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A pulse-burst laser system for Thomson scattering on NSTX-U

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Abstract: A pulse-burst laser system has been built for Thomson scattering on NSTX-U, and is currently being integrated into the NSTX-U Thomson scattering diagnostic system. The laser will be operated in three distinct modes. The base mode is continuous 30 Hz rep rate, and is the standard operating mode of the laser. The base mode will be interrupted to produce a "slow burst" (specified 1 kHz rep rate for 50 ms) or a "fast burst" (specified 10 kHz rep rate for 5 ms). The combination of *base mode→interruption→burst mode* is new and has not been implemented on any previous pulse-burst laser system. Laser pulsing is halted for a set period ($\sim$ 1 minute) following a burst to allow the YAG rods to cool; this type of operation is called a heat-capacity laser. The laser is Nd:YAG operated at 1064 nm, q-switched to produce $\geqslant$1.5 J pulses with $\sim$ 20 ns FWHM. It is flashlamp pumped, with dual-rod oscillator (9 mm) and dual-rod amplifier (12 mm). Variable pulsewidth drive of the flashlamps is accomplished by IGBT (insulated gate bipolar transistor) switching of electrolytic capacitor banks. Direct control of the laser Pockels cell drive enables optimal pulse energy extraction. The laser system has demonstrated compliance with all specifications, and is capable of exceeding design specifications by significant margins, e.g., higher rep rates for longer burst periods. Burst operation of this laser system will be used to capture fast time evolution of the electron temperature and density profiles during events such as ELMs, the L-H transition, and various MHD modes.

Keywords: Lasers; Pulsed power

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Contents

1 Introduction to pulse-burst lasers

Pulse-burst programming of a solid-state laser is intermediate between single-shot high energy operation and steady-state operation. A single-shot laser produces one large multi-joule pulse, with an interval of minutes between pulses for components to cool and power supplies to recharge. A steady-state laser pulses continuously, typically producing $\sim$ 1 J pulses at a repetition rate of10 –100 Hz. Pulse-burst laser systems produce a burst of $\sim$ 1 J laser pulses at repetition rates between 1 kHz and 1 MHz [1–4]. The number of laser pulses in a burst varies according to the system design, but is typically in the range of 10–1000. Similar to the single-shot laser, there is an interval of $\sim$ 1 minute between each burst of pulses.

Most pulse-burst laser systems have been built for specific measurement applications in fluid dynamics or plasma science [1]. Flashlamp-pumped Nd:YAG laser systems are most common, although diode-pumped systems have been constructed [5].

1.1 New base mode

Since the NSTX-U device produces plasma shot lengths that span seconds, the Thomson scattering diagnostic has operated with two standard steady-state Nd:YAG lasers, each pulsing at a repetition rate of 30 Hz [6]. This type of diagnostic operation has been highly successful, and is sufficient for many NSTX-U experimental scenarios. However, this repetition rate is not able to capture the dynamics of transient events such as edge-localized modes (ELMs), which take place on sub-ms timescales [7]. This motivated the construction of a pulse-burst laser system for NSTX-U Thomson scattering, but to maximize value and flexibility of the system it was specified to be able to operate in three distinct modes. The base mode is continuous 30 Hz rep rate, and is the standard operating mode of the laser during an NSTX-U plasma shot. The base mode can be interrupted to produce a “slow burst” (specified 1 kHz rep rate for 50 ms) or a “fast burst” (specified 10 kHz rep rate for 5 ms).

The combination of *base mode→interruption→burst mode* is new and has not been implemented on any previous pulse-burst laser system. The "interruption" can either be pre-programmed to occur at a specific time, or can be the result of a dynamic trigger occuring during the plasma shot. Laser pulsing is halted for a set period (~ 1 minute) following a burst to allow the YAG rods to cool.

The three operating modes of the NSTX-U laser system are illustrated in figure 1. The fast burst mode differs from the other two modes in that many laser pulses are produced by repetitive q-switching during one long flashlamp pump pulse. For the base and slow burst modes, each flashlamp pump pulse is short and produces only one laser pulse from a single q-switch.

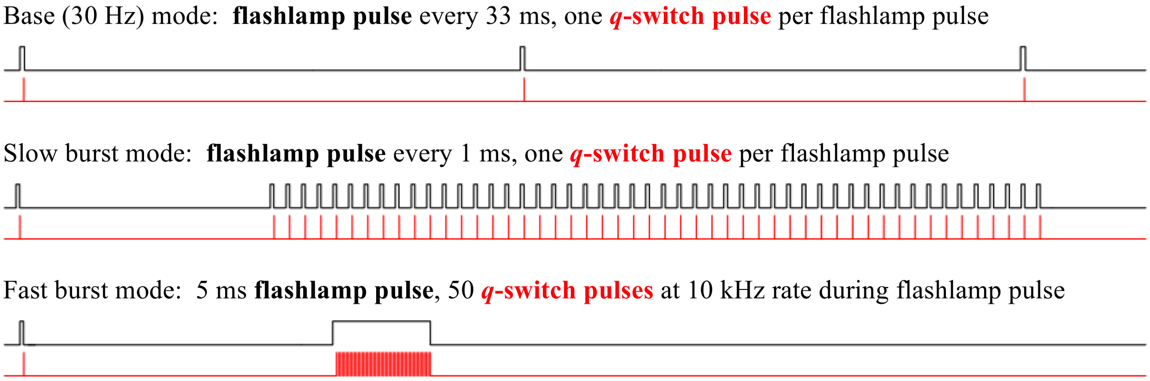

Figure 1. Schematic illustration of the three operating modes of the laser system.

2 Laser system architecture

2.1 Optical head

The NSTX-U laser is Nd:YAG operated at 1064 nm, q-switched to produce $\geqslant$ 1.5 J pulses with ~ 20 ns FWHM. It is flashlamp pumped, with dual-rod oscillator and dual-rod amplifier. The optical head was assembled by Quantel using standard commercial components (figure 2). The oscillator rods are 9 mm in diameter, and the amplifier rods are 12 mm. Flashlamps are driven two in series with the modular drive units described in the next sub-section. Each oscillator pumping chamber

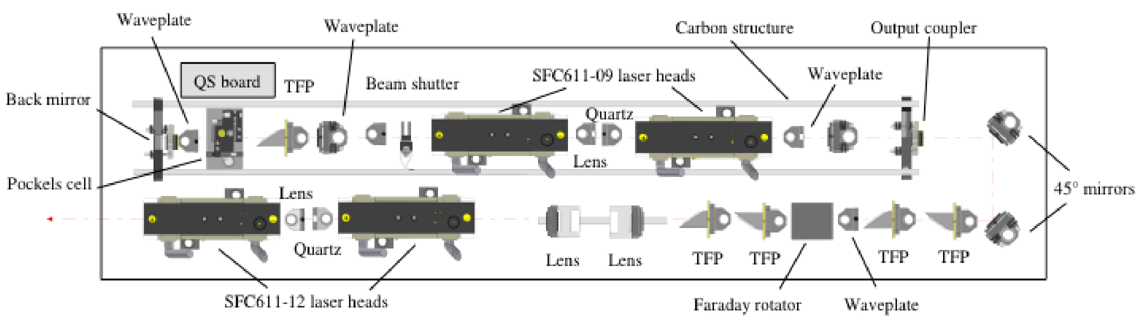

Figure 2. Layout schematic of the Quantel optical head used for the NSTX-U pulse-burst laser system. "TFP" refers to "thin-film polarizer." Drawing provided by Quantel Laser.

(SFC611-09) contains two flashlamps, and each amplifier pumping chamber (SFC611-12) contains four flashlamps.

The KD*P Pockels cell is driven by a Bergmann Messgeräte Entwicklung KG driver system model number ds12b. Direct control of the Pockels cell drive enables optimal pulse energy extraction in any of the three operating modes. The high voltage drive pulse applied to the Pockels cell must be kept to less than approximately 100 ns width to avoid exciting piezoelectric ringing of the crystal [8]. Standard KD*P Pockels cells driven this way can be operated at pulse repetition rates of 100 kHz or more.

2.2 Flashlamp drive units

A major requirement for pulse-burst operation of a flashlamp-pumped laser system is direct control of flashlamp pulsewidth and repetition rate. Standard flashlamp drive is typically a simple inductor/capacitor pulse-forming network producing a single $\sim$ 100 μs pump pulse. For a pulse-burst laser, the flashlamps are driven with a system based on solid-state switching of large electrolytic capacitor banks, which produces multiple flashlamp drive pulses of adjustable width at variable repetition rates. As illustrated in figure 3, a capacitor bank stores energy for the pulse burst, and is switched by IGBT (insulated gate bipolar transistor) to produce square flashlamp drive pulses. For the base (30 Hz) mode, the capacitor bank is recharged between flashlamp pulses. For a burst mode, the capacitor bank provides almost all flashlamp energy, as recharging during a burst is minimal. The capacitor bank (60 mF) is sized to keep flashlamp drive voltage droop to less than 10% during a burst.

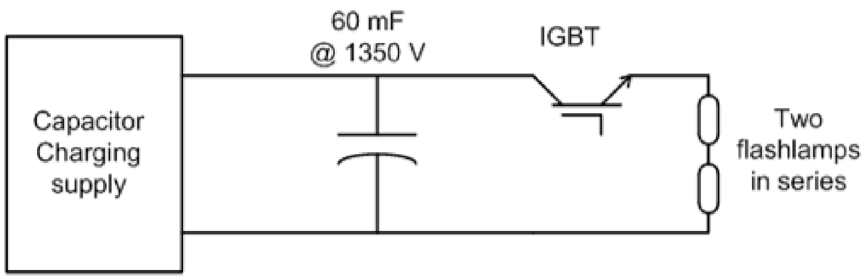

Figure 3. A simplified diagram of one of six drive units used for the NSTX-U laser system.

The laser head uses one type of standard flashlamp, filled with 700 torr of Xe, 1 mm wall thickness of cerium doped quartz. The flashlamp bore diameter is 7 mm and the arc length is 4 inches (102 mm). For two flashlamps in series the impedance $K_0 \approx 40$ ohms-amps$^{1/2}$ [9]. Pulse-burst operation requires flashlamps be driven with a large simmer current ($\gtrsim 500$ mA for these Quantel lamps) in order to avoid a substantial drop in the energy of the second flashlamp pulse in a burst.

The pulse-burst operational limits of the laser system are determined by two flashlamp limits [9]. The first is the explosion energy, defined as the electrical energy applied to the flashlamp that is likely to cause single-pulse catastrophic failure. Experience indicates that operating at $\lesssim 15\%$ of the explosion energy yields acceptable flashlamp lifetime for most operating scenarios [9]. For two flashlamps in series the explosion constant $K_e \approx 3.6 \times 10^5$ W-sec$^{1/2}$. The second operational limit is flashlamp wall loading, which for pulse-burst operation is defined as the integrated power flux to the flashlamp wall during a burst of pulses. This is not a limit that flashlamp manufacturers provide in their specificiations. Typical is the type of specification provided by Quantel, which recommends a maximum wall loading of approximately 80 W/cm^2 for steady-state operation. Lacking a better alternative, it seems reasonable to translate the steady-state wall loading specification (e.g., 80 W/cm^2) directly to a burst specification (e.g., 80 J/cm^2). This translation has an arbitrary aspect in that no systematic study has been done of flashlamp wall loading limits during burst operation, but in practice it seems to yield acceptable flashlamp lifetime. A very useful addition to the flashlamp literature would be a parametric study of flashlamp lifetime during burst operation.

The flashlamps in the NSTX-U laser system operate far below the operational limits stated above (table 1). Lengthy in-service operation will be required to determine typical flashlamp lifetime, but it should be similar to that expected for standard commercial Nd:YAG systems. Note that the voltage applied to the flashlamps for the 10 kHz fast burst is less than that required for the base 30 Hz mode. There is no provision in the flashlamp drive units to reduce the capacitor bank voltage on sub-ms timescales; this operational limitation can be resolved in one of two ways if a fast burst is required to interrupt 30 Hz base operation. The first is to lower the capacitor charge to 620 V for base operation. This requires a flashlamp pulse width of $\sim$ 300 μs in order to produce the required 1.5 J laser pulse. Since pumping of the rod is not as efficient with this longer pulse, $\sim$ 30 J pulse energy per flashlamp pair is required, but this has no negative effect on laser operation. The second, and potentially advantageous, way to produce a fast burst interrupt of base mode is to operate with a capacitor charge of 810 V for efficient base mode operation. This voltage applied to the flashlamps for the fast burst increases the pumping level of the rods and requires the q-switching to be done at >20 kHz in order to prevent the laser pulse energy from increasing to substantially more than 1.5 J. In other words, the fast burst repetition rate will be much higher than the specified 10 kHz. The percent explosion energy and wall load during the fast burst also increase due to the increased flashlamp drive voltage, but are still substantially below the operational limits described above.

Table 1. Operating parameters for two Quantel flashlamps driven in series for the three modes of operation used in the NSTX-U laser system. Note that this is not a unique set of parameters, e.g., for 30 Hz operation pulse width and voltage can be traded off as noted in the text above.

Operational mode	**30 Hz**	**1 kHz burst**	**10 kHz burst**
Burst length	steady state	50 ms	5 ms
Flashlamp pulse width t	0.125 ms	0.125 ms	5 ms
Pulse energy per flashlamp pair	25 J	25 J	750 J
% explosion energy	1.1%	1.1%	5.2%
Wall load during burst	17 W/cm^2	28 J/cm^2	17 J/cm^2
Applied to flashlamps	810 V	810 V	620 V
Voltage droop during burst	0.5 V	25 V	20 V
Current through flashlamps	410 A	410 A	240 A

3 Heat capacity laser operation

Pulse-burst laser programming is a type of heat-capacity laser operation [10, 11]. The burst of pulses is of limited duration, typically tens of ms. Waste heat accumulates in the laser rod during the burst and is not transported out, as the thermal transport timescale is much longer than the burst period. To good approximation, heat is deposited evenly throughout the rod volume during a burst, and temperature rises evenly across the rod radius [12]. Thus laser beam distortion due to thermal gradients is small during the burst. Heat is removed from rod after a burst, typically for a time of about a minute, such that the laser rod and pumping chamber are in "cold cavity" status before the next burst begins.

For the NSTX-U laser, heating of the rods during base and pulse-burst operation is moderate. Calculated thermal time constants are 4 sec for the oscillator rod, and 7 sec for the amplifier rod, confirming that the rods are in heat-capacity mode during a burst. Calculations of the temperature profiles in the rods have been done assuming 50 J pulse energy per flashlamp pair, twice the actual pulse energy. The calculated temperature profiles in the amplifier rods are illustrated in figure 4 (the oscillator rods show similar behavior). For base 30 Hz operation, the outer surface of the rod cylinder is 2–8 C above the coolant temperature, and from the outer surface of the rod to the center there is a parabolic temperature profile with a height of about 9 C. This parabolic profile gives rise to thermal lensing, which is compensated by the laser optics. When a slow burst interrupts base operation, it adds an additional 8 C uniform temperature rise across the rod; uniform flashlamp illumination leads to a uniform temperature rise as there is insignificant heat removal from the rod edge during the burst. Since the index of refraction of Nd:YAG varies linearly with temperature, this uniform temperature rise is equivalent to adding a constant phase shift to the laser light. Thus there is no significant change in the thermal lensing from base operation during a burst. Note also that the rod temperature gradient is well below the stress limit for Nd:YAG.

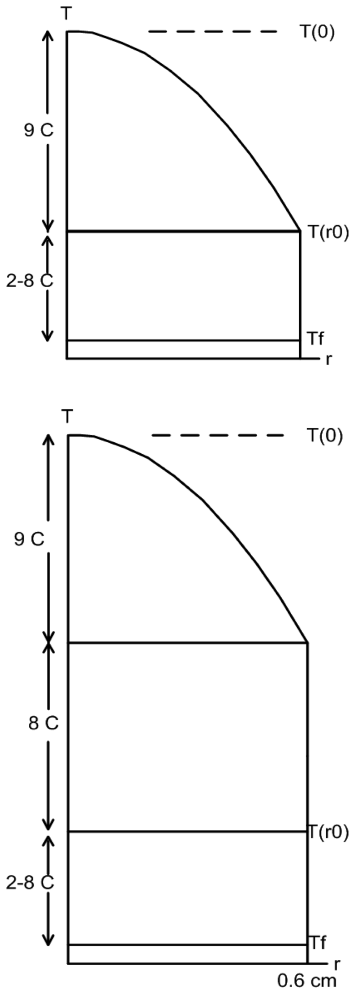

Figure 4. Calculated temperature profiles in the amplifier rods. The upper panel illustrates the profile for base 30 Hz operation, and lower panel at the end of a slow burst containing 50 pulses.

4 Laser performance

The pulse energy and beam profile are acceptable for all three operating modes of the NSTX-U laser. Data from operation of the laser system is illustrated in figure 5. Pulse energy is greater than 1.5 J and has acceptable variation. The beam pattern during bursts was recorded as a "movie" with a high-speed camera. The multi-mode structure in the beam varies as a burst progresses, but remains within acceptable limits. Note that for the burst modes the amplifier reduces the considerable pulse energy variation produced by the oscillator (figure 5). The cause of this is not known, and there may be several factors in play. For example, the beam is expanded and apertured between the oscillator and amplifier. This may remove edges of the beam that contain more variation. It could be that saturation gain is reached in the amplifier, limiting the output pulse energy. Or it could be other factors entirely.

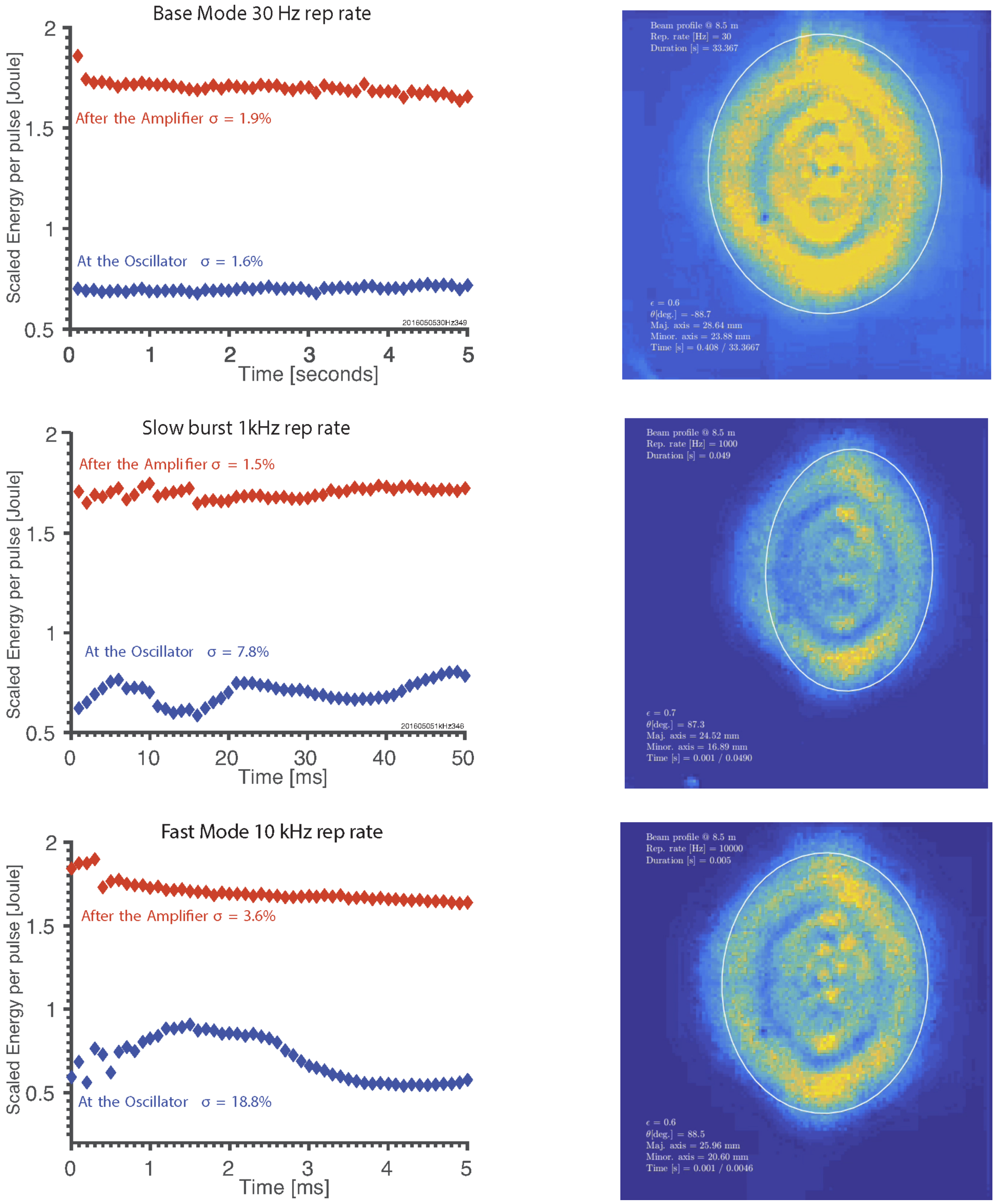

Figure 5. The pulse energy sequence (left panels) and beam patterns (right panels) for the three operating modes of the laser. The beam patterns are representative snapshots from complete movies of the beam pattern evolution during a burst.

As currently configured, the oscillator produces a double-hump output pulse (figure 6). This is acceptable for Thomson scattering data collection, but does not represent ideal performance of the oscillator. The oscillator should produce a pulse that can be approximated as a single gaussian

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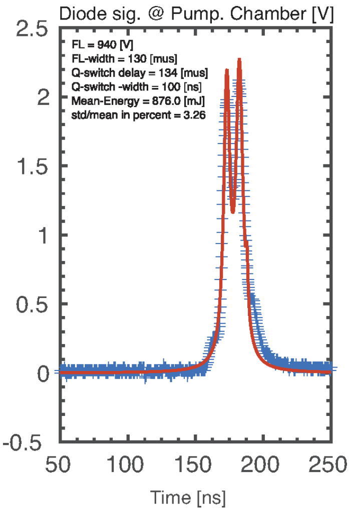

Figure 6. The double-humped output pulse of the laser system. Blue crosses are measured data, while the red line is an approximate fit consisting of two overlapping gaussian pulses.

with a FWHM of approximately 15 ns. Output pulse shape and width is a function of cavity length, pumping level, cavity loss, and the output coupler (front mirror) reflectivity. It is likely that the current output coupler reflectivity (∼ 10%) is too low. Calculation indicates that it should be increased, possibly to as high as 40% [13].

5 Summary and next steps

The pulse-burst laser system is installed in the NSTX-U Thomson scattering laser bay and has been commissioned. The laser system operates in three modes. New for pulse-burst laser systems is a base mode of continuous 30 Hz rep rate. This base mode is interrupted for a slow burst at 1 kHz rep rate for 50 ms, or a fast burst at 10 kHz rep rate for 5 ms. Laser pulsing is halted for a set period (∼ 1 minute) following a burst to allow the YAG rods to cool, as this is a heat-capacity laser. The laser is flashlamp-pumped Nd:YAG operated at 1064 nm and q-switched to produce ≥ 1.5 J pulses with ∼ 20 ns FWHM.

The laser system has demonstrated compliance with all operating specifications, and is capable of exceeding design specifications by significant margins. For example, a 5 ms flashlamp pulse at 16% of explosion energy and wall load of 50 J/cm^2 should produce a laser pulse repetition rate of 30 kHz. Or the base mode could be extended to continous 150 Hz repetition rate by operating with a flashlamp wall load of 84 W/cm^2. Both of these scenarios are within acceptable operating limits and should result in reasonable flashlamp lifetime. A useful next step in the development of pulse-burst laser systems would be to explore operation at these limits.

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