The ICF Quarterly Report is published four times each fiscal year by the Inertial Confinement Fusion Program at the Lawrence Livermore National Laboratory. The journal reports selected current research within the ICF Program. Major areas of investigation presented here include fusion target theory and design, target fabrication, target experiments, and laser and optical science and technology. Questions and comments relating to the technical content of the journal should be addressed to the ICF Program Office, Lawrence Livermore National Laboratory, P.O. Box 5508, Livermore, CA 94551.

The Cover: Image of third-harmonic light obtained using an incident-beam diagnostic, which was installed as part of the Precision Nova project. The center of this image is a sample of a laser beam as reflected from a diffuser. It shows the disk split, central beam block, KDP conversion array, and four dark fiducial regions used to correlate input and output images. Direct scattered light from the KDP array is visible around the exterior of the diffuser. See the article "Laser Diagnostics Development for Precision Nova," p. 1.
In this issue:

Foreword iii

Laser Diagnostics Development for Precision Nova 1
This article discusses the development and installation of improved laser diagnostics to achieve Precision Nova goals. We installed a CCD camera system to measure 3a and 3b beam spatial profiles. Incident beam diagnostics were installed to accurately measure 3a energy and power on target. Improved optical coupling was shown to significantly reduce the noise level in streak camera measurements of temporal pulse shapes.

Precision Nova Power Balance 10
This article discusses the upgrades to the Nova laser system and the development of new operating procedures that resulted in substantially improved power balance on target shots. We can now achieve power balance of better than 10% rms in the foot and 5% rms at the peak of temporally shaped 30 drive pulses with peak/foot contrast ratios up to 10:1 and total output energies up to 40 kJ.

Precision Beam Pointing 18
We have demonstrated alignment procedures for Nova that reduce shot-to-shot scatter in pointing to <25-μm rms and that cancel systematic offsets to produce a total pointing error of ≤30-μm rms.

Precision Targets for Precision Nova 25
We describe new capsule materials and characterization techniques. We have synthesized a variety of doped polymers, which are necessary for implosion diagnostics and have built a profilometer, based on an atomic force microscope, that allows us to characterize the surface height of ICF capsules at the nanometer level.

Target Diagnostics for Precision Nova Experiments 31
We report on the measurement techniques, implementation, and experimental results from the target diagnostics developed for Precision Nova.

Facilities Report

Publications
FOREWORD

In the 1992 National Academy of Sciences (NAS) report of its review of the U.S. Inertial Confinement Fusion (ICF) Program, it was recommended that a high priority be placed on completing the Precision Nova Project and its associated experimental campaign. Since fiscal year 1990, we have therefore campaigned vigorously on Nova and in our supporting laboratories to develop the Precision Nova capabilities needed to perform the stressful target experiments recommended in the 1990 NAS report. Our activities to enable these experiments have been directed at improvements in three areas—the Nova laser, target fabrication capabilities, and target diagnostics.

As summarized in the following five articles, we have successfully completed the Precision Nova improvements. Additional information on the Precision Nova improvements is available from presentations made at the recent Precision Nova Workshop (UCRL-MI-110474 Rev 1). These improvements have had a positive impact on target performance and on our ability to diagnose the results, as evidenced by the HEP-1 experimental results discussed in the article "Target Diagnostics for Precision Nova Experiments." However, these articles generally concentrate on improvements to our capabilities rather than on the associated target physics experiments.

The first three articles discuss the Precision Nova laser improvements, which were primarily to the laser diagnostics, to instantaneous power balance, and to precision pointing of the Nova beams. All of these efforts were directed at improving our ability to precisely control the symmetry of x-ray drive on indirectly driven ICF capsules. The Precision Nova laser improvements culminated with well-diagnosed demonstrations of 5–10% power balance among the ten beams with an on-target energy of 40 kJ at 351 nm in a temporally shaped nanosecond-duration pulse, and an on-target beam centroid positioning accuracy of 30 μm. Other Precision Nova laser improvements include the refurbishment and coating of our KDP crystals to increase their third-harmonic output, and the installation of a "fail-safe chirp system" to prevent transverse Brillouin scattering in the output optics as discussed in a previous ICF Quarterly Report (UCRL-LR-105821-91-4).

The fourth article, "Precision Targets for Precision Nova," discusses two important target fabrication developments that help us control and diagnose hydrodynamic stability in high-performance ICF targets: (1) the making of ultra-smooth, well-characterized plastic capsules to minimize the growth of Rayleigh–Taylor instabilities and (2) the doping of these plastics with high-Z diagnostic tracers to allow the spectroscopic monitoring of undesired mixing of the pusher with the high-temperature fuel.

The final article, "Target Diagnostics for Precision Nova Experiments," summarizes our target diagnostic improvements. These include: the large-area neutron-scintillation array (LANSA) for diagnosing the density of the imploded capsule core; temporally and spatially resolved neutron diagnostics for diagnosing the region of fusion reaction; high-resolution, high-energy x-ray spectroscopy for diagnosing fuel-pusher mix, as discussed above; and ultra-fast high-spatial-resolution x-ray imagers (based on the ring aperture microscope) and streak cameras for measuring the dynamics of capsule implosions. Los Alamos National Laboratory (LANL) contributed to the target diagnostic improvements. The descriptions of these target diagnostic instruments are only thumbnail-sketches, so references are provided for more detailed information.

The Precision Nova Project and its success have increased our technical capabilities and our confidence that we can obtain similar performance levels from the laser, target fabrication, and target diagnostics in the proposed National Ignition Facility (NIF). The associated target physics campaign on Nova using the Precision Nova improvements will similarly increase our confidence in the predicted performance of the NIF targets in the regime of fusion ignition.

Howard T. Powell
Scientific Editor
Introduction

Two of the major goals of the Precision Nova project were to increase the routine \(3\omega\) energy on target to greater than 30 kJ and to obtain instantaneous power balance among the 10 beams of 10% rms on the "foot" and 5% rms near the peak of temporally shaped \(3\omega\) pulses. To achieve these goals, we developed and installed new laser diagnostics on Nova, which are discussed in this article.

To operate at higher laser energy without increasing laser damage to the optics, it was necessary to install a system to monitor the beam profiles and to adjust and maintain those profiles to be as uniform as possible (peak-to-average fluence ratio close to unity). Thus, we installed an extensive electronic-camera system based on charge-coupled device (CCD) cameras to record beam profiles on shots. This system has a much faster turnaround than the film recording system used previously and allows us to identify and fix problems (such as nonuniformity of the injected beam) more rapidly. The CCD system also captures far-field beam profiles when desired. The latter capability has been useful in our efforts to increase beam pointing accuracy, as discussed in the article entitled "Precision Beam Pointing.”

The ability to balance the powers of the harmonically converted beams to meet the Precision Nova goals is critically dependent on measuring the \(3\omega\)-beam powers with a relative precision better than 5% over an intensity range of at least 10. As part of the Precision Nova laser improvements, we developed and installed incident beam diagnostics (IBD’s) on each beamline which diagnose the \(3\omega\) power and energy on actual target shots. The IBD’s use a full-aperture sample of each beam produced by a back-reflection from each target focusing lens. The \(3\omega\) performance is measured by monitoring this sample using several diagnostics. We calibrate the IBD’s with calibration shots that use calorimeters mounted on the opposite side of the target chamber to measure the \(3\omega\) energies for each beam. With a series of calibration shots over an extended period of use, we have confirmed that the beam samples are adequately stable to diagnose the relative powers delivered to target on a given shot to better than 5%. Achieving this level of performance was critical for meeting our Precision Nova goals.

To date, we have made optical power measurements with the IBD’s using vacuum photodiodes coupled to oscilloscopes, yielding 120-ps temporal resolution. Although satisfactory, this measurement requires 10 expensive oscilloscopes, which are also needed for other tasks and are hence not always available. In the future, we plan to replace the oscilloscopes and obtain somewhat better time resolution by using two dedicated streak cameras each of which will simultaneously record the power of five beams and an optical fiducial pulse. However to use streak cameras, it is mandatory when desired. The latter capability has been useful in our efforts to increase beam pointing accuracy, as discussed in the article entitled “Precision Beam Pointing.”

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Beam Profile Measurement System

We installed a beam profile measurement system on Nova consisting of 48 CCD cameras located in various optical sensor packages throughout the laser chains.
(Fig. 1). These video cameras can provide real-time viewing and capture a single frame when desired. A computer controls 28 frame-grabber channels that provide image-capture capability for any 28 of the 48 installed cameras. The locations of the cameras were chosen to provide beam profiles along each beam path. This allows us to quickly isolate discrepancies in the intensity profile to a particular section. All sensors provide near-field spatial intensity profile capability and the ten input and output sensors offer an alternative far-field imaging capability. We typically use all channels by monitoring the beam profile at the output of the master oscillator room, five preamplifier locations, and the ten input and output sensors as well as two of the ten 30 diagnostic sensors. This system allows us to continually monitor and assess the overall beam quality of Nova.

The beam profiling system can be used to track optical damage to components in Nova. We have developed effective methods to confirm that damage has occurred and to isolate the damaged components. We take an image from a particular sensor and one obtained from the same sensor one or two weeks earlier, scale them to the same peak level, and subtract the earlier image from the recent image. The resulting image identifies areas that have undergone changes over that time period. Figure 2 shows such a difference image clearly identifying a damage spot. We then isolate where the damage has occurred in the laser chain by observing diffraction fringes from the defect when pinholes are sequentially inserted (remotely) in the spatial filters starting at the input to the chain with all pinholes removed. When inserting a spatial filter pinhole smooths the diffraction fringes, the location of the defect is determined to be in the section just preceding that spatial filter. We then visually inspect the optics in that section to identify and replace the defective optic.

In addition to monitoring laser performance and identifying damaged optics, we use the beam profile system to measure spatially resolved small-signal gain, transmission, and frequency conversion. Such measurements provide further information on factors influencing the spatial uniformity of the output beams. By using input and output CCD cameras, we can measure these quantities either for large sections of the laser or for individual components.

Because sensor characteristics and cameras differ, beam profile image data must be corrected prior to analysis for pixel size, sensitivity variations, angle of view, and, with the 30 sensor, for geometric distortion. Once these corrections are made, the beam profiles must be magnified, translated, and rotated to bring them into registration. Image analysis is performed on a computer using the IDL software language. We determine the image magnification, translation, and rotation by inserting a mask into the beam just ahead of the input sensor, then record images (Fig. 3) in the appropriate sensors using low energy pulses. (The output image is rotated by 180 degrees from the input and has a shadow from the 46-cm amplifier split-disk apodizer.) The ring in the input sensor image is an alignment reticle permanently mounted just in front of the camera. To obtain registration between the input and output images, we determine a transformation matrix using the centroids of the masked areas in each image. The registration accuracy is typically better than one pixel out of the 240 × 240 arrays.

Once the image orientation data has been taken, laser arm gain and transmission data can be acquired. To preserve image registration on subsequent shots, no movement of components, either within the laser arm or the sensor packages, is allowed after acquiring data with the orientation mask. We have found the transmission data to be useful for tracking component degradation. We can also obtain the small signal gains, after correction
for spatial variations of passive transmission, using output energies less than 800 J to prevent gain saturation. Figure 4(a) shows a small signal gain image for the entire disk amplifier system; Fig. 4(b) shows horizontal and vertical lineouts at the indicated locations.

We found the uniformity of gain to be adequate on all beams. As shown in Fig. 4, gain is highest near the disk split and declines in the direction perpendicular to the split; smaller variations are seen parallel to the split. Peak-to-average variations in time-integrated small signal gain ranged from 1.6 to 2.3 among the beamlines; the average variation was 1.9. The gain uniformity is considerably improved when the output amplifiers are driven into saturation. With 10-kJ shots, the peak-to-average gain variations are typically 1.3. Gains in the right-half of the beam image (beam-side away from the space frame when passing through the 46-cm amplifiers) are generally higher than left-half gains, although significant variations occurred among the beams. This result is consistent with previous data and indicates that not all of the gain differences were removed several years ago when one 31.5-cm amplifier (per arm) was "flipped" to reduce the side-to-side gain asymmetry caused by the 31-cm amplifiers.

We checked the transmission of both the input and output sensors on one beamline (BL-9) to assess whether the sensors themselves contributed significantly to the beam transmission variations. A reference measurement was made by allowing the main beam to be directly incident on a scatter plate, and then viewing the scattered signal with a calibrated

![Figure 2](image2.png)  
**Figure 2.** Processed difference image (see text for description) of Nova beam showing optical damage. The damage site is located in the "hottest" area of the beam intensity profile. (05-00-0294-0035)

![Figure 3](image3.png)  
**Figure 3.** Images taken with recording mask are used to register the input and output CCD pictures. (05-00-0294-0036)

![Figure 4](image4.png)  
**Figure 4.** (a) Final small signal gain image (b) horizontal and vertical lineouts at the indicated location in the image. (05-00-0294-0037)
CCD camera. Average sensor transmission variations of ~10% rms were measured; these were significantly lower than the total beamline transmission variations. Thus, we concluded that most of the observed variations were due to the laser arm components.

We have also measured the spatially resolved 3ω frequency conversion on a single beam (BL-9). In the incident beam diagnostics, an optical sample is reflected from the vacuum surface of the final focusing lens and is incident on a scatter plate that is imaged by a CCD camera (illustrated in Fig. 6). The beam image at the scatter plate is significantly distorted due to spherical aberration in the lens reflection. This distortion was quantified by placing a Hartmann plate (plate with a regular array of holes) in the beam ahead of the KDP array and recording its image with the sensor's camera. The sensor data, in combination with the known geometry of the Hartmann plate, allowed us to calculate a transformation matrix that corrects the distortion. Once an undistorted 3ω sensor image was obtained, the same techniques discussed previously were used to spatially register the 1ω and 3ω images.

Figure 5 shows a spatially resolved frequency conversion image. The conversion efficiency is continuous from one KDP segment to the next and is generally uniform over the beam. The bright area adjacent to the central beam obscuration is not increased conversion efficiency but is caused by increased reflection from a damaged area of the anti-reflection coating on the lens.

Speckled areas at the right and bottom result from the beam clipping in the output sensor. The effects of beam depolarization, divergence, and uniformity on frequency conversion will be investigated in the future using this new capability.

Incident Beam Diagnostic System

The 3ω incident beam diagnostic must meet demanding specifications to achieve our goals for power balance (5% peak, 10% foot). It must measure a sample that is representative of the whole beam and that is insensitive to beam profile or polarization. Since we only expect minor variations in time dependence within the beam, our goal has been a spatial sampling uniformity better than +/- 10%. The 3ω diagnostics must be insensitive to scattered light, for example from the KDP crystals, as well as light which is back-reflected from the target. The relative accuracy of energy measurements must be better than 3% rms including errors in calibration. Temporal power measurements must have a dynamic range >100 to accurately measure 10% differences in the foot of 10:1 contrast (peak-to-foot) pulses and must have a time response of approximately 100 ps or better. The installed IBD's meet these specifications. They also have additional capabilities that have been useful: providing near-field spatial profiles at 3ω plus energy measurements at 1ω and 2ω.

The incident beam diagnostic is located between the KDP harmonic conversion crystals and the final focusing lens, adjacent to the Nova 10-beam target chamber (Fig. 6). Beam sampling is provided by a focusing back-reflection off of the vacuum surface of the final focusing lens. A primary concern in this approach is the peak intensity in the back-reflected beam when the reflection converges to the size of the central beam block. The main purpose of this beam block is to shadow the target.

![Figure 5: Spatially resolved 3ω frequency conversion image.](image-url)

![Figure 6: The 3ω diagnostic package is located between the final focus lens and the KDP crystal array, and uses a diffuser to sample the reflection from the lens.](image-url)
from 100 and 200 light (which focus with a longer focal length than 300), but it also provides a convenient, shadowed location to mount our 300 diagnostics. However, previous attempts to develop reliable incident beam diagnostics using this reflection were hampered by the high ultraviolet fluence in the back-reflected beam which caused damage and nonlinear effects in the sampling optics. This problem is enhanced because the back-reflection has a large amount of spherical aberration that causes a high-intensity caustic to form at the edge of the beam as the edge rays focus before the rest of the beam. The present design successfully attenuates the reflected beam to a level at which it can be accurately measured without causing optical damage.

To attenuate the reflected beam's fluence, a 1%-reflective sol-gel coating was applied to the lens surface. Factors of concern for this coating were: the spatial uniformity across the lens aperture (affecting sampling uniformity of the incident beam), and the stability in the target chamber environment (mandating the interval between diagnostic recalibrations). Using a technique similar to that used to produce sol-gel AR coatings, we produced coatings slightly thinner than quarter-wave by changing the draw-rate used in the dip-coating process. However, because the 1%-reflectivity coating is not used at a reflectivity minimum, it is more sensitive to thickness variations than a conventional sol-gel AR coating. This complicated the coating process. As the lens was drawn out of the sol-gel tank, solution was displaced in the tank at a non-constant rate; the drop in the surface level caused by this displacement was a significant fraction of the desired draw rate, thus creating variations in reflectivity across the lens aperture. To fix this problem, we computer-controlled a stepper motor to vary the draw rate during the coating process to give a constant drop rate of the solution.

After coating, we characterized the lens surface reflectivity at 30° of each Nova lens with measurements (Fig. 7) over approximately 100 points. Relative variations in reflectivity over this set were typically less than 6\(^{\circ}\) rms. To date, we have also remeasured two lenses coated in this manner, which were removed from the target chamber after approximately eight months of use. We have not seen any significant change in reflectivity. This was also consistent with the result of calibration shots separated by about one month where we used the same debris shield that was stored in the intervening period to keep its transmission constant. Thus we concluded that the 1% lens coating is adequately stable for our Precision Nova needs.

The back-reflected beam is incident on a Spectralon diffuse reflector (a porous Teflon-like material), which further attenuates the beam by scattering into \(2\pi\) steradians. At the diffuser, the beam diameter is approximately 180 mm and the peak fluence is approximately 0.5 J/cm\(^2\), which is below the damage threshold of the diffuser material. A small fraction of this scattered beam is collected by a cluster of sensor packages, located adjacent to the final focus lens. By locating the detecting components of the diagnostic a significant distance from the diffuser, the fluence on these components is sufficiently low that nonlinear effects, for example solarization in the color filter glass used to isolate 300 light, do not occur.

Using a diffuse reflector to attenuate the beam has several advantages. The sampling is achromatic by intercepting and equally scattering all colors, thus allowing all three wavelengths of the laser to be monitored simultaneously. The sampling uniformity (across the beam's aperture) is excellent, due to the Lambertian distribution of the scattered light and the small angle of view of the diagnostics. The design is also insensitive to

![Measurement axes on focus lens](image1)

![Reflectivity measurements](image2)

**FIGURE 7.** Measured reflectivity of sol-gel coated focus lens shows less than 6\(^{\circ}\) rms variation across its aperture (05/80-0241-0340)
any polarization variations in the beam. Finally, the alignment of the diffuser is not critical, making installation on the Nova beamlines quite straightforward.

The cluster of sensors comprises six diagnostic channels, shown schematically in Fig. 8, along with an optical alignment tool. These six channels independently measure: (1) 1o energy, (2) 2o energy, (3) 3o energy, (4) 3o power (fiber-optic bundle coupled to an LLNL optical streak camera), (5) 3o power (Hamamatsu R1328U vacuum photodiode coupled to a Tektronix 7250 transient digitizer), and (6) a near-field spatial profile (CCD camera connected to the system discussed previously). All channels use color absorbing filters to isolate the wavelength of interest, as well as several lens elements to limit the field of view to the diffuser (reducing sensitivity to undesired light) and to homogenize the sampled beam that strikes the detectors (reducing sensitivity to beam profile).

Energy measurement diagnostics use Si photodiodes (EGG FFD-100), whose output is connected to a temporally gated integrator (LeCroy 2248). A gate width of 25 ns is used to eliminate any sensitivity to backscattered light from the target. Baffles also block target backscattered target light from striking the diffuser. During the activation of the IBD, the CCD camera was particularly useful in diagnosing whether scattered light was striking the diffuser. These sensors are calibrated with a 44-cm-diam-aperture calorimeter located on the opposite side of the target chamber. During the calibration, an aperture at the center of the target chamber is used to separate the wavelengths of the beam, which focus at different positions due to the dispersion of the focus lens. Energy diagnostics have been calibrated at all three wavelengths and are routinely used to measure 3o energy on target. Excellent linearity (better than 3% rms) has been observed between the energy diagnostics and reference calorimeters over a range of incident energies from 300 to 3000 J. The temporal diagnostics yield the temporal power history of each beam when normalized to the energy measurement.

Because our incident beam diagnostics are referenced to the 44-cm calorimeters, our ability to measure power balance ultimately rests on the relative calibrations of these calorimeters. Such calibrations are made optically using a 500 W Nd:YAG laser, which illuminates the calorimeters for several seconds to accumulate adequate energy. These calibrations are reproducible to better than 1%. However, when the calorimeters are optically damaged during use, we find from "swap shots" described below that the relative calibrations change at high power use on Nova. This is consistent with localized plasma formation at the calorimeter surface, causing varying amounts of backscattered light. Hence we refurbished six damaged 44-cm calorimeters with new absorbing glass and recalibrated them. We then performed another series of shots where we exchanged calorimeters between beams (swap shots) while monitoring any changes in 3o energies with the IBD's. The rms spread in relative sensitivities found with these swap shots was 1.9% with a maximum deviation of 3.6%. Thus, we conservatively quote the relative calibration uncertainty in our power measurements of different beams to be 3%.

**Figure 8.** Each sensor cluster contains six diagnostic channels, measuring beam energies, spatial profile, and temporal pulse shape.
Speckle Noise Reduction in Streak Camera Temporal Pulse Shape Measurements

We need precision measurements of both 1o and 3o temporal pulse shapes to achieve our Precision Nova power balance goals. (See the next article, "Precision Nova Power Balance," for details.) Data taken at 1o are used to measure the saturation characteristics of the beamlines; we use this information to adjust amplifier gains to make the 1o pulse shapes equal. We use the 3o data to measure the frequency conversion efficiency and to document the incident power during target experiments. Multichannel streak cameras are used as the digitizing instruments to take advantage of existing, fast rise-time equipment. Practically, this requires us to transport the beam samples to the streak cameras via optical fibers. The present 1o diagnostic system couples light to streak cameras via a single fiber for each beam. In the output sensors of Nova, small beam samples (approximately 2-mm diam) irradiate transmitting diffusers. Light scattered from these diffusers is coupled via conical tapers into 50-μm-core-diam graded-index high-bandwidth fibers. Signals from five beams are combined at each of two streak cameras. Lens systems image the fiber ends onto the streak tube photocathodes.

The signals from the present fiber-coupled 1o streak cameras in the output sensors exhibit noise features that are 10 to 30% peak-to-peak. We measured this noise level in the output sensor of a Nova beam by comparing it to two reference diagnostics: a vacuum photodiode connected to a transient digitizer (with a temporal resolution of 120 ps and accuracy of 2%), and an air-path-coupled streak camera (coupling the beam sample to the streak camera with mirrors, lenses, and a diffuser). Both reference diagnostics agreed with each other indicating that the noise was related to the fiber transport. Figure 4 shows the comparison between the signal measured with the standard diagnostic and an air-path streak camera; the difference between the two measurements was as large as 25%. Additional tests showed that the noise source was not due to the optics used to couple into or out of the fiber but was inherent in the use of the 50-μm fiber.

We believe this problem was caused by time-varying speckle. To understand the source of the noise, note that the light incident on the fiber from a diffuser is a speckle field. From point to point in a speckle field there are large variations in the irradiance. Over an ensemble of uncorrelated, unpolarized speckle fields from the same source geometry the power within a collecting aperture fluctuates as

$$\frac{\langle \text{Noise} \rangle}{\langle \text{Signal} \rangle_{\text{rms}}} = \frac{1}{\sqrt{2M}}$$

where $\sigma_p$ is the standard deviation of the power, the angle brackets represent the average over the ensemble, and $M$ is the number of speckle correlation areas within the aperture. $M$ depends on only the wavelength and the acceptance of the aperture, which is the product of its area and the solid angle of the source that is viewed (or can be collected). Fibers typically have a relatively small acceptance, thus this noise can be large if the speckle field changes during the pulse. For $N$ (parabolic) graded index fibers viewing a uniformly irradiated diffuser the speckle noise level is

$$\frac{\langle \text{Noise} \rangle}{\langle \text{Signal} \rangle_{\text{rms}}} = \frac{\lambda}{\pi a A / N}$$

where $\lambda$ is the wavelength, $a$ is the fiber core radius, and $A$ is the fiber numerical aperture. One can also show that Eq. (2) is simply the inverse of the square root of twice the number of modes in all the fibers.

Table 1 shows the characteristics and performance of single fibers, which we use at 1o and 3o. The fiber used at 1o is a commercially available graded-index fiber, while the 3o fiber was developed in a joint effort with AT&T Bell Laboratories.

<table>
<thead>
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<th>Parameters</th>
<th>1o</th>
<th>3o</th>
</tr>
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<tbody>
<tr>
<td>Core diameter</td>
<td>50 μm</td>
<td>30 μm</td>
</tr>
<tr>
<td>Numerical aperture</td>
<td>0.2</td>
<td>0.11</td>
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<tr>
<td>Speckle noise (noise/signal)</td>
<td>0.7%</td>
<td>0.8%</td>
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![Figure 9](image-url)
We confirmed the basic noise level defined in Eq. (2) with temporal measurements obtained by irradiating fibers with speckle fields from moving diffusers. To decrease the noise level, it is possible either to accept more speckle into the fiber by increasing the fiber core diameter or numerical aperture, or by using a bundle of N fibers.

For speckle noise to affect the measured pulse shapes, the speckle field must change during the pulse. Speckle motion on Nova can be caused by: changes in the beam irradiance or phase during a pulse caused, for example, by gain saturation, self-focusing, spatial filter pinhole closure, or spatially nonuniform optical switching. We have confirmed that speckle motion does occur during Nova pulses using several measurement techniques. By directly imaging a magnified speckle pattern from a diffuser, we observed speckle motion (typically) at pulse transitions, especially at trailing edges of shaped pulses. We enhanced the effect of speckle motion on a single fiber by magnifying the speckle size at the fiber (equivalent to under-filling the fiber’s angular acceptance). The resulting signals exhibited ~40% noise features. We also compared signals transported through single fibers and fiber bundles. The single-fiber signals showed erratic fluctuations, while the bundle signals showed relatively good agreement with photodiode measurements.

We are currently upgrading the 1o and 3o streak camera measurement systems to reduce the magnitude of speckle noise. These upgraded designs trade off various competing demands. The fibers must have adequate acceptance (yielding low speckle noise) and adequate bandwidth.

Since very large fibers with acceptable bandwidth are not available, our designs use multiple fibers in parallel (i.e., “fiber bundles”). We have paid careful attention to the optics that couple into the fibers to uniformly average over the sample irradiance, exhibit low alignment and phase sensitivity, and have low pathlength dispersion and full numerical aperture excitation of the fibers. Coupling out of the fibers also requires full transport of the numerical aperture for low modal noise, uniform irradiance at the streak camera photocathode (limiting local saturation for maximum dynamic range), and low pathlength dispersion. Also, the design must be compatible with an approximate 2-mm channel-to-channel spacing at the streak cameras.

For the upgrade to the 1o system, we are using a fiber with a larger core diameter and numerical aperture than Sirecor 104. This reduces the number of fibers needed for the bundles at the cost of somewhat reduced bandwidth. Figure 10 shows the configuration at the fiber ends. At the input end, uniform averaging and filling of the fiber modes is achieved using the combination of a diffuser and an integrating rod, which is simply a light pipe. At the bundle output, a short piece of large core step-index fiber is used to obtain the 2-mm channel-to-channel spacing since our packaged bundles are larger than that in diameter. This fiber is coupled to a rectangular “homogenizer” (a rectangular light pipe) to define hard edges that conform to the space allotment at the streak camera. Finally, a graded index lens images the end of the homogenizer onto the streak camera photocathode. Using the graded index lens minimizes the number of surfaces that could cause unwanted ghost reflections.

The 3o system uses a specially fabricated fluorinated-silica graded index fiber described previously. The limited stock of this fiber constrained the number of fibers per bundle. Figure 11 shows the fiber input coupler. This assembly is in the incident beam diagnostic cluster. The main diffuser is imaged onto a field stop to reduce stray light. A second smaller diffuser scatters light at high angles into the fibers, fully filling the fibers’ numerical aperture. Coupling out of the bundles is similar to Fig. 10(b) except a UV lens assembly images the end of the homogenizer onto the streak tube. The characteristics of the two systems are summarized in Table 2.

<table>
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<th>Parameters</th>
<th>1o</th>
<th>3o</th>
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<tr>
<td>Fiber core diameter</td>
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<td>30 µm</td>
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</tbody>
</table>
The system rise time shown in Table 2 includes the effects of dispersion in the couplers and fiber bundles, as well as the streak camera response.

We have tested prototypes of the bundles for both of these systems. Figure 12 shows very good agreement between pulse shapes measured with a 10 fiber-bundle-coupled streak camera and with a photodiode and transient digitizer. Prototype bundles were fabricated with the individual fiber lengths in a bundle matched within 10 ps. We also tested coupler prototypes and measured the bandwidth of the candidate 10 fiber.

The fiber-bundle-coupled 30 streak camera system is currently being activated on Nova. The 10 system will be installed in the second quarter of FY'94.

**Summary**

To achieve our Precision Nova goals, we developed and installed several new diagnostic systems. Precision measurements of power, energy, and near-field spatial profiles are now possible using incident-beam diagnostics, fiber-optic bundles, and CCD cameras. We use these diagnostics routinely to maintain energy balance on target and to minimize damage to optical components in the system.

**Acknowledgments**

The authors are grateful to Norman Nielsen and Steven Dropinski and to Glenn Hermes and the entire Nova operations crew for their many contributions to this work.

**Notes and References**


3. This also assumes that the beam spot on the diffuser is larger than the projected numerical aperture of the fiber and that the number of speckles at the fiber face is large enough that the speckle correlation area varies slowly over the fiber radius.


5. The streak camera signal has been processed mathematically to compensate for its faster rise time for purposes of comparison.
**Introduction**

The successful implosion of inertial confinement fusion (ICF) targets requires a high degree of drive symmetry. A necessary component of this is good instantaneous power balance among the laser beams. The power balance requirement for high-performance indirect-drive targets on Nova has been estimated to be 5% rms at the peak and 10% rms at the "foot" of shaped pulses.\(^1\)\(^2\) To achieve this level of performance, we have made several improvements to Nova:

1. Accurate diagnostics to measure system performance.
2. Improved pulse synchronization to provide adequate balance at times when the drive pulse intensity is changing rapidly.
3. Regulated high-voltage power supplies to ensure constant gain in the laser amplifiers.
4. New techniques to permit compensation for differences in the harmonic conversion efficiency and gain saturation rate of the 10 Nova beamlines. Improvements to the Nova laser diagnostic system were discussed in the preceding article, "Laser Diagnostic Development for Precision Nova." Items 2, 3, and 4 are the main subjects of this article.

**Nova Laser Systems Used in the Power Balance Process**

Figure 1 gives a simplified schematic of a typical Nova beamline, including all components used in the power balance process. A single input pulse shape at the fundamental optical frequency (\(1\omega_0\)) is generated in the master oscillator room (MOR)\(^3\) and is injected into all 10 beamlines. The input pulse shape is designed to provide the desired output pulse shape for a specified energy on target, taking into account gain saturation and conversion efficiency to the third harmonic (\(3\omega_0\)).

One or more temporal sensors record the input pulse shape before it leaves the MOR. The pulse is amplified and then split using rotatable half-wave plates and fixed polarizers that provide arbitrary input fractions to each disk amplifier chain. After splitting, each beam is reflected through an optical delay path (the "trombone" in Fig. 1) to compensate for differences in propagation distance to the target chamber, as discussed in the next section.

After rod amplification, the beams are apodized by a set of input apertures that provide nearly flat-topped transverse spatial profiles for subsequent amplification. The sizes of the input apertures are adjustable, and...
because the spatial filter magnification factors are held constant, the apertures define the transverse dimensions of the beams at the output of the disk amplifier chains. Fluences in the rod amplifier section of the laser are low enough that gain saturation is negligible; thus the pulse shape at the input to each disk amplifier chain is the same as that measured in the MOR. The input energy to each disk amplifier chain is monitored by a photodiode drive in apertures like that measured in the MOR. The input energy to Calculations have shown that for short-duration shaped drive impulsions like those measured in the MOR, the input energy to each disk amplifier chain is the target is changing rapidly (i.e., when \( \frac{dP}{dt} \) is large).

Calculations have shown that for short-duration shaped drive impulsions like those measured in the MOR, the input energy to each disk amplifier chain is the target is changing rapidly (i.e., when \( \frac{dP}{dt} \) is large). The input energy to each disk amplifier chain is monitored by a photodiode drive in apertures like that measured in the MOR. The input energy to each disk amplifier chain is the target is changing rapidly (i.e., when \( \frac{dP}{dt} \) is large).

The disk amplifiers and spatial filters between the input and output sensors produce small-signal energy gain of a few times \( 10^4 \) and a fixed beam-area multiplication factor \( M \) of \( -10^3 \). Substantial gain saturation occurs only in the larger amplifier stages. The 1-\( \mu \)m output pulse shape and energy are measured in the 1\( \omega \) output sensor for each beamline (Fig. 1). Output energies at 1\( \omega \) can also be measured by insertable 74-cm full-beam calorimeters on output sensor calibration shots.

The 1\( \omega \) laser output undergoes frequency conversion to 3\( \omega \) in an array of KDP crystals located just outside the target chamber. The 3\( \omega \) pulse shapes and energies are measured by the incident beam diagnostics (IBDs). The IBD sensors are calibrated using 5\( \omega \) energies measured by the 44-cm target chamber calorimeters as described in the preceding article. The 3\( \omega \) energies and conversion efficiencies, therefore, include the effects of obscurations and attenuation in the final optics (including the debris shield). X-ray streak cameras in the target chamber are used to monitor laser pulse arrival times and to establish beam synchronization on special target shots, as discussed in the next section.

**Precision Beam Synchronization**

Beam synchronization on target is a critical component of the power balance process. The power imbalance \( \Delta P \) arising from a time delay \( \Delta t \) between pulses with identical pulse shapes is given by

\[
\Delta P = \Delta M \left( \frac{dP}{dt} \right) .
\]

Pulse-timing errors therefore produce the most significant power balance deviations whenever the power on target is changing rapidly (i.e., when \( \frac{dP}{dt} \) is large).

Figure 2 shows the target geometry used for precision beam synchronization measurements. A 400-\( \mu \)m-wide (50-\( \mu \)m-thick) Au ribbon target is illuminated by 100-ps pulses from all 10 Nova beams. The odd and even beams are aligned to produce interleaved spots on the west and east sides of the target, respectively. The time dependence of x-ray emission is monitored with streak cameras that view the target edge-on from the north and south (the north x-ray streak camera lies between beams 5 and 6, and is not shown in the figure). Adjustments to beam timing are made by varying the length of the “trombone” shown in Fig. 1.

Figure 3 shows results of measurements made before and after one set of synchronization adjustments. On beamline 9, the trombone movement was twice the desired amount, resulting in overcorrection of the delay. On beamline 10, no correction was made initially because of the large uncertainty in the preceding measurement. The rms deviation of pulse arrival times was reduced from 20 ps to less than 10 ps on eight of the 10 beams. Subsequent timing adjustments on beams 9 and 10 reduced residual timing errors to 7 ps rms. These results eliminate pulse timing as a significant source of power imbalance for pulse shapes in

![Figure 2](image)

**Figure 2.** Target shot geometry for beam synchronization measurements. Open and filled circles represent laser spots on opposite sides of the ribbon target, respectively. (North x-ray streak camera is not shown.)

![Figure 3](image)

**Figure 3.** Timing offsets measured before and after beamline trombone adjustments.
use on Nova. In the discussions that follow, we ignore timing differences among the beams because the residual errors are much smaller than the time resolution of the temporal pulse shape measurement diagnostics used in these experiments (rise times >100 ps).

**Gain and Front-End Stability**

An important requirement for power balance is precise control of the energy produced by each amplifier chain. To achieve precision power balance on Nova, we found it necessary to improve the shot-to-shot stability of both the small-signal gain and the input energy split among the beams. As a result of these improvements, the rms shot-to-shot gain variations of the individual Nova amplifier chains have been reduced to 2%.

Gain fluctuations in the amplifier chains limited the success of previous attempts at power balance. Two primary causes of these variations were identified and corrected. (1) Replacement of damaged large-aperture polarizers reduced fluctuations in transmission arising from shot-to-shot variations in the spatial distribution of beam energy. (2) The addition of regulated “top-off” power supplies to the existing MVA power supplies reduced fluctuations in the voltage supplied to the disk amplifier flashlamps.

Optical damage to components and beam depolarization in the rod amplifiers interfere with our ability to control input energies to the amplifier chains. Optical damage makes transmission sensitive to details of a beam’s spatial intensity profile, which changes from shot to shot. An aggressive campaign to eliminate preamplifier optical damage reduced the problem to tolerable levels. Depolarization was reduced by replacing polarizers that were outside of specifications.

Poor regulation of the existing Nova MVA power supplies had caused flashlamp voltage variations of up to 1 kV (out of 20 kV), which resulted in small-signal gain variations of up to 20%. We therefore added small regulating power supplies that charge the bank for the last ~1 kV. The installation of these “top-off” supplies reduced the standard deviation in flashlamp voltage to less than 50 V. This corresponds to less than 1% variation in gain.

Another cause of apparent gain and input energy fluctuations was imprecise calibration of the charge amplifiers used with the input sensor photodiodes. The input sensors must measure energies ranging from 10 mJ to 10 J with a precision of 2%. This requires accurate calibration of the charge amplifiers over gains spanning three orders of magnitude. We calibrated each gain range of our charge amplifiers with 1% precision to reduce uncertainty in the measured input energies to an acceptable level.

**Power Balance Process**

Given precision beam synchronization and good gain stability, the two primary causes of power imbalance on target are beam-to-beam differences in net gain (i.e., including losses) and in frequency conversion efficiency. Independent control of the input energy to each arm has always been used to compensate for differences in net gain. In this section we show how beam areas can be adjusted to compensate for differences in frequency conversion efficiency. This technique works for output fluences that are low enough that beam-to-beam differences in gain saturation are not significant, as is the case for most current Nova shots. In the three sections following this, we show how differences in gain saturation, which become noticeable at very high output fluences, can be compensated by adjusting the distribution of gain in the final amplifier stages. These techniques are described and preliminary results are given in Ref. 5. The combination of beam-area modification and gain redistribution can be used to achieve power balance up to the highest output fluences available from Nova.

Frequency conversion from 1ω to 3ω is a nonlinear process that depends on the input irradiance. Figure 4 shows typical conversion efficiencies measured in a series of calibration shots for four Nova beamlines. We have found that the functional dependence of conversion efficiency on 1ω irradiance is the same for all of the Nova KDP arrays within our measurement accuracy, except for different multiplicative scaling factors C_i. The C_i account (among other things) for differences in transmission from the KDP arrays to the target (including the variable debris shield transmission). These differences can be substantial, given that variations in the C_i are often as high as 20%. The 3ω power on target for the i-th beam is therefore given by

---

**FIGURE 4.** 3ω harmonic conversion efficiency measured on Nova for four beamlines. Performance of the worst converter was later identified as due to slightly detuned KDP alignment.

(90-08-0294-0334)
The combination of beam area adjustment, so that $A_i = C_i^{-1}$, and input irradiance scaling, so that $S_i = C_{sat,i}^{-1}$, provides adequate $30 \mu$ power balance for most Nova pulse shapes currently in use. For highest precision, the IBD sensor calibrations and the conversion efficiency scaling factors must be updated with a $30 \mu$ calibration shot fired into the 44-cm target chamber calorimeters. This allows any recent changes in debris-shield transmission to be taken into account. Appropriate input aperture sizes are then selected to yield the proper output beam areas, and these apertures are inserted in kinematic mounts in each of the beams ahead of the input sensor (Fig. 1).

Figure 5 shows typical power balance results achieved by this method for two pulse shapes commonly used for Nova target experiments. The temporal records for all 10 beams were obtained using the new 30 IBD sensors, Hamamatsu R1328U fast vacuum photodiodes coupled to either Tektronix 7250 or SCD-5000 transient digitizers. The standard deviation $\sigma$ of power imbalance shown in Fig. 5 includes an estimated energy sensor calibration uncertainty of $3\%$. The results show that our power balance goals of $10\%$ rms in the “foot” and $5\%$ rms at the peak are readily achieved for these pulse shapes using only beam area scaling.

The combination of beam area adjustment, so that $A_i = C_i^{-1}$, and input irradiance scaling, so that $S_i = C_{sat,i}^{-1}$, provides adequate $30 \mu$ power balance for most Nova pulse shapes currently in use. For highest precision, the IBD sensor calibrations and the conversion efficiency scaling factors must be updated with a $30 \mu$ calibration shot fired into the 44-cm target chamber calorimeters. This allows any recent changes in debris-shield transmission to be taken into account. Appropriate input aperture sizes are then selected to yield the proper output beam areas, and these apertures are inserted in kinematic mounts in each of the beams ahead of the input sensor (Fig. 1).

**Figure 5.** Overlays of 30 pulse shapes on target for all 10 beams, with normalized standard deviation in power, as measured by the newly installed IBD sensors for (a) shot #23100682, $E_{beam} = 210 \mu$ kJ, pulse shape 30 for the HEP-I target campaign; and (b) shot #23100682, $E_{beam} = 210 \mu$ kJ, pulse shape 22. **(a)** Power balance of 30 pulse shapes on target for all 10 beams, with normalized standard deviation in power, as measured by previously installed IBD sensors for shot #23100682, $E_{beam} = 210 \mu$ kJ, pulse shape 30 for the HEP-I target campaign. **(b)** Average power imbalance across all 10 beams, with normalized standard deviation in power, as measured by newly installed IBD sensors for shot #23100682, $E_{beam} = 210 \mu$ kJ, pulse shape 22.
Extension of Power Balance to High Output Fluence

As the output fluence of the laser increases, so does pulse shape distortion arising from gain saturation. When the 1\(\omega\) output fluence reaches 2 J/cm\(^2\) (after beam expansion by the output spatial filter), pulse shape distortion measurements on Nova begin to reveal differences in the gain saturation on different beamlines at the same output fluence. In the context of Eqs. (4) and (6), this means that the gain saturation parameters \(\phi_{\text{sat}}\) are not exactly equal. Differences in the \(\phi_{\text{sat}}\) arise from differences in the distribution of gain and loss in the amplifier chains, even though the intrinsic saturation parameters of the 31.5- and 46-cm amplifiers are essentially the same (because they are made of the same laser glass material).

At very high output fluences, differences in residual gain become substantial, and a method of compensating for these differences is needed. In the next section we discuss how precise measurements of the beamline saturation parameters are made. In the section following that we show that we can compensate for these differences by changing the relative amount of energy (and hence gain) that is stored and then extracted from the 46-cm amplifier stages.

Measurement of Small-Signal Gain and Gain Saturation Parameters

We determine small-signal gains and gain saturation parameters on Nova from measurements of input and output pulse shapes and energies. The output pulse shapes were measured with fast vacuum photodiodes and transient digitizers at the 1\(\omega\) output sensors; the input pulse shapes were measured by a single fast photodiode and transient digitizer in the MOR. The 1\(\omega\) output energies were measured with 5-cm-diam calorimeters in the output sensors, and/or with 74-cm-diam full-beam absorbing calorimeters. Input energies were measured with Si diodes in the input sensors, which were calibrated with respect to 5-cm-diam full-beam absorbing calorimeters on separate front-end calibration shots. All of our calorimeters are calibrated relative to a single NBS-traceable reference calorimeter in our off-line calibration facility, giving an estimated relative precision of \(\pm 2\%\). Absolute intensities versus time were obtained by setting the integrals of the measured pulse shapes equal to the corresponding measured energies. Figure 6 shows input and output pulse shapes for a single beam producing an 11-kJ (1\(\omega\)) square output pulse.

Each raw temporal record requires significant data processing before it can be converted to a power pulse shape. First, missing data points are estimated by interpolation. Then, the baseline offset is removed by subtracting a baseline recorded on a shot with no optical signal to the diodes. Next, all temporal distributions are temporally aligned and converted to a single, universal time base. Temporal alignment is done by shifting the 50\% point on the leading edge of each pulse to zero time. This is a good approximation to the actual beam timing, because (as described above) the beams arrive at the target within 10 ps of each other. Temporal scaling to obtain a common time base scale is done by stretching...
or shrinking each time base so that the 50% level on the trailing edge of the pulse occurs at the same time as the 50% level of the reference pulse. The standard deviation of the required scale factor changes is typically between 1% and 2%, consistent with specified digitizer sweep rate calibration inaccuracies.

We obtain small-signal gain and gain saturation parameters from the input and output pulse shapes using the following steps. (1) The output fluence as a function of time is calculated for a beam [Fig. 6(c)]. (2) The instantaneous power gain of the beam is calculated by dividing the output power by the input power [Fig. 6(d)]. Gain values near the beginning and trailing edges of the temporal pulse are noisy because of low input power, pulse alignment, time base scaling, and input and output detector temporal response. (3) Figures 6(c) and 6(d) are combined to yield gain as a function of output fluence, as shown in Fig. 7.

The small-signal gain and gain saturation parameter for each arm are obtained by fitting the gain function of Eq. (4) to measured gain curves, as shown in Fig. 7. The Nova gain saturation curves can be fitted very well by a third-order exponential function of the form

$$F\left(\frac{\phi_{10,i}}{\phi_{\text{sat},i}}\right) = \exp\left[-\frac{\phi_{10,i}}{\phi_{\text{sat},i}} - \left(\frac{\phi_{10,i}}{\phi_2}\right)^2 - \left(\frac{\phi_{10,i}}{\phi_3}\right)^3\right],$$  \(7\)

where the $\phi_{\text{sat},i}$ are allowed to vary between the beams. To get good fits to the data we apply two constraints. First we limit the range of the fit to exclude data near the beginning and end of the temporal pulse, where the data can be quite noisy. Our fits start 200 ps after the start of the pulse and stop when 90% of the total output fluence is reached. Second, the coefficients $\phi_2$ and $\phi_3$ of the second- and third-order exponential terms in Eq. (7), which have a small effect, were determined empirically by averaging over all of the beams; $\phi_2$ and $\phi_3$ were thereafter treated as constants.

**Gain and Saturation Parameter Adjustments**

Once the gain data for all beams have been analyzed, adjustments can be made to compensate for differences in the measured gain saturation parameters. It is important to check that the analytical method for determining the gain parameters is stable and reliable, however.

Over a large number of shots of varying output energy, we determined that the standard deviation of the measured $G_{\text{sat},i}$ and $\phi_{\text{sat},i}$ for each beam was about 2%. Since this is the same as the expected gain fluctuations and the uncertainty in the calibration of the energy sensors, we believe that the processing with the temporal pulse shape data has introduced no significant error.

To adjust the gain saturation parameters, we vary the energy stored and extracted from the most highly saturated amplifiers in the chain. Reducing the energy stored in the 46-cm amplifiers while maintaining the same output fluence requires that more energy be extracted from smaller amplifiers and decreases the effective saturation parameter. Of course the overall gain is thereby decreased, and the input energy must be increased to compensate for the decrease in gain.

The energy stored in the amplifier disks can be varied by adjusting the flashlamp voltages or by adjusting the flashlamp trigger pulse timing relative to the incident optical pulse. The latter approach works because it allows the optical pulse to be amplified before the amplifier's gain has reached its peak. Because of difficulties with precision variable voltage regulation, we have found that flashlamp pulse timing adjustments provide the most convenient method. Figure 8 shows the variation of measured saturation parameters with flashlamp pulse timing. Using our knowledge of the dependence of the $\phi_{\text{sat},i}$ on timing, we selected delays that match them to within 2% rms for all arms. Once appropriate trigger time delays are chosen, it is simple to readjust the input energies to compensate for the resulting changes in gain.

Figure 9(a) shows the measured normalized gain curves $F(\phi_{10,i}/\phi_{\text{sat},i})$ for a shot with 11 kJ per arm output at 10% and no flashlamp timing adjustments. The saturation parameters range from 1.8 to 2.35 J/cm². The very large range may be due to the abnormally high gain for the 46-cm amplifiers in one arm. This range could probably be reduced by exchanging amplifiers among the arms or by upgrading the rest of the 46-cm amplifiers.

![Figure 7](image-url)

**Figure 7.** Gain from Fig. 6(d) as a function of output fluence from Fig. 6(c) parametric in time. Smooth curve is the best fit third order exponential function used to determine $G_{\text{sat},i}$ and $\phi_{\text{sat},i}$.
We were able to show, however, that our power balance technique works even for this large of a range of gain saturation parameters. Figure 9(b) shows the gain curves after optimization of the flashlamp trigger time delays. The $\phi_{im}$ now range from 1.80 to 1.87 (4\% maximum variation). The largest timing change needed to achieve this was 230 usec, which resulted in a 40\% reduction in small-signal gain for the best-performing arm.

Figure 10 shows the resulting improvement in measured 10\(\mu\)s irradiance balance. The standard deviation in the 10\(\mu\)s irradiance among the 10 arms at the beginning of the pulse is reduced from over 8\% to less than 3\%. The improvement in the standard deviation in the middle of the pulse is also due to better energy balance on the shot after timing changes were made.

**Achievement of 3\(\omega\)

**Power Balance at 40 kJ**

One of the major goals we established for the Precision Nova project was to demonstrate that power balance could be achieved with high-contrast pulse shapes up to the highest available output energies. Thus, a goal was set to achieve 5\% power balance at the peak and 10\% power balance at the foot of a pulse with total output energy of 40 kJ at 3\(\omega\) and a 10:1 contrast pulse shape. Since the conversion efficiency in the foot of a shaped pulse is much lower than at the peak, it was necessary to drive the total 10\(\mu\)s output energy to nearly...
100 kJ and the 10 output fluences to over 3 J/cm². It was necessary to introduce flashlamp timing adjustments to produce adequate balance of 10 output irradiance throughout the pulse. The technique of using beam area adjustments to compensate for differences in frequency conversion efficiency was also required.

The required increase in gain saturation on all but one beamline resulted in higher fluences through the smaller-diameter sections of the amplifier chains on which the timing adjustments were made. This resulted in higher nonlinear phase distortion of the wavefronts (i.e., higher values of B-integral accumulation), and a careful analysis was undertaken to ensure that we were still operating in a safe regime. We also checked that our limits on transverse stimulated Brillouin scattering in the final focusing lens were not exceeded with this pulse shape and energy.

The results shown in Fig. 11 for two consecutive shots show that we met the stated goals. The average standard deviation of beam power is seen to be 10% in the foot and less than 5% at the peak of these pulses (with calibration uncertainties of 3%, which are included in the σ plots). With these results we have met the Precision Nova power balance goals.

**Summary**

To obtain power balance among the Nova beams, we made improvements to the Nova laser beam synchronization, gain stability, and sensor accuracy, and we developed techniques to compensate for differences in performance of the 10 beams. We have shown that there are three primary causes of third harmonic power imbalance on Nova. Differences in total gain of the arms require independent control of the input irradiance on each arm. Gain saturation parameters can be made equal by adjusting the stored energy in the final amplifier stages. Differences in frequency conversion efficiency can be compensated for by adjusting the area of each beam. As a result of these efforts, we can now achieve power balance of better than 10% in the foot and 5% at the peak of shaped 30 Nova drive pulses with contrast ratios up to 10:1 and total output energies up to 40 kJ.

**Acknowledgments**

We are very grateful to the Nova laser operations staff, who worked so diligently on our experiments throughout the process that allowed us to achieve these goals. We are also indebted to the ICF program management for their patience and continuing support throughout the long learning process. Finally, we owe a great deal of thanks to Howard Powell and Ralph Speck, who saw the path to a solution when they initiated the project several years ago.

**Notes and References**

4. M. D. Cable, Lawrence Livermore National Laboratory, Livermore, CA, internal memorandum (April 7, 1993).
Introduction

We improved the accuracy of placing Nova beams on target—a major element of the laser enhancements for the Precision Nova project. Pointing accuracy is an important factor for indirect-drive target experiments, because it determines the position of the primary sources of x-rays in the hohlraum. This affects the symmetry of capsule irradiation and the convergence that can be achieved with stable implosions. The Precision Nova pointing improvements discussed here contributed significantly to the success of the high-convergence HEP-1 experiments on Nova as described in a subsequent article entitled “Target Diagnostics for Precision Nova Experiments.”

The Precision Nova goal was to position beams on target with an uncertainty, the difference between the actual and aimed-for positions, of 30-μm rms or less when averaged over the 10 beams. Since the targets are placed near the focal plane of a 3-m focal length lens, this goal is equivalent to having a pointing uncertainty of ≤10 μrad.

A primary part of our Precision Nova pointing effort was to develop reliable diagnostics for measuring beam positions on target. We developed accurate techniques to perform pointing calibration shots and to analyze their results, which are discussed in the “Pointing Shots and Image Analysis” section. Using dedicated Nova shots as well as so-called no-shot tests, we monitored our pointing accuracy and assessed how various factors contribute to beam pointing uncertainty. As discussed in the “Sources of Scatter and Offsets” section, we found that the Nova alignment instruments were adequate for our Precision Nova needs and that only operational improvements were required. We implemented new procedures and can now routinely meet our 30-μm accuracy beam-pointing goal.

Pointing Shots and Image Analysis

Generally, it was not possible to measure the beam pointing during actual Nova implosion experiments; therefore, we measured our pointing accuracy with standardized pointing shots.1 For these shots, we used planar targets in the 10-beam chamber with the five beams from the east and the five from the west incident on opposite sides (Fig. 1). We pointed the beams at aim points positioned around the circumference of circles with different diameters for the two sides (2- and 3-mm diam). X-ray pinhole cameras imaged the two sides of the target and recorded the time-averaged images of x-ray emission during the shot. Be filters in front of the film blocked x-ray energies below about 1.5 keV, and 100-ps pulses minimized the effect of plasma motion during the pulse.

As shown in Fig. 2, the pointing targets have two rings of fiducial holes at the aim points and a larger central hole used for positioning. The targets are thin (50-μm thick), Au-coated, single-crystal Si wafers with small, etched fiducial holes (25-μm square). Figure 1 shows the beams are incident at 40 degrees to the target surface; therefore, the targets must be very flat so that surface modulations do not affect the results. We chose Si because very flat wafers are commercially available. The fiducial holes allow x-rays to pass through to the opposite side of the target and to be imaged along with the beams incident on that side. Etching of these crystalline targets produces square craters with rectangular through-holes, as indicated in Fig. 2. It is optimal for the beams to illuminate the cratered side of the target so that the small through-hole produces a spatially well-defined fiducial image on the x-ray camera when viewed from the other side. The cratered side of the fiducials are small enough (120-μm square) compared to the typical beam size (500 x 800 μm²), that they do
not significantly affect the images of the beams. We found it advantageous to locate the holes, and therefore the aim points for the beams, asymmetrically on the targets, so that the fiducial images could be uniquely identified without knowing the orientation of the film in either the target chamber or the digitizer used for film analysis. Notice in Fig. 2 that the two fiducials directly to the right of the central hole are displaced upwards from their symmetric positions.

Figure 3 shows x-ray images obtained with pointing calibration shots. In the “Matching Beam-to-Beam Focal Areas” section, we discuss the obvious differences in beam size. Both images have been properly flipped and rotated to match the asymmetric pattern shown in Fig. 2. The x-ray fiducials are visible inside the ring of beams on the left [Fig. 3(a)] and slightly outside it on the right [Fig. 3(b)]. Since the positions of the holes are measured with target metrology before a shot, the fiducial image locations provide a means of determining the transformation from film to target coordinates. More fiducials are available (up to five per image) than the number of unknowns in the transformation (three), allowing the calculation of a fitting error. To have confidence in the analysis, we insist on using at least four fiducials and having a fitting error <1-μm rms.

We developed interactive software to standardize procedures and to minimize operator influence in obtaining beam positions from the digitized x-ray film images. Using the digitized film data, we convert film density first to x-ray fluence and then to laser fluence. From the latter, we determine the beam intensity centroid, that, by definition, is the beam position. The software first defines a fog level, which is subtracted from the overall image data. The histogram of optical densities for the digitized image determines the fog level. The histogram generally shows a large peak near the origin corresponding to the large number of pixels at the background density level of the film. The software defines the film density corresponding to this maximum of the histogram to be the fog level. Once the fog level is subtracted, image density is converted to x-ray density.

**Figure 2.** Schematic diagram of a planar pointing target showing the square, cratered fiducial holes produced by etching the crystalline Si substrate. The outer circle of fiducials was etched from the front side and the inner circle from the back side.

**Figure 3.** Digitized x-ray images showing beams and fiducials from the two sides of a pointing target. The data were taken early in the Precision Nova Project before improvements were made.

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*Image 1: Schematic view of a planar target as positioned for a pointing calibration shot. The beams are incident on the two sides, and the viewing angle of the camera is normal to the target from each side.*

*Image 2: Diagram of a planar pointing target showing the square, cratered fiducial holes produced by etching the crystalline Si substrate.*

*Image 3: Digitized x-ray images showing beams and fiducials from the two sides of a pointing target. The data were taken early in the Precision Nova Project before improvements were made.*
fluence using calibration information for the particular film type. We then convert from x-ray fluence to laser fluence using \( I_{\text{laser}} \sim (I_{\text{x-ray}})^{1/3} \), which is an approximate relationship for our intensities and the x-ray energy range measured in our x-ray pinhole cameras.

The final step in the determination of the beam positions requires the operator to define a threshold laser fluence, which defines the outer limits of the beam. The operator then selects a region of interest, and the software calculates the intensity-weighted centroid for that region, ignoring pixels with illumination below this threshold.

To estimate data analysis errors, we tested the software with repeated calculations on the same data, using different operators and different assumptions. Although the software removes most of the operator judgment, it still requires the choice of a threshold fluence to define the beam boundary. However, test calculations showed that varying the threshold from zero to 10% of the image maximum caused only a 2-\( \mu \)m rms change in beam positions. We also tested sensitivity to the assumed relationship between laser and x-ray fluences by comparing results with the standard relationship and with \( I_{\text{laser}} \sim I_{\text{x-ray}} \). These two relationships gave centroid positions differing by 11-\( \mu \)m rms, which is again small compared to our beam positioning goal of 30-\( \mu \)m. Finally, separate analyses of the same data by two different operators gave the same centroids to within 10-\( \mu \)m rms. Therefore, we conclude that the data analysis uncertainties of the centroid positions are \(<10-\mu m\) and are thus insignificant compared to our pointing accuracy goal.

To describe beam pointing uncertainty, we have found it useful to distinguish offset and scatter from the total measured pointing error. The total error for a given beam is the distance between the aim point and the actual position of a shot on target. Offset is the distance from the aim point to the average shot position for a group of shots. (To be precise, the offset for each beam is a vector.) Scatter is the root-mean-square combination of the distances from the individual shot positions to the average shot position. With these definitions, the three quantities for a given beam are related by

\[
\text{total error}^2 = \text{(offset)}^2 + \text{(scatter)}^2 .
\]

To describe all Nova beams, it is useful to speak of total error, offset, and scatter values that are rms averages of these quantities over all beams.

Figure 4 shows results from a four-shot series of pointing shots taken in January 1991, before most of the improvements for this project had been made. The \( y \)-direction in the plot corresponds to outward radial directions on the pointing target (Fig. 2), and the \( x \)-direction corresponds to the clockwise azimuthal direction on the target. The aim point for each beam is at the origin on the plot. Each circle represents a single Nova beam; its radius is the measured rms scatter and its position is the offset from the aim point. The magnitudes of the \( x \) and \( y \) displacements are measured in a plane orthogonal to the beam direction rather than in the plane of the pointing target itself. The total pointing error for the shot series was 102-\( \mu \)m rms, and the offset and scatter were 97- and 31-\( \mu \)m rms, respectively. These are typical of early results and show that an overall improvement of three- to fourfold was required to meet the Precision Nova pointing goal of 30-\( \mu \)m rms.

### Sources of Scatter and Offset

Figure 5 shows the instruments used for aligning beams to a target. There are four steps to accomplish target alignment. (1) Position a surrogate target, usually a reticle on frosted glass, at the center of the chamber using the three target alignment viewers (TAVs). These TAVs have mutually orthogonal viewing angles, one along the axis of the chamber and the other two in the chamber mid-plane. All have internal crosshairs that are pre-aligned to an alignment sphere placed at the center of the chamber to define the target chamber center. (2) Co-align a UV laser used for target alignment with the 1064 system alignment laser. A cw Ar ion laser, injected in
the output spatial filter, is used for this purpose since its wavelength is close enough to the frequency-tripled 1-μm beam to eliminate chromatic differences in focusing. A 5-cm-diam subaperture sampling mirror is translated into the beamline to direct a portion of both alignment lasers into a wavelength-independent pointing reference (IPR).  

The IPR consists of a dispersion-free Cassegrain telescope and a camera to show the far-field positions of both beams. Superimposing their far-field positions co-aligns the two beams. (3) Point the UV beams to the appropriate positions on the surrogate target. Beam positions are controlled by moving the focusing lenses, using the target plane imager to view beam positions on the surrogate target. (4) Replace the surrogate target with the real target using the TAVs again to view the positioning.

We evaluated the scatter that these instruments produce in our pointing results by measuring the reproducibility of each step in the alignment procedure. These "no-shot" tests consisted of several repetitions of one or more alignment steps. Operators who normally align targets for Nova performed these tests. We recorded the positions of either the target focusing lenses or the target positioner to provide a measure of reproducibility. These tests showed that placing either the surrogate target or the actual target contributes 8-μm rms uncertainty; the pointing step contributes 10-μm rms uncertainty; and, compared to these, the co-alignment step contributes insignificantly. Combining the three sources gave a total of 16-μm rms uncertainty from the alignment procedure. These tests confirmed that the Nova alignment instruments are capable of producing a scatter well within the Precision Nova pointing goal of 30-μm rms. Furthermore, combining this 16-μm rms estimate of scatter from target alignment with the previously estimated 10-μm rms scatter from data analysis, gives an expected scatter of 19-μm rms. Since that is substantially smaller than the scatter found in early pointing tests (Fig. 4), this clearly shows that operational use of these instruments adds significantly to our pointing uncertainties.

We conducted a number of shots series on Nova to identify operational sources of pointing uncertainty. We found that a significant source of scatter comes from centering errors of the UV alignment beam during the IPR co-alignment step. As previously done, this step made the UV and 10 alignment beam samples point in the same direction, but did not guarantee coincidence of the near-fields of the two beams. Since the 10 beam is significantly aberrated after passing through most of the laser chain, and the target lenses have spherical aberration due to design compromises, centering errors between the UV and 10 beams at the target lenses produce pointing errors on target. We demonstrated this with back-to-back pointing series, without and with centering the UV alignment beam. Centering reduced scatter from 33- to 21-μm rms.

We found another source of scatter resulted from starting re-alignment to the chamber too soon after a full-system shot. The location of the subaperture sampling mirror used by the IPR to co-align the UV and 10 alignment lasers is very close to the edge claddings on the disk splits in the 46-cm amplifiers. The temperature rise of these edge-claddings (about 15°C) causes a temperature gradient and hence beam steering that takes about 45 min to decline. We eliminated this scatter by waiting 45 min after a shot before beginning re-alignment.

We found other sources of scatter that had nothing to do with the alignment instruments. First, in "walk-about" tests we observed that movement of personnel on the 10-beam target chamber frame causes flexure of the frame and significant pointing changes at the target. Consequently, we now require personnel to stay

![Diagram](https://via.placeholder.com/150)

**FIGURE 5.** Schematic diagram of the arrangement and hardware used for target alignment (TAV) is not shown because it is mounted directly below TAV 2.)
off the target frame during alignment of the beams into the chamber. Second, we noticed an error in the co-alignment of one of the 1α alignment lasers relative to the pulsed beam actually used for shots. The alignment laser was typically aligned into the system once at the beginning of the day and then only re-aligned as needed. However, without a regularly scheduled check, we found it sometimes drifted significantly out of co-alignment. An automatic alignment program does this co-alignment procedure very quickly; therefore, we added a step at the beginning of the alignment procedure to run the program for each shot.

Figure 6 shows the improvement in the scatter of pointing shots over time as these improvements were added to our operational procedures. By the beginning of 1992 when the above improvements were all implemented, the observed scatter in our pointing tests had declined to approximately 20 μm. This was extremely close to our expected scatter, based on the uncertainties in our analysis and in the use of the alignment instruments as discussed earlier. However, Fig. 6 shows that we were still left with sizable offsets between the aimed- and the actual target beam directit on the pulsed beam actually used for shots. The operators position the reticle according to the alignment geometry in (a) which is more like the alignment geometry shown in Fig. 7(b), which is more like the alignment geometry used for holtraums. The beams are all aligned to the average alignment. This offset is sizable for at least one Nova beamline. For beam 10, the sampled portion of the 1α beam is pointed about 20 μm away from the average beam direction. Co-alignment produces a corresponding 60-μm offset on target. This offset is stable in time but cannot be easily eliminated. Moving the IPR sample mirror to obtain a more representative sample would reduce the offset, but the position would probably vary from beam to beam, making the mechanical modifications expensive.

A second source of offset results from the poor edge visibility of the alignment reticle in the TAVs. The depth-of-field of the TAVs is substantially shorter than the width of the alignment reticle. Consequently, when the reticle is viewed from the side, the TAV shows a blurred edge. The operators position the reticle according to the leading edge of that blur, and measurements show that the actual reticle surface is 37 (±6 μm) into the blur. For holtraum shots, this causes a 37-μm offset for both the odd and even beams toward the center of the chamber. This offset remains constant for a given target geometry, unless the alignment reticle is replaced with one of a different width.

Offsets can also arise from the target geometry used in pointing tests. Early pointing shots used the geometry shown in Fig. 7(a), where beams were aligned to circles on the reticle exactly where they were to hit the pointing target. Although straightforward, this geometry differs from that actually used in holtraum target experiments and can potentially lead to different offsets. Thus, we have evolved into the geometry shown in Fig. 7(b), which is more like the alignment geometry used for holtraums. The beams are all aligned to the

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**Figure 6**: History of measurements of beam pointing errors (offset and scatter) obtained during the Precision Nova Project. (70-10-0294-017)

**Figure 7**: Different geometries used for beam pointing tests. The geometry in (b) is preferred since it closely approximates that used for holtraum experiments. (70-10-0294-0180)
center of the reticle, and the target is placed a distance beyond the reticle, which is calculated to put the beams at the desired radial positions on target. This position closely corresponds to where the beams hit the hohlraum wall.

Another potential source of offset differences between target experiments and our pointing calibration shots is the use of defocusing techniques. All beam alignment is done with the beams focused on the reticle, whereas most shots are taken with the target about 2-mm beyond best-focus. Defocusing is done by moving the lens a calculated amount with no visual references. In principle, misalignment of the lens focusing axis with respect to the beam direction would cause pointing errors whose magnitude would depend on how far the lens was moved after alignment. We investigated this potential problem by mounting a CCD camera at the center of the chamber and determining the centroid of the alignment beam as either the lens or target was moved. We concluded that defocusing produces negligible offset changes for the lens motions that are typically employed.

**Implementation of Precision Pointing**

By implementing these operational improvements, we have reduced the scatter in pointing tests to an acceptable level. We have also identified several sources of pointing offsets and adopted the strategy of introducing offsetting corrections at shot time. The offsets appear to be quite stable; most of the points in Fig. 6 (after November 1992) are averages of data taken over four or more days and some span seven to eight weeks. Nonetheless, Nova is a complicated system and we cannot be completely certain that we have identified all potential sources of offset changes. Therefore, we have made the following three additions to the precision pointing procedure:

1. Periodic pointing calibration shots are required (every other week at present) to keep track of offset changes.
2. No changes can be made to optical components in the laser or to beam centering at the beam-forming apodizer, between the last pointing shot and a target series requiring precision pointing.
3. The alignment geometry for the pointing calibration shots should be as close as possible to that of the target campaign.

Figure 8 shows recent pointing results, similar to Fig. 4, for six shots scattered throughout a six-day target series that used precision pointing with offsets canceled at shot time. The total pointing error was 30-µm rms. This series demonstrated our ability to reach the Precision Nova goal. A comparison of Figs. 4 and 8 shows the progress we made on pointing accuracy during the Precision Nova Project.

We have also defined a procedure for doing quick-turnaround shots that maintains precision pointing accuracy. With quick turnaround, targets are positioned using the TAVs, and small beam alignment changes are made blind using encoders to reposition the target lenses, but without visually confirming the new beam positions. Quick-turnaround shots reduce the time between shots from about 3 hrs for a full precision pointing re-alignment, to about 2 hrs with a corresponding increase in shot rate. There is, however, the potential for drift in beam alignment over the many hours typical of shot campaigns, which would increase scatter. Since we want the total pointing error to be less than 30-µm rms, scatter must be kept to <25-µm rms to allow for some imperfection in offset cancellation.

Most, if not all, of the drift in beam alignment results from the heat deposited in the amplifiers during a shot. We find no evidence for alignment drift in any of the transport sections between the chain outputs and the target chamber. Consequently, we are able to use the output sensors, which are located after the laser amplifiers, as pointing references to eliminate thermal drift. We establish the output sensors as temporary pointing references just before the beams are aligned for the first shot. For subsequent shots, we re-point each beam to its output sensor just before shot time to eliminate any alignment drift during the time since the first shot. In a series of pointing calibration shots, we confirmed that this technique maintains the required Precision Nova pointing accuracy.

![Figure 8](image-url)
Matching Beam-to-Beam Focal Areas

Another motivation for routine pointing shots is to monitor and provide corrections for beam-to-beam focal area differences. Such differences affect beam irradiances and could potentially affect hohlraum performance. Early pointing shots showed large beam-to-beam differences in focal areas (Fig. 3). As shown, the measured beam areas varied by more than a factor of three with an rms variation of 47%. These differences result from a mismatch in collimation between the UV alignment beam and the 1µ pulsed beam. Since the UV alignment beam is used to set the target lens position for best-focus Nova, we have also demonstrated procedures which allow quick-turnaround shots with this same total pointing error, and for matching beam-to-beam focal area differences to 10% rms.

The authors are grateful to Russell Wallace and Edward Hsieh for skillful target fabrication; to Paul J. Van Arsdall for development of the interactive software; to Glenn Hermes and the Nova operations crew for steadfast support; and to Howard Powell and the other members of the Precision Nova team for constructive comments.

Notes and References

3. Because the x-ray energies measured are well above the peak thermal values, the x-ray fluence varies nonlinearly with laser fluence. Calculations by Lawrence Suter predict that Jx,τ < τ /τ lasers in this regime. Lawrence Livermore National Laboratory, Livermore, CA, private communication.
PRECISION TARGETS FOR PRECISION NOVA

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Introduction

Capsule convergence is probably the most fundamental quantity of ICF capsule implosions. A major goal of the Precision Nova campaign has been to achieve reproducible and predictable yields at high convergence. The yield is determined by the temperature of the compressed fuel, which is affected both by the symmetry of the implosion and by mixing of the cold pusher into the compressed core. The symmetry of the implosion is determined by the symmetry of the radiation drive, which can be affected by the power balance and pointing of the separate laser beams as well as the design of the hohlraum. The mix of the pusher and fuel is determined by hydrodynamic instabilities during the implosion, which produce mix at the capsule–fuel interface. These instabilities are caused by surface perturbations on the inside and outside of the capsule, which are amplified during the implosion. Understanding how these factors influence the implosion dynamics is a principal motivation for the Precision Nova improvements and a major goal of our Nova technical contract effort. In this article, we discuss work particularly relevant to hydrodynamic instabilities and mix: the development of improved techniques for mapping the topology of capsule surfaces, and the creation of unique polymeric materials for implosion diagnostics.

The amount by which capsule surface perturbations are amplified during the implosion is dependent on the ratio of the capsule circumference to the wavelength of the perturbation. This ratio is called the mode number. The relevant mode numbers for a capsule are determined mainly by design features such as ablator dopants and wall thickness. Computer simulations, and some experimental evidence, indicate that mode numbers between roughly 10 and 30 are particularly important for Nova-scale targets in determining the amount of mix. Because such low mode numbers are important, the capsule as a whole must be characterized. Analysis of a patch of the capsule surface, as performed in the past with conventional atomic force microscopy, is not sufficient.

The evolution of the plasma temperature and density in the mix region can be determined spectroscopically. Density and temperature information can be extracted by measuring the intensity and spatial distribution of the emission and absorption associated with the various H-like and He-like ions in the plasma as a function of time, and relating these intensities to plasma models. The temperature inside the capsule during the implosion is such that the diagnostic atoms must have a considerably higher atomic number than carbon, the primary component of the plastic target, to avoid becoming fully ionized. Historically, argon has been mixed with the fuel, and Cl has been added to the inner wall of the target to provide the spectroscopic signal from the capsule–fuel interface. However, new target designs and laser pulse-shaping have produced more energetic implosions, resulting in the need for dopants of higher atomic number to maintain the populations of H-like and He-like ions necessary for our spectroscopic techniques.

A typical target, shown schematically in Fig. 1, is constructed in layers. The inner layer is called the mandrel or pusher and is composed of a polystyrene (PS) microballoon about 0.5 mm in diameter with a wall thickness of a few micrometers. These microballoons are produced using a drop-tower procedure with PS dissolved in a volatile solvent. The mandrel is coated with a layer of polyvinyl alcohol (PVA) a few micrometers thick, which serves as a permeation barrier for the hydrogen isotope fill. The outer layer, known as the ablator, is built up through plasma polymer deposition. Since we want to diagnose conditions at the fuel–pusher
interface, our dopant atoms must be incorporated into the PS mandrel.

The need to dope our mandrels with intermediate-Z elements has led us to synthesize a number of new polymers. The essential requirement of these polymers is that they be soluble in volatile organic solvents and that they contain from 0.1 to 1.0 at.% of the desired dopant atom. Since the production of the microballoons is still largely an empirical process that is quite sensitive to the properties of the polymers used, we have tried to keep our new polymers as PS-like as possible. We have also tried, where possible, to produce a polymer sample with a very narrow molecular weight distribution (monodisperse), though we have found that this is not essential for microballoon formation. Thus far, we have produced modified PS polymers with Br, Cl, I, Cr, and Ti dopant atoms covalently attached to the polymer molecules. Mandrels have been prepared with all but the Br-doped polymers, which, though not useful for mandrel formation, have proved useful in calibration experiments, in planar Rayleigh-Taylor instability experiments, and for shock-breakout witness plates for drive characterization.

In the following sections, we first describe our new surface characterization techniques using atomic force microscopy. We then review the status of our synthesis efforts with doped polymers. Finally, we discuss two examples that demonstrate the intimate connection between the polymeric materials used and the surface finish of the mandrels produced from them.

**Measurement of Capsule Surface Topology**

As stated earlier, one of the goals of the ICF Program is to relate capsule surface finish to capsule performance. Haan proposed a theoretical framework for doing this, and an experimental program to test the theory has been initiated. The model requires a description of the capsule surface in terms of the 2-D power spectrum obtained from a spherical harmonic expansion of the surface height. We developed a profilometer that can generate equatorial traces of a capsule surface using an atomic force microscope (AFM). Fourier analysis of these traces yields a 1-D power spectrum (a plot of the square of the amplitude of the kth mode as a function of k). For isotropic surfaces, the 2-D power spectrum can be expressed in terms of the 1-D spectrum.

Figure 2 shows the apparatus we use to characterize capsule surfaces. The principal mechanical components are a precision air bearing with a rotary encoder and a standalone AFM. We use a Macintosh computer,
equipped with data acquisition boards, to control the apparatus and analyze the data. The sample to be traced is mounted on a vacuum chuck that is attached to, and rotates with, the air bearing. A measurement begins with the bearing stationary while the AFM tip is brought into contact with the sample surface. A standard tip consists of a silicon nitride pyramid, approximately 4-μm wide at the base and 2.5-μm high, at the end of a 200-μm-long cantilever. The radius of curvature of the tip, where it touches the surface, is about 40 nm. The engagement force is adjusted by monitoring the deflection of the tip (i.e., the cantilever) while moving the AFM. The sample is then rotated, typically at about 1 rpm. The feedback circuit in the AFM controller maintains constant tip deflection by varying the voltage applied to a piezoelectric tube to which the tip is attached. This voltage, which is proportional to the surface height at the tip, is digitized with a 16-bit D/A converter and recorded as a function of angular position. The resolution of the encoder is 0.1°, so each trace consists of 3600 points, with each point representing an average of up to 100 voltage measurements. Three parallel traces are normally taken: one at the equator, and two others 20 μm on either side. To characterize a sample, this procedure is performed for three independent (approximately orthogonal) orientations of the capsule on the vacuum chuck, for a total of nine traces. The power spectra of these traces are averaged together to provide the final result.

The data are reduced as follows: each trace is extended to 4096 points by cubic spline interpolation, and its fast Fourier transform and related power spectrum are computed. The final result is obtained by averaging the spectra together. On some traces, the tip encounters a dust particle or some other defect that generates a signal much larger than that of the underlying structure of the capsule. In extreme cases, such traces are not included in the averaged power spectrum.

This new tool has given us our first quantitative measurements of the complete modal structure of capsule surfaces. Unlike the conventional AFM patch data, which do not yield useful information for wavelengths longer than about 40 μm, these traces give us accurate measurements of the longer-wavelength modes. This information can be fed directly to the simulations that are used to predict capsule performance.

Doped Polymer Synthesis and Mandrel Topology

In previous articles in the ICF Quarterly Report,6,7 we have reported on the synthesis of Br-, I-, Fe-, and Cr-doped polymers and on the formation of microshells from the latter three. In this section, we briefly review that work and report on recent results involving preparation of a Ti-doped polymer that produces acceptable microshells. We then present two examples that illustrate the relation between mandrel quality and polymer chemistry, which was first revealed with the advent of the AFM-based profilometer.

Polymer Synthesis

Our initial attempts to produce doped polymers began with halogen dopants. Partially brominated PS was prepared by direct reaction of Br₂ with pendant aryl rings of commercial monodisperse PS. The degree of substitution was controlled kinetically on the basis of an experimentally determined calibration curve that gave substitution level as a function of reaction time. Polymers with Br doping up to 3.5 at.% can be prepared routinely.

Molecular iodine, I₂, is not sufficiently electrophilic for direct iodination of aryl systems. Therefore, we used trifluoroacetyloxyiodide, CF₃COOI, as our electrophile.8 Because CF₃COOI is so active, we controlled the level of iodine addition stoichiometrically rather than kinetically. Polymers with I doping up to 0.9 at.% can be predictably produced. Targets have been routinely produced from mandrels made with the 0.55 at.% I-doped polymer and have been used in implosion experiments for both spectroscopic and imaging diagnostics.

Iron-doped polymers have been prepared by the copolymerization of styrene with vinylferrocene.9 The dopant concentration in the polydisperse polymer product is controlled by the initial stoichiometry. We produced a number of acceptable target mandrels at a doping of 0.35 at.% Fe, which were used as spectroscopic mandrels in implosion targets for ICF experiments.

A Cr-doped polymer was prepared by reacting Cr(CO)₆ directly with the pendant phenyl rings of PS, yielding an arene-Cr(CO)₃ coordination. Using this approach, we controlled the dopant level kinetically by quenching the reaction at the appropriate time. As in the Br-doping process, the relation between the reaction time and the doping level was determined empirically by performing calibration runs. The bulk Cr-doped polymer is bright yellow when freshly prepared, but gradually darkens when exposed to light. The darkening is due to the photocatalyzed loss of CO and subsequent oxidation of the Cr⁰ to Cr³⁺, probably in the form of Cr₂O₃. Samples stored in the dark retain their yellow color for months. The impact of the CO loss and Cr oxidation on the microshells produced from 0.2 at.% material is discussed below.

The production of a soluble Ti-doped polymer suitable for solution drop-tower techniques was difficult. Many examples exist for cross-linked (and thus insoluble) materials, which are frequently used as catalyst
supports. Our first attempts at producing a soluble Ti-doped polymer involved attempts to selectively carboxylate some fraction of the para ring positions of monodisperse PS to provide sites for the attachment of a titanocene adduct. However, this attempt at macromolecular modification was plagued by low-level cross-linking reactions, making the resulting polymer insoluble. We next tried copolymerizing styrene with p-carboxystyrene to produce a polydisperse polymer with a controllable fraction of pendant carboxy groups. This polymer was isolated and reacted with various Ti-containing adducts, but in each case cross-linking reactions either during the adduct addition or in the subsequent cleanup produced insoluble (presumably cross-linked) polymer.

We have recently succeeded in copolymerizing a vinyl titanate, (2-methacyloxyethoxy)-trisoproxytitanate, with styrene to produce a soluble Ti-doped polymer. Preliminary results indicate that the doping is about 0.06 at.% Ti. Efforts to increase this level are under way. Mandrels have been produced from this polymer and are being used in implosion experiments.

**Mandrel Topology**

The development of AFM equatorial trace measurements opened up quantitative characterization at length scales not previously accessible on spheres. Our first analyses of completed targets showed that many were characterized by significant roughness at long wavelengths \(k = 10\) to \(100\); \(k\) tens to hundreds of micrometers. This was particularly unfortunate because hydrodynamic instability growth is most pronounced in this region. We determined that at least some of this roughness originated with the doped plastic microshell on which the complete target is fabricated. In this section, we review two specific examples that are of interest since they demonstrate a connection between the details of the polymeric materials used and the resulting surface topology of the microshells.

One of our first troublesome results was the fact that targets built around our CI-doped mandrels, which we prepared from a blend of monodisperse PS and commercial poly(p-chlorostyrene), showed significant long-wavelength roughness. To understand this, we mapped the surfaces of both the pure, undoped PS mandrels and the Cl-doped mandrels produced by blending polymers. Figs. 3(a) and 3(b) show representative traces from these shells; Fig. 4 shows the corresponding power spectra. The traces show that the pure polystyrene shells were in most cases very smooth, with power of about 1 nm\(^2\) at mode number \(k = 10\) and less than 0.01 nm\(^2\) at \(k = 100\). Departures from sphericity are most pronounced at lower \(k\). The large \(k = 2\) mode gives the traces their sinusoidal appearance. The blended, Cl-doped shells show a much rougher surface in the \(k = 10\) to 100 range. This is clearly visible in the actual trace plots, with oscillations of up to 100 nm in amplitude at wavelengths of 20 to hundreds of micrometers (5 to several tens of degrees). The power spectrum for the blended Cl-doped shells ranges from about 40 nm\(^2\) at \(k = 10\) to 0.1 nm\(^2\) at \(k = 100\), or roughly an order of magnitude more power than the undoped shells in the same \(k\)-mode range. It is important to emphasize that these Cl-doped mandrels were made by blending two polymers, undoped PS and fully doped...
PS (6.25 at.% Cl), to produce the desired doping of 1.0 at.% This suggests that the bumpiness might be due to phase separation.

If the roughness of the Cl-doped shells is due to phase separation, the problem should be eliminated by using a single, partially chlorinated polymer (with 1.0 at.% Cl doping) to prepare the shells. Since such a polymer is not commercially available, we synthesized one by copolymerizing styrene with p-chloromethylstyrene. The mix of monomers and the extent of reaction were adjusted to give 1.0 at.% Cl in the resulting polymer.

Shells were made with this polymer using the same drop-tower parameters as for our pure PS shells. Figure 3(c) shows typical equatorial traces from a p-chloromethylstyrene-styrene copolymer shell, and Fig. 4 shows the corresponding power spectrum. The traces and power spectra of the copolymer shells are comparable to those of our baseline PS shells. We have thus solved the problem of producing smooth Cl-doped shells, although we are not certain why the blended shells are bumpy. One certainly expects the components in a blend of polymers to phase separate on some length scale as solvent is removed during shell formation, but it is not clear over what length scales the phase separation should manifest itself.

A second example of the connection between polymer chemistry and surface topology is demonstrated by our Cr-doped mandrels. Using the AFM equatorial scanning technique, we discovered significant surface roughness on microshells produced from the Cr-doped polymer discussed earlier. Figure 5(a) shows representative equatorial scans of a 5-month-old Cr-doped shell that had been stored in a dry box under ambient fluorescent light. Significant long-wavelength roughness with amplitudes of up to several hundred nanometers is clearly visible. Since the polymer used for these shells was a homopolymer and not a blend, phase separation phenomena cannot play a role.

To test whether the roughness was due to aging, fresh mandrels were prepared and scanned immediately. Figure 5(b) shows representative scans of these shells. The newly formed shells show none of the surface roughness observed in the 5-month-old shells.

Figure 6 shows the power spectra for the aged shells, the new shells, and the smooth undoped PS shells. Note that the aging roughness manifests itself only at relatively low (k < 40) mode numbers, where the power is as much as a factor of 100 higher for the shells aged in ambient light. Also note that the Cr-doped mandrels, even when freshly prepared, are not quite as smooth as the undoped PS shells at the higher (k > 50) modes.

As stated earlier, the Cr-doped polymer is light sensitive. To determine if light played a key role in the aging process, some of the new shells were stored in the dark for 7 weeks while others were stored under various light conditions. We found by further AFM scanning of shells from these sets that those stored in the dark showed no increase in surface roughness, while those that were exposed to light from any source showed significantly increased roughness. The traces and spectra are qualitatively similar to those already shown in Figs. 5 and 6.

A likely explanation for this phenomenon is that following a photocatalyzed loss of CO and CR oxidation, the resulting Cr$_2$O$_3$ is no longer chemically bound to the polymer molecule and may migrate. This would create voids or stresses that might allow the polymer to relax, leading to deformations.
We confirmed the loss of CO from the shells exposed to light by IR spectroscopy of the individual shells. Shells held in the dark for 7 weeks still show the strong carbonyl bands characteristic of the Cr(CO)₅ linkage to the pendant aromatic rings. By contrast, a shell exposed to light for 20 days shows almost no carbonyl band intensity, while all other bands due to the PS remain unchanged. Clearly, the loss of the CO, whether or not it is followed by Cr oxidation and/or migration, represents a significant change in the local environment of the polymer chains and must be followed by chain relaxation. It is not obvious on what length scale these relaxations should manifest themselves in terms of surface deformations. The traces and power spectra show that the deformations appear most strongly in the long-wavelength regions, indicating coupling between local chain relaxations, with a length scale of a few nanometers, and global shell deformations, with length scales of tens to hundreds of micrometers.

Summary

An ongoing objective of the ICF program is to achieve a better understanding of implosion dynamics. Efforts in this area have driven the development of better characterization techniques and new capsule designs, which in turn require new polymers for implosion diagnostics. We have discussed progress in two areas: the measurement of capsule surface finish and the production of mandrels containing various high-atOMIC-number dopants.

Because of the presence of hydrodynamic instability during an implosion, the initial surface topology of a target capsule is extremely important. We have developed an instrument for nondestructively profiling capsules that is based on an atomic force microscope. This instrument provides information to gauge the quality of both the mandrels and the finished capsules. Moreover, the power spectra that are derived from these traces are used as input to the computer simulations that predict the capsule performance. Dopants in the mandrel, which are ionized during the implosion, are important for diagnostic purposes. The use of new target designs and laser pulse shaping has led to more energetic implosions, which requires dopants with higher atomic numbers to maintain the necessary populations of H-like and He-like ions. We have successfully synthesized Br, Al, F, Cr-, and Ni-doped polymers and have produced usable mandrels from all but the Br-doped polymer.

Acknowledgments

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References

TARGET DIAGNOSTICS FOR PRECISION NOVA EXPERIMENTS

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Introduction

The improvements to the Nova laser system, which are part of Precision Nova, are necessary for performing the high-convergence and high-density implosions that are the hydrodynamically equivalent physics (HEP) experiments of the Nova technical contract. However, the diagnosis of these implosions is of primary importance to determine whether the goals specified for Precision Nova are necessary and sufficient conditions for the success of HEP experiments. Therefore, we have determined the diagnostic improvements necessary for Precision Nova target experiments. In every case tested, these improvements have proven to be sufficient to diagnose the implosions produced by Precision Nova. Table 1 lists the specifications and the status of the diagnostic systems. This article briefly summarizes the measurement techniques, implementation, and experimental results achieved to date using these diagnostic systems.

*Los Alamos National Laboratory (LANL)

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<thead>
<tr>
<th>Diagnostic System</th>
<th>System Function</th>
<th>Upgrade Specification</th>
<th>Status</th>
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<td>Obtains neutron image of imploded core</td>
<td>Ax - 10 µm</td>
<td>Ax - 15 µm (initial version complete)</td>
</tr>
<tr>
<td>X-ray diagnostics:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High-resolution, high-energy x-ray spectroscopy</td>
<td>Diagnoses core electron temperature conditions</td>
<td>v/AW - 3,000</td>
<td>v/AW - 3,000 (completed)</td>
</tr>
<tr>
<td>Fast x-ray framing camera</td>
<td>Obtains x-ray images of the implosion core</td>
<td>M - 30 ps</td>
<td>M - 32 ps (completed)</td>
</tr>
<tr>
<td>Imaging at high x-ray energies</td>
<td>Obtains x-ray images of the implosion core</td>
<td>hv - 8 keV</td>
<td>hv - 5 keV (completed)</td>
</tr>
<tr>
<td>High-speed x-ray streak camera</td>
<td>Diagnoses core conditions</td>
<td>M - 2 µm</td>
<td>M - 5 µm</td>
</tr>
<tr>
<td>Short-pulse x-ray backlighter</td>
<td>Provides backlit images of core</td>
<td>M - 5 ps</td>
<td>M - 20 ps (completed)</td>
</tr>
</tbody>
</table>

TABLE 1. Specifications and status of the diagnostic systems.
Neutron Diagnostics

Fusion targets that contain deuterium (D₂) and tritium (T₃) produce neutrons during the time of peak implosions. We gain important information about the implosions by diagnosing the characteristics of these neutrons. Specifically, the neutrons from a given implosion will have a characteristic energy distribution, emission time, emission duration, and spatial distribution, which are directly related to average fuel areal density (<pR>), fuel temperature, and fuel compression during the burn process. We designed several diagnostics to measure these parameters as part of Precision Nova.

Neutron Spectrometer

Fuel areal density is an important fundamental ICF parameter that has steadily increased in Nova experiments. Since neutrons can escape from the core of even the largest, most dense targets, measurements of fuel areal density are primarily neutron based. In an initially pure D₂ target, tritons T are produced by the main reaction

\[ D + D \rightarrow n + (E_n = 2.45 \text{MeV}) \quad (1) \]

The reaction of deuterons D with T produces secondary neutrons

\[ D + T \rightarrow n + \alpha(E_n = 12 - 17 \text{MeV}) \quad (2) \]

and the areal density of the fuel determines the number of secondary neutrons produced. The difference in energy \( E \) of these two varieties of neutrons requires a detector that can differentiate neutron energies (usually by time-of-flight). This measurement requires a high-sensitivity, high-resolution neutron detection technique, therefore, we constructed the large-area neutron scintillation array (Lansa).\(^1\) This array is a large area (96,000 cm\(^2\), 960 individual scintillators) time-of-flight detector with a 20-nm flight path. The long flight path plus the use of fast scintillators (resolution 2.3 ns FWHM) gave good energy resolution (170 keV at 14.1 MeV); the required high sensitivity was achieved from the large area and the use of the individual scintillators as single particle detectors. To achieve low background, another important requirement, we used a combination of shielding, collimation, and geometrical arrangement.

Using a series of Nova experiments, we characterized each scintillator in the entire array: (1) We measured the signal propagation delay of each channel with hard x-ray producing shots, which allowed the measurement of the photon arrival time for each channel. (2) We characterized the neutron response using low-yield DT implosions to produce \( 10^8 - 10^9 \) 14 MeV neutrons. Such an implosion produces a single 14 MeV peak in the Lansa detector with a width that is determined by the intrinsic detector resolution (170 keV) and thermal broadening.

We then advanced to a series of high-density implosion experiments, where the effect of the Precision Nova effort is the most apparent; Fig. 1 shows the extracted fuel density for experiments both before and after Precision Nova. Such high densities (approaching 20 g/cm\(^3\)) are only achievable with the greater symmetry provided by Precision Nova.

Neutron Emission Duration\(^2\)

We are interested in measuring the fusion reaction rate of ICF targets relative to the incident laser power. This burn history is a sensitive indicator of our ability to accurately model energy transport in our experiments. Because burn times are of the order of 100 ps, a detector system with time resolution of ~20 ps is desirable. Fusion reactions produce monoenergetic charged particles and neutrons, except for broadening due to thermal motion of the reacting ions. For neutrons leaving a target simultaneously, this reaction causes a spread in the arrival times at the detector; to limit this spread to below 20 ps, the distance of the detector to the target for 14.1 MeV neutrons must be limited to <16.4 cm.

We developed and demonstrated a fast, sensitive neutron temporal detector (NTD) for recording the fusion reaction rate history of ICF implosions. Our detector is based on the fast (<20-ps) rise time of a plastic scintillator. A 1.5-mm thick, 6-mm diam piece of plastic scintillator converts neutron kinetic energy to
light. We use an achromatic 1/2 zoom lens system to couple the scintillator light to a fast (15-ps temporal resolution) optical streak camera. This streak camera also records an optical fiducial pulse, which allows the burn history to be related to the timing of the incident laser beams with ±15-ps accuracy.

We have made excellent burn history measurements with this instrument. We have measured burn histories with a resolution of about 25 ps for targets producing as few as $10^8$ DT neutrons. We have shown temporal resolution to be <20-ps FWHM by recording signals generated by 20-ps bursts of X-rays. Figure 2 plots an example of a complete reaction rate history. The NTD represents a significant step forward in our ability to measure the reaction rate history for ICF targets.

**Ion Temperature**

Neutron time-of-flight detectors provide important information about the fuel-ion burn temperature ($T_i$) in ICF targets. As described earlier, motion of the ions in a plasma broadens the otherwise monoenergetic burst of neutrons produced in an implosion. We constructed and installed on Nova an ion temperature diagnostic (Tion), which measures the neutron arrival time distribution using an array of scintillators 27.1 cm from chamber center. Like LANSA, the scintillators in this array are operated as single particle detectors with good temporal resolution (~1 ns). (Although LANSA may, in principle, be used for this measurement, the LANSA detectors are optimized for ~14 MeV neutrons; for this experiment, an instrument optimized for 2.5-MeV neutrons was required.) A 1-keV ion temperature gives a distribution in arrival times of 21.7-ns FWHM at Tion for a DD reaction (2.5-MeV neutrons), and the same ion temperature gives 3.4 ns for a DT reaction (14.1-MeV neutrons). The diagnostic covers DD neutron yields for $10^7$ to $2 \times 10^8$, a dynamic range of 200.

Initial experiments with Tion will characterize the detector time response as installed. These experiments will use targets filled with $99.7\%$ D$_2$ and $1\%$ T$_2$, a fill that should produce about the same number of DT and DD neutron hits in the detector array. For typical ion temperatures in these implosions, the expected ratio of DT to DD hits will vary from 0.6 to 1. The detector time response and the neutron energy spread influence the time spread of the DT neutron peak; the temperature-induced energy spread dominates the time spread of the DD peak. By obtaining both peaks in the same implosion, we can determine the detector time response.

We will examine yield degradation by fuel-pusher mixing and implosion asymmetry in high convergence experiments. Yield degradation as convergence is increased (caused by asymmetry) will be indicated by decreasing $T_i$ and an asymmetric core shape. A mix-dominated implosion is calculated to exhibit the same or somewhat higher $T_i$ because the $T_i$ profile is modified by cooling in the outer region of the fuel. These predicted differences may be used to assess the relative contributions of mix and asymmetry.

**Neutron Imaging**

The neutron penumbral-aperture microscope (NPAM) provides images of a neutron burn region in imploded laser-fusion targets. X-ray imaging of the imploded core produces complex images that depend on many processes during the implosion; neutron imaging simply produces an image of the fusion reaction region (and, as noted earlier, neutrons escape from the core of the densest implosions). A penumbral aperture uses the information contained (encoded) in the penumbra of an image produced by an aperture (such as a pinhole) which is larger than the source it images. The initial implementation of the NPAM has a spatial resolution of about 15 µm and has recorded legible images on targets yielding about $10^{11}$ neutrons. The NPAM uses a 6-cm-thick Au aperture with a particular taper to achieve good spatial resolution over a 200-µm field-of-view. The aperture has a diameter varying from approximately 500 to 900 µm. A tapered aperture is used rather than a pinhole because a 6-cm-thick pinhole (required to stop neutrons) does not produce a point spread function that is the same everywhere in the image, unlike a more usual thin pinhole substrate. The aperture is therefore much larger than the neutron source region, so it will produce a coded (penumbral) image. Straightforward deconvolution techniques are used to make an estimate of the source region from the coded image. Because the NPAM field-of-view is quite small, we devised a very precise alignment system that

![Figure 2: Reaction rate history as measured by the NTD and compared with the laser pulse history. The duration of the burn is about 110-ps FWHM.](image-url)
points and centers the thick aperture on the target to within ±25 μm. The neutron image is recorded by a 200 × 200 array of 10-cm-long, 1-mm-square scintillator elements. About half the neutrons that strike the scintillator array interact with H nuclei and produce light at about λ = 430 nm. Thus, the neutron spatial distribution incident on the detector is converted to a light image. The image is segmented and reduced by a set of four fiber-optic tapers. Each segment is then intensified, further reduced, and finally recombined and read out by a CCD camera. The readout system is very sensitive: 90% of all single-neutron interactions in a scintillator element should be detected, giving an overall quantum efficiency close to 50%. Such high efficiency is essential; a target producing 3 × 10¹⁰ neutrons will produce a peak fluence of 17 and a minimum fluence of 3 neutrons/scintillator elements.

Installation of the NPAM at the Nova laser facility is complete. We have used the detector to record neutrons produced by direct- and indirect-drive implosion shots on Nova.

X-Ray Diagnostics

X-ray measurements are also crucial in inferring conditions in the compressed fuel.⁵⁷ Time-resolved x-ray measurements are essential in the investigation of laser-driven ICF, where neutron and x-ray emission are the only observable signatures of the compressed core conditions. High-speed detectors, available for x-ray measurement, provide a means of measuring the rapidly evolving conditions in imploding capsules on picosecond time scales. We address a wide range of issues in our indirectly driven implosion experiments on Nova, with a large variety of x-ray measurement techniques. Critical issues include symmetry of the compressed core, fuel density and temperature, and hydrodynamic mix at the pusher/fuel interface.

High-Resolution, High-Energy X-Ray Spectroscopy

By doping the D₂ fuel with Ar (0.1 at. %), we measured K-shell emission in the 3–4 keV spectral region. We inferred the time-dependent fuel density from measurements of the Stark–broadened emission line profiles, and the electron temperature from line ratios. Spectroscopic measurements were made using two streaked crystal spectrometers with resolving powers (Δλ/λ) in the range of 500 to 3,000 and ~35-ps temporal resolution.⁶ High-performance targets that use more extreme laser-pulse shaping have increased pusher opacity. This has forced us to study the emission from higher-Z elements, whose spectroscopic features appear at higher photon energy. In preparation for these conditions, we have studied Li-shell (n = 3 – 2) emission from DD filled capsules doped with Xe (0.02 at. %), in the 5–6 keV spectral region.

Figure 3 shows Xe spectra from an experimental series where the fuel electron temperature was varied by altering the radiation drive. These two spectra were obtained from implosions driven by 28 kJ (high drive) and 19 kJ (medium drive) respectively, of 0.35-μm laser light in a 1-ns duration square pulse incident into the hohlraum. We observed clear differences in the spectra, showing increased fluorine-like emission for the high-drive case (due to the higher temperature). Measurements of the ionization balance for these spectra, though not as precise as the line ratio technique used for the Ar spectra, will serve to specify a range of temperatures of the fuel.⁶ Measurements of fuel density from line broadening will be difficult until high densities are achieved (>30 g/cm³) because of the relatively small broadening (<10 eV for the 4d–2p line) at lower densities.

![Figure 3: Xe spectra from an indirectly driven capsule at (a) high and (b) medium drive conditions.](image-url)
Fast X-Ray Framing Camera

Current single microchannel-plate (MCP) x-ray framing cameras deployed at Nova have a minimum frame time of ~100 ps, too slow for adequate (<10 μm) spatial resolution of x-ray sources moving at ~3 • 10^7 cm/s, and too slow for adequate temporal resolution of sources lasting ~200 ps. We therefore built a high-speed framing camera with frame times as short as 30 ps. A faster electrical pulse and a thinner MCP provide the faster gate time. Its main use will be to image imploding ICF capsules.

The active area of the new camera consists of two MCPs assembled in close proximity. (Two plates are necessary to compensate for the low signal gain in the first, faster plate.) The first plate (200-μm-thick, 10-μm-pore) is coated with four 8 Ω microstrips and is gated by 90-ps FWHM, 0.9-kV pulses. We applied a reverse bias of typically 300 V to the first plate to reduce the effective electrical gate width and to sharpen the leading and trailing edges. The second plate (450-μm-thick, 10-μm-pore) provides further signal amplification and is typically run with 500-V forward bias. We measured the camera line spread function FWHM at 56 μm (compared with 33 μm for the usual single-plate models). We tested the camera temporal resolution on the bench by uniformly illuminating the MCP with 3-ps, 203-nm laser pulses. Figure 4 shows a typical measured frame profile with FWHM = 32 ps. A second prototype camera with a 5-μm (rather than 10-μm) pore first plate demonstrated 35-ps gate times.

Imaging at High X-Ray Energies

X-ray imaging, through the use of pinholes and ring apertures, provides information on the symmetry of the imploding capsule. These techniques can be applied to soft emission from the capsule, or x-ray transmission through the capsule from backlighters. Imaging systems used in conjunction with gated MCP detectors routinely provide ~10-μm spatial resolution in the object plane and ~100 ps temporal resolution (30-ps temporal resolution is now becoming available as described earlier).

Pinhole cameras are the most common way of measuring soft emission from an imploded ICF capsule. Arrays of pinholes are used in conjunction with gated MCP detectors to provide up to 16 separate images at different times through the implosion. However, as the resolution of a pinhole camera is increased (by reducing the diameter of the pinhole) its sensitivity is reduced. Coded imaging, however, can produce substantial improvements in signal-to-noise ratio (SNR) over pinhole imaging because of the larger aperture. Experiments comparing ring aperture coded imaging to pinhole imaging demonstrated a 20-fold improvement in SNR in good agreement with simple theory.

We constructed a simple ring-aperture microscope (RAM) for routine use in the Nova laser facility. The principal component in this device is a 1-mm-diam, 5-μm-wide annulus fabricated in 9-μm-thick Au, which is positioned ~4 cm from the target chamber center. The projected ring image is recorded on a stack of x-ray film with filters, providing several energy bands of sensitivity. The recorded images are digitized and unfolded using a Wiener-filtered deconvolution. We measured the spatial resolution of this instrument to be ~5-μm FWHM.

Recently, we began testing a time-resolved version of the RAM. This instrument resembles our gated x-ray pinhole cameras, except a 4 × 3 array of 5-μm-wide, 250-μm-diam annuli replace the array of pinholes. The instrument operates at a magnification of ~10, providing a spatial resolution of 5 μm. Figure 5 shows a...
sequence of five unfolded images from a directly driven implosion of a D$_2$-filled glass capsule taken at the University of Rochester's Omega Laser Facility. The sequence shows an initial diffuse glow from the partially imploded glass shell, followed by core emission. The core diameter is approximately 20 μm, and the constant-intensity contours exhibit l = 3 or 5 asymmetries that appear to be well correlated with the laser-beam illumination pattern. In the final image, the core is beginning to disassemble.

**High-Speed X-Ray Streak Camera**

High-speed, high spatial resolution, x-ray measurements are essential in ICF research. With implosion velocities in excess of 10 cm/μs, and spatial scale lengths of order 1 μm, some measurements must be performed with temporal resolution better than 10 ps to avoid motion blurring. High spatial resolution imaging of imploded ICF capsules is required to measure features in the compressed fuel core. Detector resolution can limit the convolved system resolution in some cases.

Streak cameras offer the only means for making x-ray measurements with temporal resolution better than 10 ps. We developed an x-ray streak camera, suitable for operation inside the Nova target chamber, which is capable of several picosecond resolution. The camera operates entirely in a vacuum and is designed to operate in an electrically noisy environment. This camera is based on a previously reported\textsuperscript{12} modification of a commercially available design. The sweep plates are driven by a MOS-FET pulser,\textsuperscript{13} capable of producing 1.8 kV with a slope of 1.5 kV/ns into 50 Ω. A transmission line balun transformer is used to drive two parallel 100 Ω coaxial lines (with opposite polarity), which are terminated in a matching network at the sweep plates (6 pt plate capacitance). The output of the pulser is adjustable over five rates (125, 257, 514, 900 and 1,800 V/ns) resulting in streak speeds of 149, 71, 31, 20, and 12 ps/mm.

Initial tests of the temporal resolution and linearity of the x-ray streak camera have been performed by viewing the UV light pulse (302 nm) from a frequency doubled dye laser. A series of 1.5-ps pulses with known spacing were produced by sending the beam into an etalon with adjustable spacing. As shown in Fig. 6, the recorded pulse duration as detected by the camera is ~2 ps (when operated at the highest streak rate of 12 ps/mm). Streak linearity over the 450-ps sweep duration is better than 15%. Measurements of the temporal resolution when detecting x-rays, which will be somewhat worse due to the broader spectrum of emitted photoelectrons, are in progress. We measured the linearity of the sweep rate at slower streak speeds in the Nova environment by shooting one arm of the laser in a "beat mode" configuration at an Au disk and observing the resulting x-ray emission. In this test, we found no disruption from the associated electrical noise.

**Short-Pulse X-Ray Backlighter**

An alternative approach to the requirement of high temporal resolution for diagnosing implosions is to use a flash x-ray backlighter; x-ray detectors with slower gating times may then be used to obtain a single frame of data, and good temporal resolution is provided by the short duration of the x-ray flash. The goal of an x-ray backlighter with a duration of less than 20 ps requires a laser pulse of less than 20 ps with sufficient intensity to produce x-rays sufficient for backlighting experiments. Such pulses are now available routinely on Nova; Fig. 7 shows a temporal measurement of the x-ray pulse, and the use of such a pulse to backlight a resolution grid. The backlighter duration is about 18 ps, and the spatial resolution is ~<10 μm. The high spatial resolution is a consequence of the short duration of the backlighter laser pulse that limits the expansion time of the x-ray emitting region.

**Summary**

While the experimental campaign is not currently complete, Precision Nova improvements to the target diagnostics have met the requirements for diagnosing the implosion hydrodynamics, the core conditions, and the implosion degradation. Specifically, the neutron spectrometer (LANSA) measured the core areal density, the neutron emission diagnostic (NTD) measured burn durations, the neutron imaging (NPAM) and the ion temperature (Tion) diagnostics are installed and are ready for experimental series. The high-resolution, high-energy x-ray spectroscopy technique has been
used to diagnose core electron temperature conditions. The high-resolution, high-energy x-ray imaging diagnostic (RAM) and the fast-gated x-ray imager have been used to obtain images of the implosion core, and the high-speed x-ray streak camera and the short pulse x-ray backlighter are in use on Nova.

Notes and References
During this quarter, Nova Operations fired a total of 321 system shots, resulting in 364 experiments. These experiments were distributed among ICF experiments, Defense Sciences experiments, X-ray Laser experiments, Laser Sciences, and facility maintenance shots.

In early December, indirect drive ICF targets and experiments were declassified; therefore, most of our Nova experiments are now unclassified. Two positive effects of this transition are: (1) the facility will now be easier and more efficient to operate due to the reduced overhead previously required to classify it; and (2) uncleared personnel can now work on more of the experiments.

In support of experiments required for the December ICF Advisory Committee Target Physics review, Nova Operations ran two periods of 24-hr operations the first two weeks of December. These operations began on a Tuesday morning and ran contiguously until the following Saturday evening. During that period, operations were very efficient and the system worked well. As part of the review, we also applied precision pointing and power balance techniques to several shots with excellent results.

This quarter, we completed and activated the neutron penumbral aperture microscope on the 10-beam chamber. This instrument images neutrons emitted by Nova implosions to a resolution of ~15 micrometers.

Work continues to support experiments that measure the scaling of stimulated Brillouin scattering and laser-beam filamentation in large-scale plasmas. We relocated the KDP array on beamline 7 of the 10-beam chamber several meters farther away from the chamber in preparation for the f/8 focus lens to be installed late in the second quarter. We installed the full-aperture backscatter system on beamline 7 of the 10-beam chamber and activated the diagnostic system, which consists of a fast diode, a calorimeter, and a streaked spectrometer.

We installed a new six-inch manipulator (SIM 7) on the 10-beam chamber to support re-entrant diagnostics. SIM 7 is located on the east side of the chamber on the port formerly used by the old target plan imager.

A vacuum leak was encountered on the 10-beam chamber, which took several days to find and repair. We speculate a small piece of target debris punctured a small hole (~0.015-in. diam) in the stainless-steel bellows (0.018-in. thick) on the arm 2 focus lens. We also discovered numerous small pits on all the focus lens bellows. To shadow the bellows from target debris, we plan to install thin metal flanges on the 10 bellow-can ends.
PUBLICATIONS

A

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C


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E


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P


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