Identification and Removal of High Frequency Temporal Noise in a Nd:YAG Macro-Pulse Laser Assisted with a Diagnostic Streak Camera

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Abstract

This paper discusses the use of a reference streak camera (SC) to diagnose laser performance and guide modifications to remove high frequency noise from Bechtel Nevada's long-pulse laser. The upgraded laser exhibits less than 0.1% high frequency noise in cumulative spectra, exceeding National Ignition Facility (NIF) calibration specifications.

Inertial Confinement Fusion (ICF) experiments require full characterization of streak cameras over a wide range of sweep speeds (10 ns to 480 ns). This paradigm of metrology poses stringent spectral requirements on the laser source for streak camera calibration. Recently, Bechtel Nevada worked with a laser vendor to develop a high performance, multi-wavelength Nd:YAG laser to meet NIF calibration requirements. For a typical NIF streak camera with a 4096x4096 pixel CCD, the flat field calibration at 30 ns requires a smooth laser spectrum over 33 MHz to 68 GHz. Streak cameras are the appropriate instrumentation for measuring laser amplitude noise at these very high frequencies since the upper end spectral content is beyond the frequency response of typical optoelectronic detectors for a single shot pulse.

The SC was used to measure a similar laser at its second harmonic wavelength (532 nm), to establish baseline spectra for testing signal analysis algorithms. The SC was then used to measure the new custom calibration laser. In both spatial-temporal measurements and cumulative spectra, 6~8 GHz oscillations were identified. The oscillations were found to be caused by inter-surface reflections between amplifiers. Additional variations in the SC spectral data were found to result from temperature instabilities in the seeding laser. Based on these findings, laser upgrades were made to remove the high frequency noise from the laser output.

1. INTRODUCTION

At Bechtel Nevada Livermore Operations (BNLO), the support of the NIF program and other High Energy Density Physics (HEDP) projects utilize streak cameras that require strict calibration standards. These requirements can become a conundrum when diagnostics are trying to keep pace with the experiment requirements, while the systems calibrating the diagnostics are attempting to perform at levels emulating the experiments.

Feedback from NIF customers indicated that the calibration capabilities utilized with an older laser (Nd:YAG) were insufficient for calibrating the streak cameras. A decision was made to have another laser built to meet the calibration requirements for NIF. The task of determining how to verify that the laser would meet the technical specifications rested on the manner of how and what to test the laser with. The critical problem of laser performance was identified as a laser noise level in the high frequency region from 1 to 50 GHz, where Nd:YAG laser noise measurements have been short in supply, partly due to the lack of proper instrumentation with fast response.

In this paper, we will describe the custom macro-pulse Nd:YAG laser and its performance. We will then show how a streak camera was used to make high frequency noise measurements in the region of 60 MHz to 70 GHz¹⁻⁶. We will further present a maximum value sampling method in streak camera data analysis⁷. We will discuss the modifications that removed the high frequency noises in the laser temporal output. Our work led to the successful improvement of a macro pulse Nd:YAG laser, which is the foundation of a calibration source at 213 nm with an output energy of greater than 260 mJ per shot.

2. CRITERIA FOR TESTING THE MACRO-PULSE ND:YAG LASER

The limitations of BNLO's previous laser were the temporal pulse length, the available wavelengths and the quality of the spatial profile. The previous laser was capable of generating a 7 nanosecond (ns) gaussian, full width half max (FWHM) temporal pulse at 532 nm while producing an energy of 280 milli-joules (mJ) per pulse. The temporal duration of the pulse was too short compared with the 400 ns requirement. Therefore, a divide-restacking scheme was used to stretch the pulse, as shown in Fig. 1. Figure 2 represents the expected time shifting of the split beams and the resulting recombination. However, as shown in Fig. 3, the best result obtained with this technique was a 30 ns flat top pulse. Further, there were problems with the stretched flat top temporal pulse such as low energy to the diagnostic and degradation of the spatial profile. Therefore, a new laser was needed for a high performance calibration source.

Figure 1. Layout of Optical Pulse Stretcher for Long Pulse

Figure 2 Predicted simulation of combined pulses

Fig 3 Optical pulse stretch of 50.3ns FWHM, with 2.8% deviation over 30ns

The new laser was required to be versatile over a broad range of diagnostics. The increased use of X-ray streak cameras required the generation of UV to stimulate the gold (or cesium) photo cathodes used on these diagnostics. The

required wavelengths needed would be 1064, 532, 355, 266, and 213 nm. To cover the swept temporal range of both the X-ray and optical SC's, the laser had to be capable of generating a minimum base pulse of 400 ns. The base pulse must be amplitude controlled to help shape an output temporal beam intensity to meet a required minimum 100 ns flat top with temporal variation of less than 10% peak-to-peak about the mean flat top value. One of the most stringent requirements is that the total intensity fluctuation from 1 GHz and above (up to 100 GHz) must be smaller than 0.1%. In addition, the spatial quality of the laser must be capable of producing a spatial flat top with a variation of less than 10% peak to peak. The laser ultimately had to produce a minimum energy of 30 mJ's at 213 nm. To verify these requirements, existing photo-diode detectors alone are inadequate due to slow response at the required wavelengths. Figure 4 shows the laser pulse temporal shape taken with a "fast" photoconductor detector with a frequency response of 3 GHz. The result shows no systematic oscillation except for small amplitude noise at lower frequencies. The other problem with photo-detectors is that they cannot measure the spatial profile. A streak camera was selected as the best method of testing the new laser because of its fast temporal-response and high resolution spatial imaging capability.

Figure 4 Photodiode showing location of SC sweep and limitation of frequency response

Streak cameras²⁻⁶ represent a class of imaging devices that involve multi-step photo-electron conversion processes. In Fig 5, the streak camera first converts the incoming laser signal photons to electrons at the photo cathode which has multiple layers of thin film photoelectric materials. The emission of the electrons reflects both a deterministic transfer function of the cathode layer structure and stochastic noise due to the photon arrival time statistics and the transport process. The electrons are then accelerated toward the anode⁸. The deflection voltages will convert temporal arrival time into a spatial distribution to form the "streaked" image. At the anode phosphor screen, the electron kinetic energy is converted to photons. Similar to the inverse process at the photo-cathode, the electrons that impinge on the phosphor screen will fluoresce a pattern characterized by a point-spread function^{2,9,10}. Further, a micro channel plate intensifier (MCPI) between the streak tube and the CCD is usually needed due to the weak illumination signal at the streak camera input. In the MCPI, multiple photon to electron, and then electron to photon conversions will occur with an increase of light gain. At each step, the conversion process will add deterministic transfer function signatures and noise in both the spatial distribution and temporal arrival time. The CCD camera image is a multi-step convolution of all the sequential response processes. In such a multi-step conversion chain, the resultant output is a Gaussian curve symmetric about the mean electron count in the CCD. This can be deduced from the central limit theorem in stochastic analysis and linear system theory^{11,12}. The noises that result from the conversion processes are generally signal dependent. The signal to noise ratio is therefore highest at the signal peak plus the noise output. Approaching a Gaussian process further makes the peak value a statistically robust point for sampling. The sampling of the representative signal values captured in the temporal images is therefore possible by taking only the temporal peak value.

Figure 5 Streak camera functional block

The selected SC for laser diagnostics has the following characteristics: 1) High resolution imaging capability with a CCD array of 4096 x 4096 pixels. 2) Sweep speed of 30 ns to detect temporal frequencies into the high GHz region. 3) Spatial aperture of 50 mm, which is twice the size of most SC's on the market, therefore providing a higher spatial-temporal image quality. 4) Custom built by Bechtel Nevada with over 20 years of experiences.

3. USING A STREAK CAMERA AS A LASER DIAGNOSTIC TOOL

The S-20 photo cathode of the optical streak camera is typically sensitive in the range of 400 - 800 nm. Thus the streak camera can not see the fundamental 1064 nm mode of the new laser without using a harmonic doubler to generate the needed 532 nm. This nonlinear optical conversion process essentially maps the noise characteristics of the 1064 nm fundamental into the 532 nm wavelength. Therefore, we were able to identify and correct all out-of-specification conditions as soon as the second harmonic became available. A baseline measurement at 532 nm was conducted on another system with a similar front end being built by the sub-contractors. The overall laser diagnostic layout for the experiment and the collection of data for analysis during the build up of the laser is shown in Fig 6.

Fig. 6 Block diagram of test setup

Fig. 7 Actual test setup during buildup

The laser consists of an oscillator and an amplifier chain of six optical gain sections to provide enough energy for multiple nonlinear optical conversions. The actual imaging set up is shown in Fig 7. The streak camera is used behind the doubler with proper attenuation. Care was taken to allow the SC aperture to sample the representative spatial profile.

In the SC initial run, the sweep speed of the SC was set for 27 ns as a result of balancing the temporal resolution and total data length in time. This speed provided a frequency response up to 73 GHz. The trigger control timing adjustment allowed the SC to sample different segments of the laser pulse. During the first captures of the 532 nm beam, it was discovered that a temporal oscillation was present. In Fig 8, it is possible to see the uncorrected oscillation in lower spatial lobe of the streaked image, but more precise data analysis shows that the oscillations with largest amplitude are actually located in the overexposed upper spatial lobe.

Fig. 8 First captured image showing temporal anomalies

There was concern with the oscillation because one of the tests used during the calibration and characterization of a SC system is taking a flat field. This means that the laser beam must be a top hat and flat to within the tolerances specified. A non-varying temporal beam can help to identify the system anomalies in a streak camera system. These can range from nonlinear deflection sweeps, sweep bias offsets, non-uniformities on the anode phosphor or on the photocathode, imperfections or damaged fiber bundles and other induced problems. Any temporal oscillations or noise present in the beam could interfere with the analysis of the calibration and characterization of the SC.

4. ANALYSIS OF TEMPORAL DATA USING PEAK VALUE SAMPLING METHOD

The available sweep times for this streak camera were 27, 30, 60, 120, 240, and 480 ns. This would cover the common ranges of calibrations used at NIF. When using a 4K x 4K CCD^{1,13} with the SC at the fastest scan of 27 ns, the sampling time interval is 6.6 picoseconds (ps), corresponding to a sampling frequency of 152 GHz. This high end sampling frequency range is well beyond the bandwidth of the conventional photo-diode detection.

As a preliminary procedure, a background correction is first applied to the image. This procedure reduces non-intrinsic noise, such as CCD dark current and stray light images. Shown in Fig. 9 is a 3D representation of a temporally swept laser beam image recorded on an array of CCD pixels. This shows the phosphor photon intensity profiles along each spatial column of pixels. The peak intensity along each spatial column is identified by the red peaks.

For every time value t_i , the CCD image is sampled along the spatial column j ($j=1,2,\dots,N$, where N is the image size in space) to obtain the response $\mathbf{R}(t_i)$,

$$\mathbf{R}_i = \max_{\forall j} \{ \mathbf{R}_{i,j} \}, \quad \text{for } t_1, \dots, t_i, \dots, t_M, \quad (1)$$

where M is the image size in temporal dimension. As the peak value, $\mathbf{R}_i$ represents the most probable accumulated peak value at time moment t_i . This simple procedure is effective to immediately produce a clear waveform for the time analysis. A Discrete Signal Processor filter is applied to $\{ \mathbf{R}_i \}$ after the peak value sampling. However, the result is

insensitive to the specific form of the filter. A Fourier spectral analysis using the Welch algorithm^{11,12,15} is performed to find the laser power spectra using the block diagram steps shown in figure 10.

Fig. 9 Simplified representation of streaked temporal laser intensity profile on CCD pixels

Figure 11 shows the temporal peak-value sampling profile of the streak camera image. For clarity, Figure 12 shows a portion of the peak-value profile at an expanded time scale.

Figure 10 Steps required to perform analysis

At the time of measurement, the peak-value oscillations in Figure 13 (a) had a nominal period of 17 pixels with each pixel representing 7.3 ps. This represents an oscillation frequency of 8 GHz. Figure 13 (b) shows the calculated power spectrum, which shows clearly that there is a hump from 6 to 10 GHz. This indicates that an oscillatory instability existed in the laser beam. This oscillation was subsequently determined to be the result of multiple reflections.

Figure 11 Temporal peak-value sampling profile

Figure 12 Expanded time scale of temporal oscillation

Figure 13a (upper) and 13b (lower) Analysis of frequency content (lower) from temporal peak-value profile (upper)

5. APPLICATION OF ANALYSIS RESULTS TO SOLVING OSCILLATIONS

To ensure that the data plotted in the power spectrum was correct, a novel method of performing a cross check was found. Streak cameras are two-dimensional recording devices. The spatial dimension provides transverse cross-sectional information of the laser beam. Peak-value sampling is a sensitive method to utilize this feature. Figure 14 shows the peak value spatial track during the entire temporal sweep. A small geometric distortion is observed in the temporal dimension. Further, the trace of peak values is actually oscillatory in the spatial domain as time evolves. We determined that a detailed transverse mode beat in the laser amplifier chain was causing the spatial oscillatory behavior. The oscillatory range is only 10 pixels in spatial dimension. Conventional moving area averages normally used in analyzing streak camera data would have smeared the observation of such a minute oscillatory movement. Out of the 4000 plus data points (pixels) in the temporal profile of Figure 13a, there were less than 10 spurious points (hot or weak CCD pixels) needing window limitations.

Figure 14 Peak value spatial track

Figure 15 Frequency analysis of spatial track

Figure 14 was obtained from the same streak image shown in Figure 8 by tracking the spatial-temporal coordinates of the peak points in each column. Small oscillatory spatial movements of the peak points were observed in Figure 14. Further, Figure 15 plots the temporal frequency Fourier spectrum of peak track data in Figure 14. Indeed there is again a spectrum hump in the 6-10 GHz range. This demonstrated that the oscillation anomaly in the laser beam is *both* temporal and spatial. This suggested that the oscillation was due interference from several slightly different spatial modes. This revealed the unique ability of streak cameras to diagnose complex spatial-temporal oscillatory activity in lasers. In contrast, photodiodes do not provide spatial information, and CCD cameras alone do not have temporal response.

Based on the analysis using peak value sampling, we looked for reflections between optical surfaces separated by a beam path length of 30 to 60 mm. We worked with the laser manufacturer to test the light pulses as potential solutions were investigated. Using the same peak-value sampling technique, we noticed improvements in the laser spectrum when a double pass amplifier was removed from the system. Redesigning and laying out the front end of the laser as a single pass system, the unwanted oscillatory noise was successfully removed. Figure 16 (a) shows an improved streak camera recording, (b) shows the temporal profile of the streak using peak value sampling, and (c) shows the power spectrum. There is no large amplitude repeatable high frequency oscillation observed. The spectrum falls smoothly, following a typical CCD noise spectrum.

Figure 16(a) Improved laser temporal image on SC

Figure 16(b) Improved peak-value temporal profile of laser beam with oscillation removed

Figure 16(c) Improved laser power spectrum

To relate the spectrum to rms noise value in the time domain, we calculated cumulative spectra for each frequency segment from 2.5MHz to 100GHz. We define cumulative spectra as the summation of frequency components in each frequency section, and then further find the statistics of the spectra. Multiple laser shots were taken by the same streak camera at various sweep speeds to insure the statistical significance. These procedures characterize global frequency distribution of the laser power. Meanwhile, they provide an important test of the robustness of the peak value sampling method.

During the process of collecting the data, we discovered another noise anomaly. The level of noise in the frequency segments kept shifting in amplitude. Further investigation revealed that the system was experiencing a thermal stability problem with the continuous wave (CW) seeder. By externally adjusting the temperature control, we found that the controller was defective. After repairing the unit, we decided to continue plotting the effects of frequency bins by adjusting the temperature control in equal voltage offset steps. Although this required the collection and analysis of a lot of captured data, the result was a plot (Figure 17) showing the different modes of the CW seeder as a function of temperature.

From the plot we determined the best voltage setting for the CW seeder temperature controller by observing the noise content in the plotted frequencies. Figure 17 shows the data collected during the temperature stability test as well as the optimum setting for each frequency range.

Figure 17 Plot of CW seeder modes with respect to temperature

Robustness of Simple Peak Value Sampling Method: Cumulative Spectra in Frequency Segments

Figure 18 Plots of cumulative spectrum (a) and the accumulative spectral mean & standard deviation (b)

The cumulative spectra and statistics for the sweep speed of 27 ns are shown in Figure 18. In each set of statistics, subfigure (a) shows the cumulative spectrum calculated from the peak value line profile. Subfigure (b) shows the accumulative spectral mean and standard deviation in each group. For each frequency section specified in the contract, the spectral components are summed to obtain the cumulative spectra. The cumulative spectra from 5 to 10 shots are shown as bars in each frequency section.

6. CONCLUSION

In our attempt to utilize a streak camera to diagnose unwanted oscillatory frequency content in the temporal beam of a laser meant to be utilized as a calibration tool, we have demonstrated the following practical capabilities: 1) A streak camera is a very useful tool for diagnosing laser output at very high frequencies. 2) A peak value sampling method is a simple but effective analysis tool for spatial-temporal imaged data from streak cameras. This method is based on the intrinsic process in streak cameras. 3) In the process of analyzing data from the incoming laser, we found that the laser output had a 6~10 GHz oscillation. We determined that these oscillations were due to the reflections caused by the high gain (double pass) amplifier stage. 4) We have demonstrated a method of verifying the temporal peak value sampling data by utilizing the data contained in the spatial track data. 5) By using multiple incremental voltage steps to control the temperature of the CW seeder, we demonstrated the streak camera's ability to determine the optimal temperature setting for minimizing modal noise effects. 6) The peak value sampling and statistical cumulative spectrum are new characterization methods in laser diagnostics. This method is very sensitive, and handles the high band-filter nature of the streak camera very well.

To our knowledge this is the first time that a Nd:YAG long pulse laser amplifier chain was diagnosed with a streak camera using the laser's 532 nm second harmonic for both temporal and spatial output characteristics. The laser was discovered to contain both an unwanted fast oscillation above 6 GHz and thermal control instabilities in the CW seeders that caused modal noise content in the laser's temporal beam. These problems would be very difficult, if not impossible, to detect by a traditional optoelectronic detector in a shot-per-shot observation. With streak cameras now reaching into the UV spectrum, a versatile array of laser diagnostic tools has become available. These systems will likely become a standard characterization tool for the calibration of high-speed instrumentation.

Keywords: Streak camera, laser, maximum value sampling, image processing, high frequency, spectral analysis

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