability	< 0.1 ns	< 1 ns	< 0.5 ns	< 0.5 ns
Pulse width	0.25–33 ns	5–9 ns	8–12 ns	3–6 ns
Pulse shape	fully adjustable (0.25 ns)	non-adjustable	non-adjustable	non-adjustable
Interchangeability	Yes, proven	no	no	no

10 C. **Describe how your product improves upon competitive products or technologies.**

Due to the modular and scalable architecture of NIF, a system of fully interchangeable high-gain pre-amplifiers was sought in the early design phases. Requirements for the design and production of the PAMs were put out for competitive bid, but no commercial laser company could meet the requirements. While some commercial lasers came close to meeting energy requirements at low energy stabilities and are within factors of two to five on allowable spatial and temporal jitter, they did so with simple spatial beam and temporal pulse formats (typically Gaussians, which are the preferred natural modes). The PAMs amplify beam profiles tailored to fit within efficient and scalable square beam architectures and support arbitrarily crafted beam shapes for long-term laser reliability and pulse shapes optimized for target ignition. They do this with a degree of precision unmatched by commercial laser amplifiers.

Progress towards a robust and reproducible design continued even as a PAM factory was being constructed at LLNL. In early reviews of the NIF project, many reviewers familiar with the fastidious operation of high-energy laser systems considered the production of 48 “identical” PAMs to be an impossible task. The PAMs offer an existence proof that ultra-stable high-energy lasers can indeed be produced in a manner that allows them to be used as building blocks in large-scale, fusion-class laser systems. This has been further validated by purchase orders coming from the Laboratory for Laser Energetics (LLE) at the University of Rochester and the Atomic Weapons Establishment (AWE) of the United Kingdom.

11 A. **Describe the principal applications of this product.**

Several nations (France, Russia, United Kingdom, Germany, Japan, and China to name a few) are pursuing high-energy laser programs. Livermore's National Ignition Facility (NIF) and Photon Science Program is the first to reliably mass-produce a Pre-Amplifier Module with the precision energy gain and beam quality control needed for high-energy lasers.

When NIF's full constellation of 192 laser beams are firing, they will compress a tiny target filled with deuterium–tritium fuel to the conditions required for thermonuclear burn, liberating more energy than was required to initiate the fusion reactions. NIF will provide the first laboratory setting for examining fusion reactions that naturally occur only in supernovae, in exploding nuclear weapons, and in our Sun and other stars.

NIF was designed with three specific research goals in mind: strengthen stockpile stewardship for a safe and reliable nuclear stockpile, show the feasibility of inertial confinement fusion (ICF) as a clean source of energy, and make significant strides in high-energy-density physics to understand the basic physical processes that drive the cosmos. These three missions share the need to prepare materials at extreme conditions—pressures of up to 10 billion megapascals, temperatures of 100 million kelvins, and densities of 100 grams per cubic centimeter.

11 B. **List all other applications for which your product can now be used.**

As the front end for the world's most energetic laser, the Pre-Amplifier Module offers the precisely controlled laser light essential to expanding the frontiers of high-energy science. NIF will be uniquely capable of producing conditions similar to those in the cores of stars, supernovae, and giant planets. The data from NIF experiments will provide new insights into how the universe operates at both the smallest and the largest scales.

12. **Summary**

The great promise of a clean, virtually unlimited energy source lies in the production of controlled fusion energy. New, clean sources of energy are of paramount importance to solving many of the country and greater world's problems. However, to date, fusion ignition has only been unleashed in the form of uncontrolled thermonuclear explosions. The National Ignition Facility will enable the first demonstration of controlled inertial confinement fusion where the energy released is greater than the laser energy input. The commercial viability of fusion-based power plants is still poorly understood at this time, but many unanswered questions will soon be finally addressable by NIF. For NIF to operate consistently and reliably, a system of dozens of robust and operationally identical Pre-Amplifier Modules is essential. The PAMs meet this need and set a new defining standard for stability, beam and pulse precision, and consistency for high-energy lasers, enabling interchangeability on a large and upwardly scalable system architecture. The ability to tailor the spatial beam profile to avoid defects in the main laser will add greatly to the reliability and operability of NIF.

Organization Data

13. **Contact person to handle all arrangements on exhibits, banquet, and publicity.**

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List of Appendices

Appendix A

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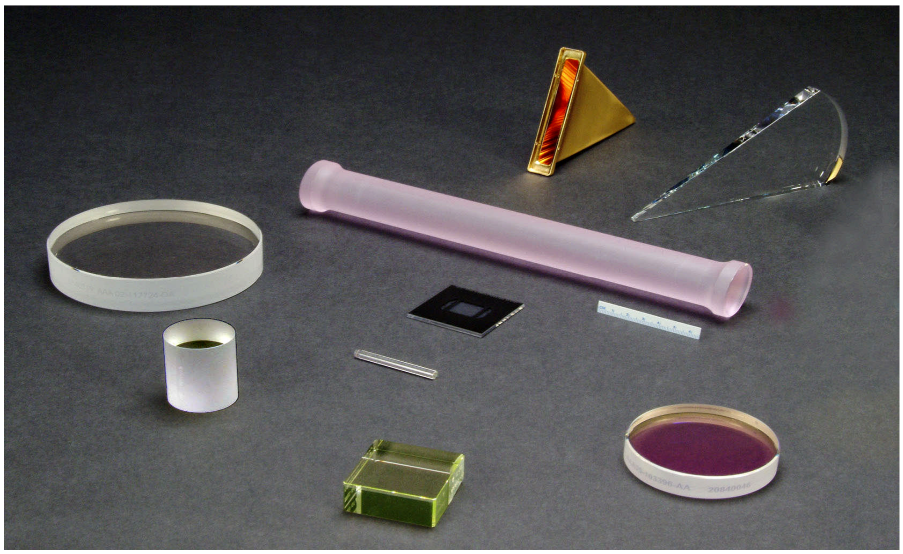
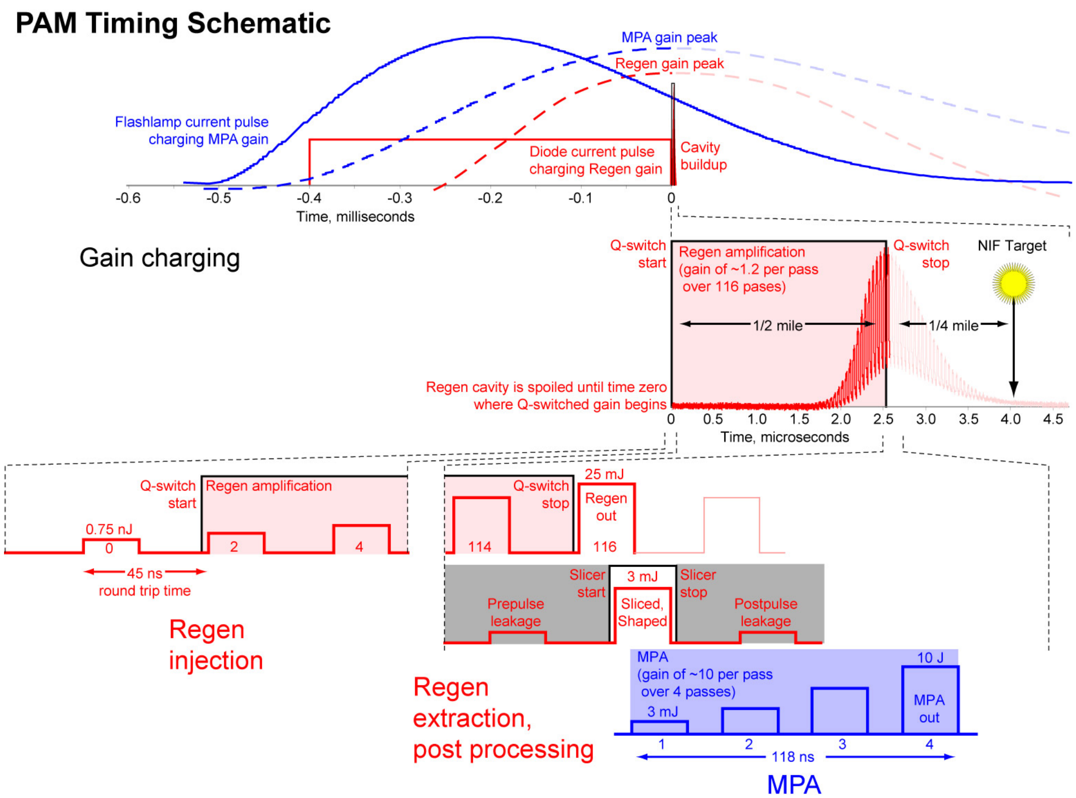
Appendix B

PAM Optics Photographs



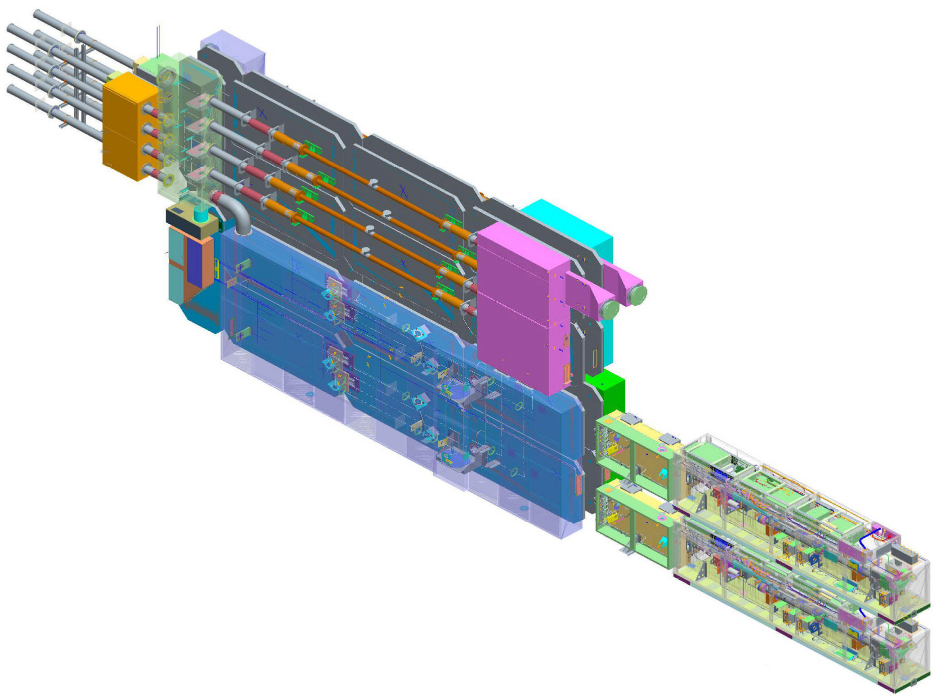
Critical optical components manufactured to tight tolerances specifically for the PAM. From left to right: MPA polarizer, centering glass, MPA barbell rod, regen rod, Faraday rotator FR5 magneto-optic glass element, absorbing blue chrome mask, regen diode pump hollow duct concentrator, regen diode pump glass duct concentrator, MPA end mirror.

PAM Timing Schematic



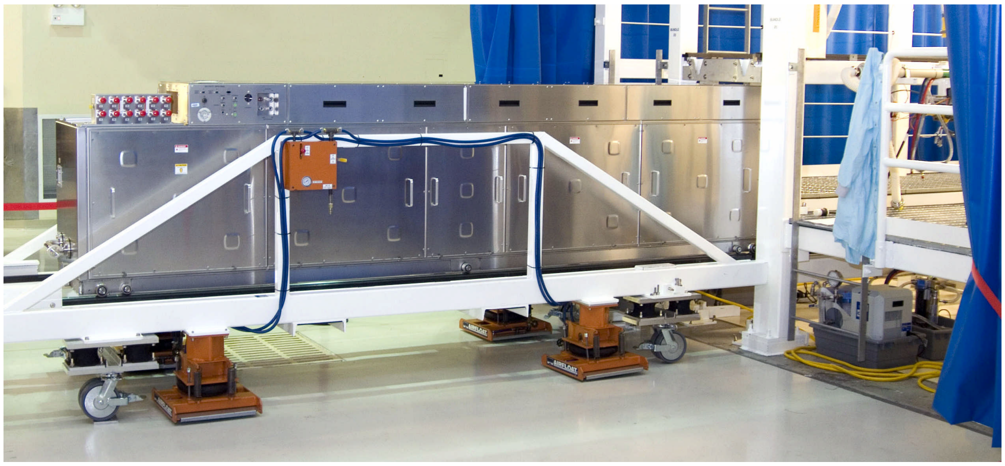
Overview of PAM order of events involved in firing a shot. Note the existence of 3 separate timescales broken out covering milliseconds microseconds, and nanoseconds.

PAM and Beamline Splits



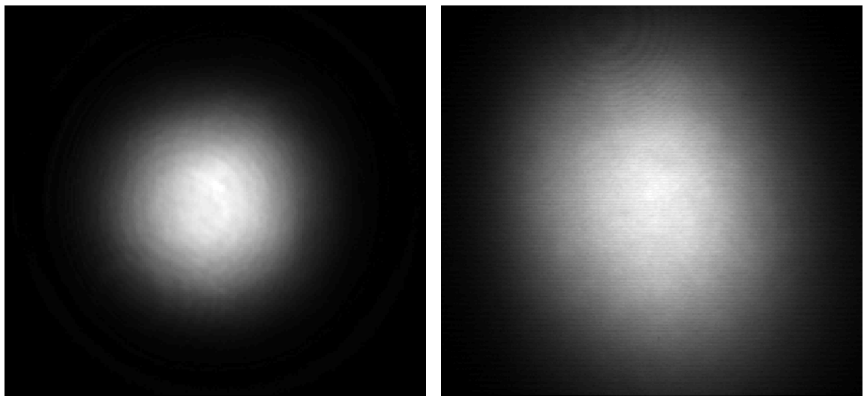
CAD rendering of a bundle of 2 PAMs (lower right) in relation to the branching optics feeding 8 main beamlines downstream (upper left). This is one of 24 modular subunits illustrated in whole in figure 1.

PAM Installation Photographs



A PAM being installed into the NIF laser bay.

PAM Regen Fluence Profiles



Regenerative Amplifier mode profile images in a) the rod and at b) the output prior to the 20X beam expander that back illuminates the beam shaping masks. These clean images illustrate the uniformity of the beam prior to user-programmable shaping.

Appendix C

Multimedia

Tour of the PAM Factory

This movie presents a narrated walkthrough of the facility where more than 50 PAMs have been built. In this clip, one can see technicians assembling / aligning the components that go into a PAM in a class 100 clean room environment. A few flybys of the PAM vertical breadboard architecture showcase the internal optical components and layout described in the text. Note that there are four workstations in the factory that facilitate the assembly, alignment, and testing of PAMs in parallel. Also one can see the operation of the Regen flashing at 1 Hz on a phosphor card held by a technician and, at the end, the flash of the MPA amplifier capable of delivering 10 Joules of optical energy.

A PAM being installed into NIF

This movie follows the installation of a working PAM into a slot in the NIF laser bay. This is accomplished with the help of an automated guide vehicle built specifically for loading and unloading PAMs. The PAMs were specifically designed to function as line replaceable units analogous to interchangeable boards installed into a slot of a computer motherboard. Here of course the motherboard is a fusion class laser system that demands a scalable, modular architecture. When proposed, this was an unprecedented concept for a multi-Joule laser system. This clip demonstrates the realization of this concept.