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ABSTRACT

We recently demonstrated the production of over a petawatt of peak power in the Nova/Petawatt Laser Facility, generating > 600 J in ~ 440 fs. The Petawatt Laser Project was initiated to develop the capability to test the fast ignitor concept for inertial confinement fusion (ICF), and to provide a unique capability in high energy density physics. The laser was designed to produce near kJ pulses with a pulse duration adjustable between 0.5 and 20 ps. At the shortest pulse lengths, this laser is expected to surpass 10^{21} W/cm^2 when focused later this year. Currently, this system is limited to 600 J pulses in a 46.3-cm beam. Expansion of the beam to 58 cm, with the installation of 94-cm gratings, will enable 1 kJ operation. Target experiments with petawatt pulses will be possible either integrated with Nova in the 10 beam target chamber or as a stand alone system in an independent, dedicated chamber. Focusing the beam onto a target will be accomplished using an on axis parabolic mirror. The design of a novel targeting system enabling the production of ultrahigh contrast pulses and an easily variable effective focal length is also described.

1.0 INTRODUCTION

The Petawatt Project was initially proposed as a high risk, potentially high payoff project to develop the capability to test the “fast ignitor” concept[1] for inertial confinement fusion (ICF), and to provide LLNL with a unique capability in high energy density physics. Conventional ICF relies on creating a hot, dense central core formed by compression of a deuterium/tritium plasma. The necessity of forming the hot central core requires substantial energy and places severe requirements on implosion symmetry.[2] In the fast ignitor concept, ignition is decoupled from compression. The pellet is assembled cold, and at the point of maximum compression is ignited by raising a small section of the pellet on the periphery of the dense core rapidly above the ignition temperature. The fusion burn then propagates throughout the compressed fuel before the pellet disassembles. In order to transfer enough energy to the ions in a small, well-defined volume faster than hydrodynamic disassembly, or the heat can conduct away, the energy must be deposited directly in the dense fuel in a volume less than ~ 4000 μm^2, and in a duration ~ 10 ps, dependent on the density, convergence ratio, etc.. If this energy can be deposited in the dense fuel, ignition could, in principle be achieved with substantially less laser energy than conventional ICF.

In addition to testing the concept of fast ignition, the extreme conditions produced by the Petawatt open a new regime of laser-matter interactions to study. Coupled with the short pulse duration , the enormous light pressure (> 300 Gbar) and high irradiance make possible the production of extremely dense matter at kilovolt to megavolt temperatures. Focused irradiance above 10^{20} W/cm^2 is required to achieve the simultaneous conditions of hot (> 1 keV), dense (~ 10^{24} cm^{-3}) matter of relevance to equation of state and hydrodynamic measurements. Lower irradiance lasers result in high-density absorption occurring early in the laser pulse, while remaining energy is absorbed at lower densities. With an irradiance > 10^{21} W/cm^2, the absorption physics enter a new regime where it may be possible to achieve high temperatures at solid density. The Petawatt will also enable the production of copious amounts of hard (10 keV to > 1 MeV) x-rays, which can serve as a high energy backlighter for radiographic measurements on Nova implosions.

Several new advances in technology enabled the production of petawatt pulses. The first was the development of broadband laser materials for solid state laser systems, such as Ti:sapphire and Cr:LiSAF. Second is the application of the chirped-pulse amplification (CPA) technique[3] to solid state lasers.[4,5] By stretching the pulse prior to amplification, the limitation on pulse energy imposed by beam filamentation due to small scale self-focusing can be overcome. The CPA technique has been applied by to existing , large scale Nd:glass laser systems at CEA, Limeil[6,7], the Rutherford-Appleton Laboratory[8], ILE, Osaka[9], and at LLNL[10,11]. Manufacture of pulse compression gratings of sufficient size and quality to permit the demonstration of a petawatt-scale laser was considered to be one of the most challenging aspect of the Petawatt Laser Project. At the onset of the project there was not a facility in the world capable of making such optics. To address this issue, a facility was built at LLNL, and unique processing techniques were developed to allow the fabrication of high laser-damage, high-efficiency diffraction gratings with a uniform submicron period over a length scale approaching 1 meter.[12] Using these technological advances, the LLNL Petawatt laser can produce kilojoule level pulses with a duration adjustable between 0.5 and 20 ps, and peak power of over one petawatt.

2.0 LASER SYSTEM

2.1 Petawatt Front-end

A schematic of the Petawatt front end is shown in Fig. 1. The Petawatt laser begins with a commercial mode-locked Ti:sapphire oscillator which produces transform-limited 100-fs, 1054-nm pulses at 300 mW and 83.5 MHz. These pulses are stretched to 3 ns in a single-grating (1480 lines/mm), single lens (210 cm focal length) pulse stretcher ($\theta_i = 48.0°$). The output bandwidth is clipped at 17 nm due to the 180-mm diameter lens in the stretcher. Following the stretcher, a single pulse is switched into a linear, TEM_{00}, Ti:sapphire regenerative amplifier operating at 1054 nm[13], producing a total gain of ~ 10^8. The linear cavity is composed of two 5-m radius of curvature mirrors separated by 120 cm, forming a stable TEM_{00} cavity. The 0.1% doped Ti:sapphire crystal is pumped from both sides by 130 mJ of energy, produced by a Q-switched, frequency doubled Nd:YAG laser, focused to ~ 5 J/cm^2. The initial gain per pass is 1.35, producing ~ 6.5 mJ after 130 passes. The spectrum is reshaped by the polarizing optics to a Gaussian profile with a 8 nm spectral full width at half maximum (FWHM), and a temporal FWHM of 1.5 ns. Above the 6 mJ level further amplification is achieved in a Ti:sapphire ring regenerative amplifier with a larger mode size, to prevent the onset of nonlinear effects, such as self-phase modulation and self-focusing.[13] Another 0.1%-doped Ti:sapphire crystal is pumped from both sides by 350 mJ of energy, produced by a Q-switched, frequency doubled Nd:YAG laser, focused to ~ 6.5 J/cm^2. After 15 round trips the output energy is ~ 50 mJ, while maintaining a TEM_{00} spatial mode. Up to this point, the system runs at 10 Hz with an energy stability of 2%. A pulse slicer eliminates pulse leakage from the regenerative amplifier, while a half-wave slicer switches a single pulse into the Nd:glass amplifier stage of the system. The remaining pulses are compressed to 320-fs in a single-grating, variable pulse width, air compressor for use in sub-terawatt level experiments[14,15] and Nova x-ray diagnostic characterization.

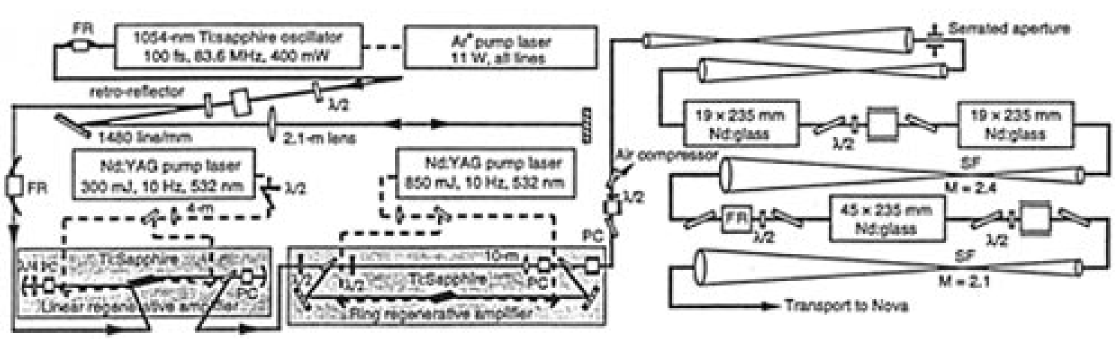

Fig. 1: Chirped-pulse amplification in two 1054.5-nm Ti:sapphire regenerative amplifiers produces 50-mj, 1-ns stretched pulses.

The pulse selected for further amplification is spatially expanded and clipped on a serrated aperture to give a near-uniform top-hat spatial profile for efficient energy extraction in the Nd:glass amplifiers. The beam is image relayed and spatially filtered between each stage of amplification. Following expansion to 15- mm diameter, the pulse is amplified in two 19-mm diameter Nd:doped phosphate glass rods (LG-760), separated by a Pockels cell for isolation. Each amplifier head produces a gain of ~12, amplifying the 20 mJ input to 2 J. The beam is further expanded to 38-mm diameter, then amplified in a 45-mm diameter Nd:glass (LHG8) amplifier to 15 J. A Faraday rotator between the second 19-mm amplifier and the 45-mm amplifier isolate the system. Following expansion to 80-mm diameter, the beam can either be propagated to the 100 TW Laser System in the Nova 2-beam chamber[11], or through an image-relayed beamline which injects the beam into Nova beamline-6 for further amplification. For experiments in the 10-beam chamber, a 37-actuator deformable mirror can be installed in the beam at the output of the 45 mm amplifier in the MOR to pre-correct for pump-induced abberations in the disk-amplifier section.

2.2 Beam Transport and Diagnostics

The Nova preamplifier system has multiple stages of amplification and magnification. These optics represent a significant source of spectral gain narrowing due both to amplification and bandwidth limiting optical components. The bandwidth, near field beam profile, and pulse length are measured in the Petawatt MOR, as well as at the output of the Nova amplifier chain in the output sensor diagnostics package. Comparative measurements in the two diagnostics indicate that the passive bandwidth losses due to the Nova amplifier chain are less than 10%. In order to minimize the gain narrowing of the spectrum caused by high gain amplification of the laser pulse, we chose to inject the beam as far down the Nova amplifier chain as possible. The petawatt injection beamline is vacuum relay imaged from the serrated aperture in the Petawatt MOR to the injection point after the first 10-cm amplifier on Nova. The output beam diameter from the Nova chain for the petawatt beam is reduced 80% from the normal Nova configuration (70-cm to 58.3-cm) to reduce the fill in the amplifier chain and thereby improve the beam quality by minimizing edge effects in the disk amplifiers.

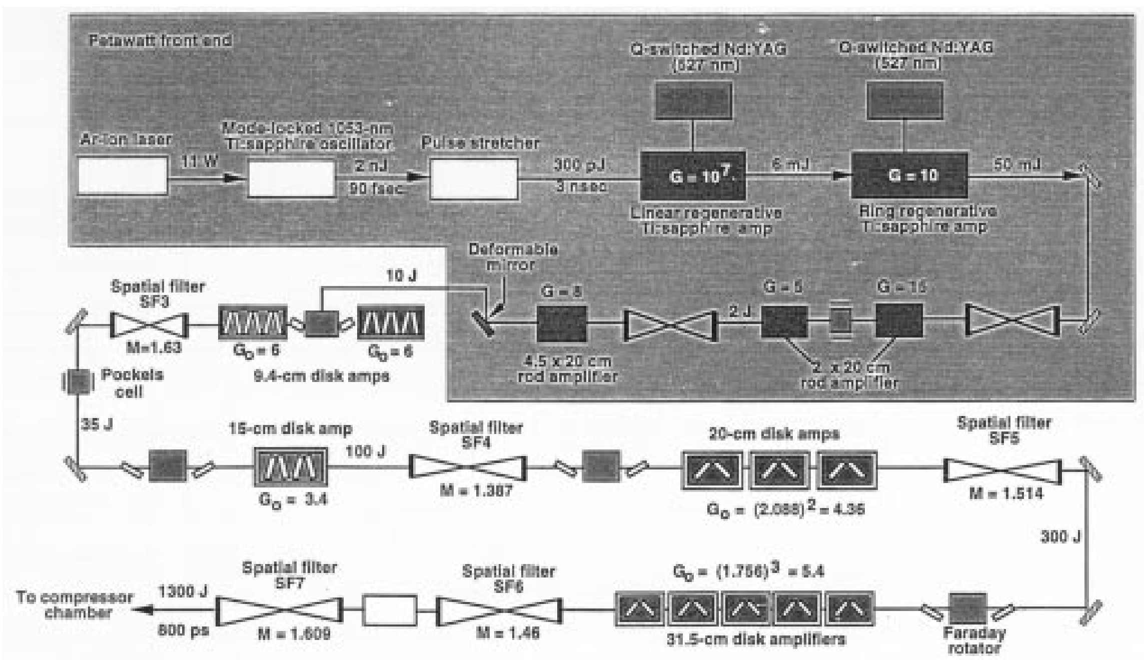

Fig. 2: The Petawatt beam injects into Nova in the 9.4-cm disk amplifier section of beamline-6.

The component schematic for the Petawatt laser system is shown in Fig. 2. With the Petawatt MOR capable of up to 10 joules of laser output energy, a gain of only a few hundred is needed from Nova to reach the Petawatt maximum expected energy of ~1 kJ (allowing for passive transmission losses). As a result, a limited set of Nova disk amplifiers can be fired to obtain the necessary energy. The 46-cm disk amplifiers produce a two-fold problem. First, the amplifiers are split into two halves to prevent parasitic oscillations in the amplifier slab, this destroys the coherence between the two halves of the beam. Second, the two halves of the 46-cm disks thermally distort in opposite directions when fired, steering the two halves of the beam. Together, these effects would limit the peak focal plane irradiance to much less than the diffraction limit. As a result, the 46-cm amplifiers are removed for Petawatt experiments. The space left by the amplifier removal is sealed by a section of beam tube to limit phase errors due to turbulence, and ensure optical cleanliness.

Above a certain fluence level, nonlinear effects begin to degrade the beam quality, due to the intensity-dependent refractive index $n = n_o + n_2 I$, where *I* is the intensity of the pulse, and n_o and n_2 are the linear and nonlinear refractive indices, respectively. This intensity-dependent refractive index produces a nonlinear phase retardation which results in wave front distortion and eventually beam filamentation.[16,17] The nonlinear phase retardation, or *B*-integral, is given by

$$B = \frac{2\pi}{\lambda} \int_0^{\ell} n_2 I(z) dz$$, where ℓ is the propagation length.

We have calculated the fluence levels and *B*-integral in each component of the amplifier chain. For a 46.3-cm diameter output beam, the output intensity from the amplifier chain is 0.83 GW/cm^2. To achieve a petawatt pulse, the total nonlinear phase retardation, or *B*-integral, is 1.0 in the Nova driver section and 1.52 in the power section. This corresponds to total ΔB of ~ 2.52 in the Nova amplifier section. In addition to *B*-integral, self-phase modulation in the amplifier chain can degrade the quality of the compressed pulse in CPA systems, ultimately limiting the pulse contrast.[18]

2.3 Pulse Compressor and Diagnostics

Following amplification, the beam is propagated through the Nova switchyard to the 10-beam target bay using the normal chain optics. Figure 3 is a layout of the major Petawatt components located in the Nova 10-beam target bay. The photograph of the interior of the compressor chamber, shown in Fig. 4, provides a sense of scale. The Petawatt system is designed to operate with a nominal input beam diameter of 58 cm. For experiments to date the beam diameter was limited to 46.3 cm, since the current generation of gratings (74-cm diam.) can only support a 46.3-cm diameter beam. Full aperture gratings (94-cm diam.), to be installed in May 1997, will allow use of a 58-cm diameter beam. A 94 cm Nova turning mirror (M1) is inserted into the beamline just inside the target bay to divert the beam into the Petawatt compressor. The beam passes through a fused silica vacuum window (W1) at the entrance to the compressor, and is reflected by a second mirror (M2) onto the first diffraction grating (G1). The single pass pulse compressor comprises G1 and G2, nominally spaced by 8.4 meters. The grating separation and angle are set to match the stretcher parameters in the Petawatt front-end. At the input to the compressor the frequency components of the beam are dispersed in time from red to blue. As the beam propagates to the second grating the blue components catch up with the red components. The second grating stops the dispersion process at this point, producing a temporally compressed pulse. The diffraction efficiency of each grating is 94 and 95%, respectively. The optical throughput of the compressor was determined to be 84%, due to M1, M2, G1, and G2. The compressed beam is reflected off of a full aperture beamsplitter (B1), with a reflectivity of 99.92% and sent to the focusing on-axis parabolic mirror (M3), located in the target chamber. A low energy beam sample transmitted through B1 is focused by a diagnostic beam reducing telescope (L1, L2). Following L1, a second beam splitter (B2) is inserted into the beam for full energy shots to reduce the B-integral in the diagnostic path. An uncoated duplicate optic is inserted during alignment to provide sufficient energy for the diagnostics. A gold coated mirror (M5) directs the beam down out of the compressor, through L2 to M6 on the laser diagnostic station beneath the compressor chamber. To reduce B-integral in the optical path, L2 serves as the vacuum barrier for the compressor. The 80-cm gold coated mirror (M4) behind B1 is used to direct back scattered light that is

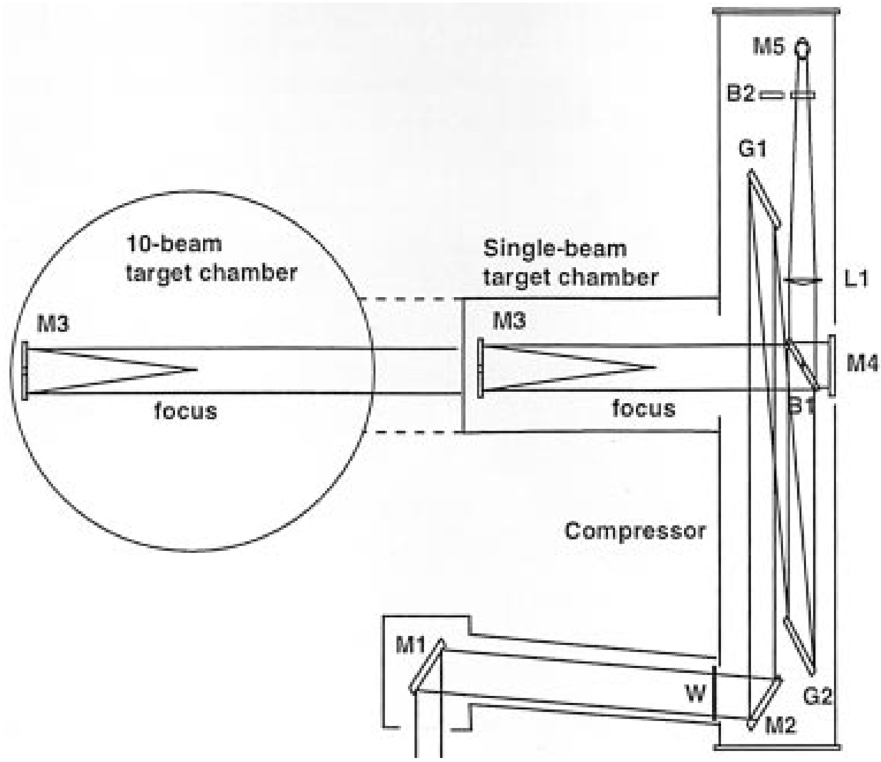

Fig.3: Layout of the major Petawatt components located in the Nova 10-beam target bay.

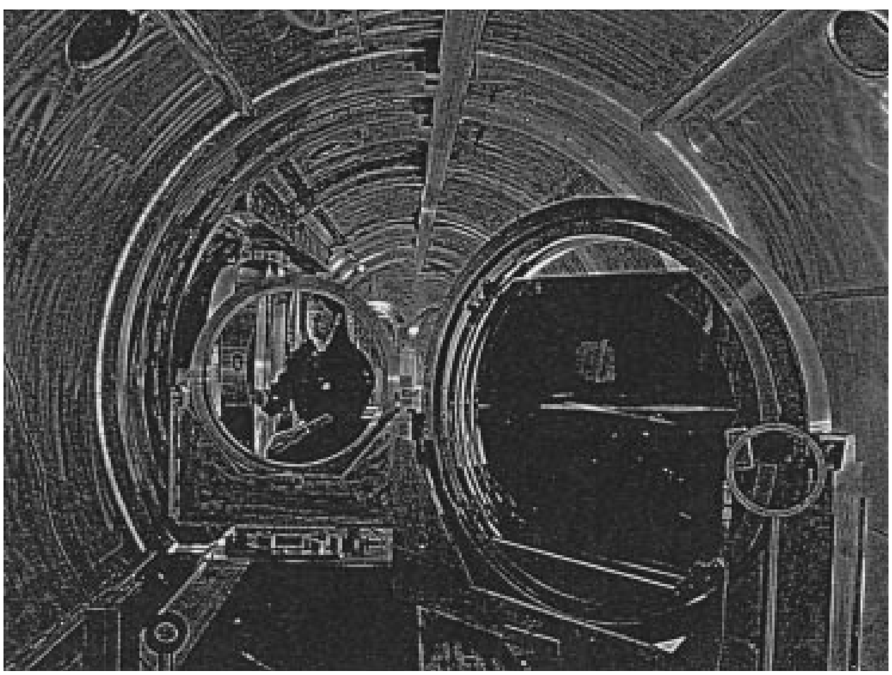

Fig. 4: Photograph of the interior of the compressor chamber provides a sense of scale.

transmitted through B1 to the diagnostics via a reflection off of the back surface of B1. M4 is tilted to separate the back scattered light in angle from the laser output beam sample.

2.4 Laser Output Diagnostics

Diagnostic measurements at the output of the compressor include energy, near field irradiance, far field irradiance, single shot autocorrelation, spectrum, and wave front. The output beam sample is transmitted through B1 then reduced in size by a telescope made up of L1 and L2. This is followed by an additional relay and the beam splitters that distribute samples to the instruments. Since the output beam peak power is extremely large the beam sample must be attenuated significantly to avoid phase errors due the nonlinear refractive index of the optics (B-integral effects). Our experiments indicate that nonlinear temporal diagnostics, such as the autocorrelator, are significantly impaired for B-integral values greater than ~1.0. However the transmission to the diagnostics must be high for initial alignment and operation of the autocorrelator with a low energy beam. Following L1 an additional reflecting surface, on B2, is inserted to reduce the ΔB on the small optics for high power operation.

The near field camera is used both for alignment and shot diagnostics. The nominal object plane in the compressor is just before L1. The far-field camera is a telephoto system with an overall system focal length of 60 m (referred to the full beam size). A 0.3 m spectrometer operated in second order provides a wavelength range of 27 nm with a resolution of 0.106 nm/pixel, collected by a CCD camera. The second order single shot autocorrelator uses a 0.5 mm thick $LiIO_3$ doubling crystal and has a range of 4.6 ps, with a resolution of 18 fs/pixel. The autocorrelation signal is collected on a CCD camera to provide a measure of the compressed pulse length. The wave front diagnostic is a Hartmann sensor for the deformable mirror located in the Petawatt MOR. The lens system for the wave front sensor puts a telecentric image (collimated light at the image) of the deformable mirror at the lenslet array. The magnification is set to put the lenslets at prescribed locations relative to the deformable mirror actuators.

3.0 SYSTEM PERFORMANCE

Several experimental shot series have been performed to characterize the propagation issues associated with and performance of the Petawatt Laser System. For initial Petawatt demonstration, we used a sub-aperture (46.3 cm) beam. A 46.3-cm diameter beam produces the equivalent intensity on the current 74-cm diameter gratings as a full aperture (58.3 cm) beam would on the 94-cm gratings. An aperture was installed in the Petawatt MOR to produce a 46.3-cm beam diameter at the output of the Nova chain. In May, 1996, the compressor was activated with the 46.3-cm diameter beam, and sub-aperture (17-cm diameter) diagnostics. Full aperture diagnostics were activated in December, 1996, demonstrating good compression across the beam aperture.

Spectra, energy and pulse length measurements were obtained in the MOR at the output of the 45-mm amplifier, in the Nova output sensor diagnostic, and at the output of the Petawatt compressor. Figure 5 shows the progression of spectral gain narrowing as amplifiers were sequentially fired, as measured at the output of the compressor. The output of the two regenerative amplifiers in the Petawatt MOR is nominally Gaussian, with 65 Å of bandwidth FWHM. When the two 19-mm and the 45-mm Nd:glass amplifiers in the Petawatt MOR are fired, this spectrum narrows to approximately 53 Å FWHM, producing an 18% decrease in the total bandwidth. As the beam is progressively amplified in the Nova amplifier chain the bandwidth continues to narrow, but the spectrum remains Gaussian in shape. Addition of the 9.4-cm and 15-cm disk amplifiers reduces the spectrum by an additional 19%. In order to obtain sufficient energy out of the laser chain, all three 20-cm disk amplifiers are fired, producing another 7% reduction in bandwidth. The final three 31-cm amplifiers reduce the bandwidth by 5%. No additional narrowing is observed when the MOR energy is increased with all the aforementioned amplifiers fired. The total spectral gain narrowing observed with all amplifiers fired is ~ 41% from the output of the regenerative amplifiers to the output of the Nova chain. The energies recorded in the Nova output sensor calorimeter provide the gain achieved with each stage of amplification.

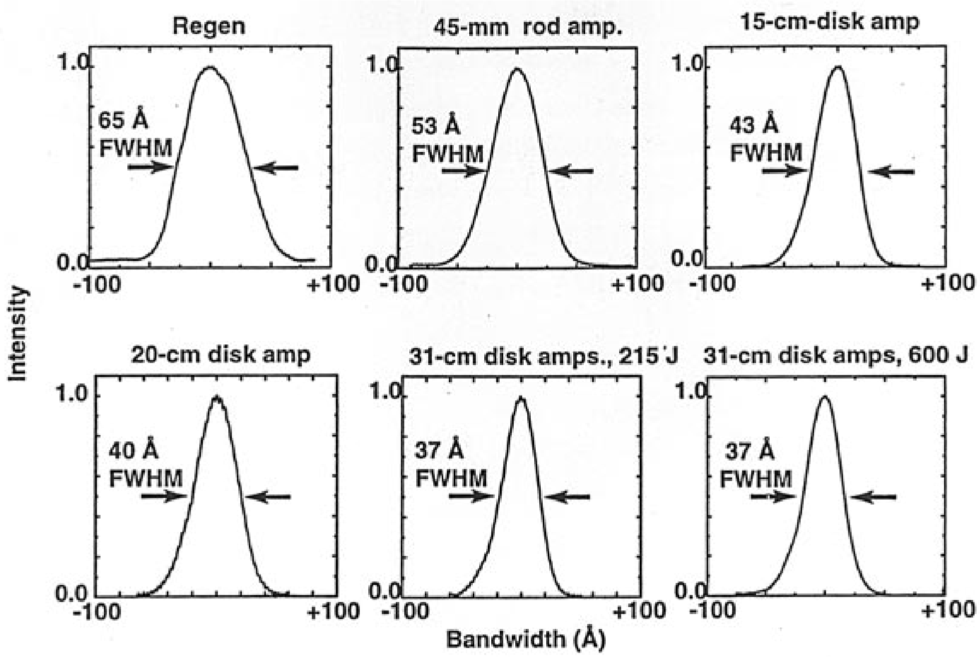

Fig.5: Progression of spectral gain narrowing as amplifiers were sequentially fired, as measured at the output of the compressor.

A measure of the compressed pulse length was determined from the autocorrelation. For a Gaussian spectrum, the actual pulse width can be estimated by the relation $\tau_{pulse} \approx \tau_{ac} / \sqrt{2}$. A 375 fs pulse length was achieved at low power. The pulse width is near transform limited at the output of the compressor. The highest peak power obtained in this series was 1.23 PW, with 680 J out of the Nova chain and a pulse width of ~ 440 fs FWHM, with a time-bandwidth product of $\Delta\nu\Delta\tau$ ~ 0.44.. No evidence of optical damage was observed on the gratings at this power level. The autocorrelation shown in Fig. 6, indicates on the order of a few percent of the energy is in the temporal wings of the pulse.

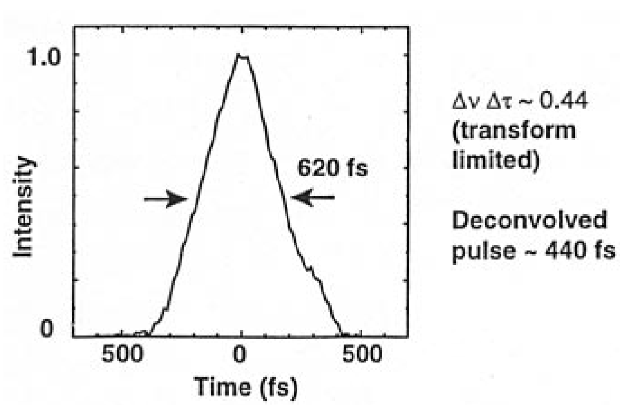

Fig.6: The autocorrelation of a 600 J shot indicates a 440 fs deconvolved pulse width. On the order of a few percent of the energy is in the temporal wings of the pulse.

Near field irradiance profiles were also obtained in the MOR at the output of the 45-mm amplifier, in the Nova output sensor diagnostic, and at the output of the Petawatt compressor. Representative examples of the near field irradiance for each location are shown in Fig. 7. No evidence of beam filamentation was observed in the images over the range of intensities in our experiments. The far field irradiance distribution was obtained at the output of compression. A representative image is shown in Fig. 8. The primary intensity spot is near diffraction limited in size. Thermal distortion of the amplifier disks due to repeated firing throughout the day causes the focal distribution to broaden by a factor of 2-3, as expected. These pump-induced abberations can be compensated with the use of the deformable mirror wavefront correction system, which will be operational mid-1997. Experiments on the Beamlet laser have shown that deformable mirror pre-correction can produce a nearly diffraction limited focal spot.[19] With the deformable mirror system, the Petawatt laser system should achieve a near diffraction limited focal spot with a high shot rate.

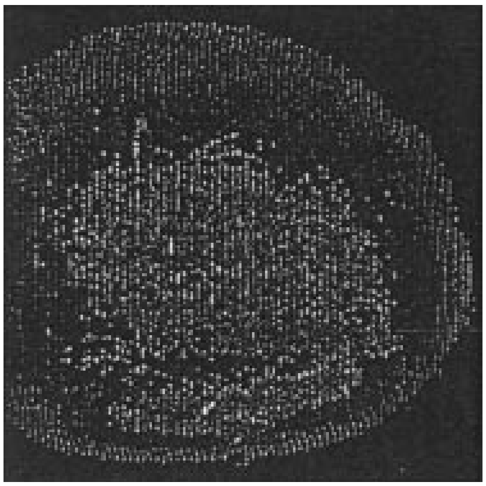

Fig. 7: A representative example of the near field irradiance at the output of the compressor.

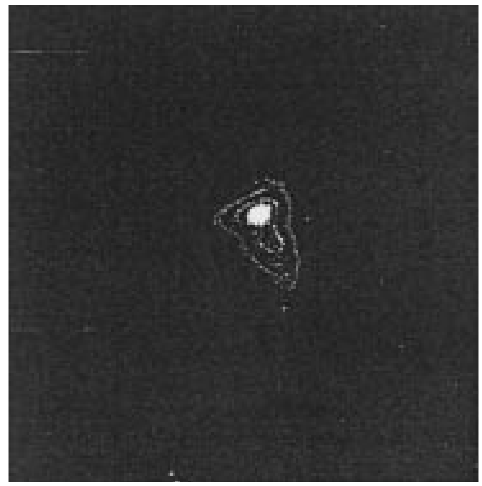

Fig.8: The far field irradiance distribution obtained at the output of the compressor.

4.0 TARGETING SYSTEM

The Petawatt will be used both as a stand-alone beamline in an independent target chamber for high energy density experiments and in conjunction with the other nine arms of Nova in the 10-beam chamber. The 1-beam chamber has been installed in between the Petawatt compressor and the 10-beam chamber to allow single beam experiments. The primary target chamber focusing optic is an on-axis parabolic mirror with a focal length of 1800 mm, nominally F/3. The mirror diameter is 700 mm, with an 80 mm diameter hole through the mirror on axis for diagnostic access, and as a keep out zone for target debris. An alignment telescope is mounted behind the back surface of the parabolic mirror to align the optical axis. Two target alignment viewers define the plane of the target perpendicular to the beam. A microscope and reticle assembly are used to view the focal spot. The entire parabola assembly will be transferable between the 1-beam and 10-beam chambers. For 10-beam shots, the 1-beam chamber will remain in place, acting as a vacuum beam tube between the Petawatt compressor chamber and the 10-beam chamber.

For long pulse (~20 ps) experiments, the parabola will be protected from target debris by a full aperture debris shield. For short pulse experiments, however, a conventional 1-cm thick fused silica debris shield would produce an unacceptable accumulated nonlinear phase retardation of ~ 28 radians, double-passed! To protect the parabola from line-of sight debris without incurring a large nonlinear phase retardation, a secondary "plasma mirror" will be used in conjunction with the primary parabola, as shown in Fig. 9. Small-scale experiments done at the output of the Petawatt front-end indicate that greater than 90% reflectivity can be achieved with good reflected wavefront quality.[20] These measurements are in good

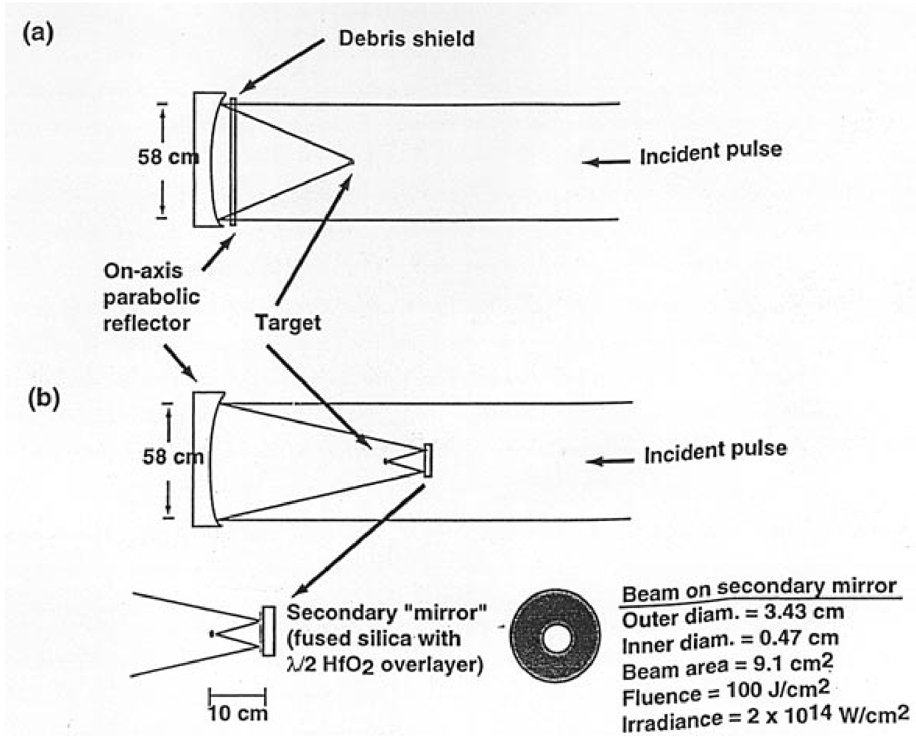

Fig 9: (a) A conventional debris shield cannot be used in the Petawatt targeting system for short pulses. The accumulated nonlinear phase retardation for double-pass through a 1-cm thick fused silica debris shield would produce 28 radians of B. (b) Debris shields can be eliminated by focusing with a plasma mirror.

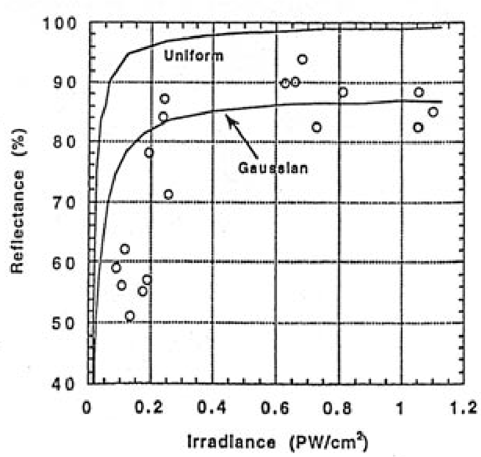

Fig. 10: Small-scale experiments done at the output of the Petawatt front-end indicate that greater than 90% reflectivity can be achieved with good reflected wavefront quality. Measurements are in good agreement with the theoretical calculations.

agreement with the theoretical calculations shown in Fig 10. For irradiances > 10^{14} W/cm^2 , short pulse radiation creates a critical density plasma on the surface of dielectric materials. For incident pulses < 500 fs, the plasma has insufficient time to undergo hydrodynamic expansion, producing a density scale length less than the incident wavelength. The resulting reflected wavefront is comparable in quality to that reflected from a conventional high precision optic, as seen in Fig 11. The plasma mirror substrate can be either flat or curved to produce a variable F number focal geometry. This substrate also acts as a single shot debris shield for line-of-sight target debris. Targets will also be specially shaped to help deflect debris away from surrounding optics and diagnostics. An additional benefit of the plasma mirror is that the temporal pre-pulse on the beam is used in forming the plasma mirror, producing a high contrast ratio (10^7) pulse.

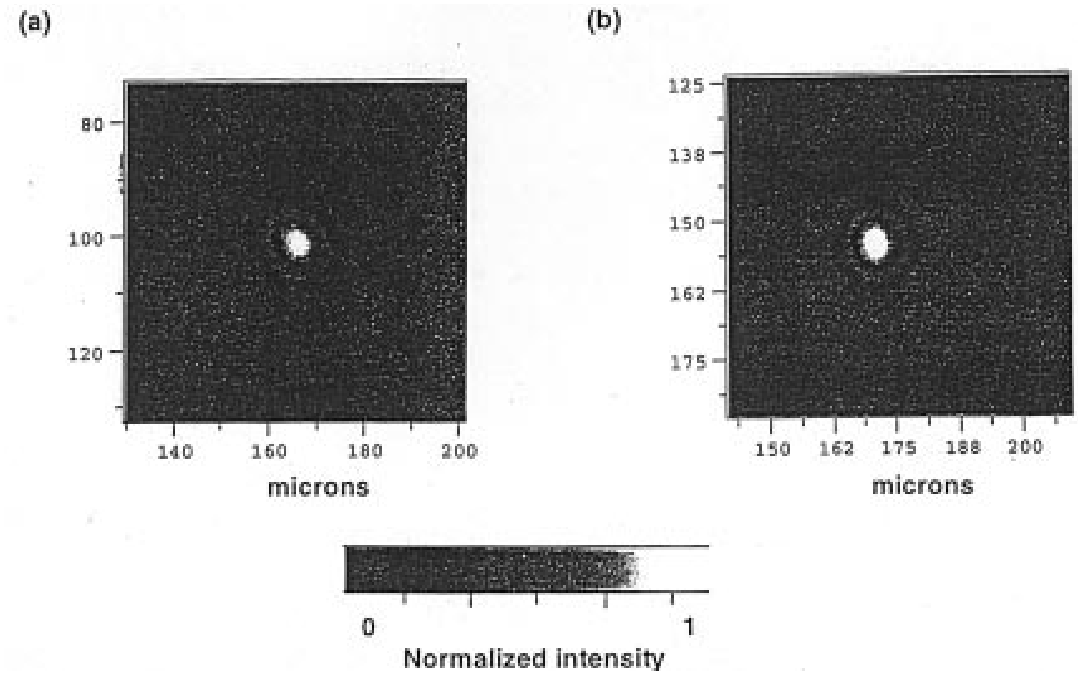

Fig11: For femtosecond pulses, the resulting reflected wavefront from (a) a plasma mirror is comparable in quality to that reflected from (b) a conventional high precision optic.

5.0 SUMMARY

The overall performance of the Petawatt Laser to date has exceeded expectation. We have demonstrated the production of over a petawatt of peak power in the Nova/Petawatt Laser Facility, generating > 600 J in < 500 fs. Currently, this system is limited to 600 J pulses in a 46.3-cm beam. Expansion of the beam to 58 cm, with the installation of 94-cm gratings, will enable 1 kJ operation. Target experiments with petawatt pulses will be possible either integrated with Nova in the 10 beam target chamber or as a stand alone system in an independent, dedicated chamber. Focusing the beam onto a target will be accomplished using an on-axis parabolic mirror either alone, or in conjunction with a plasma mirror, enabling the production of ultrahigh contrast pulses and an easily variable effective focal length. At the shortest pulse lengths, this laser should surpass 10^{21} W/cm^2 when focused in May.

6.0 ACKNOWLEDGEMENTS

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