Pulse-burst operation of standard Nd:YAG lasers

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Abstract. Two standard commercial flashlamp-pumped Nd:YAG lasers have been upgraded to “pulse-burst” capability. Each laser produces a burst of up to fifteen 2 J Q-switched pulses (1064 nm) at repetition rates 1–12.5 kHz. Variable pulse-width drive (0.15–0.39 ms) 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, and up to four 2 J laser pulses during one flashlamp pulse. These lasers are used in the Thomson scattering plasma diagnostic system on the MST reversed-field pinch to study the dynamic evolution of the electron temperature.

1. Laser configuration and standard operation
The Thomson scattering plasma diagnostic system on the Madison Symmetric Torus (MST) reversed-field pinch (RFP) has been successfully operated for several years with two standard commercial Nd:YAG laser systems (Spectron SL858) [1]. This type of flashlamp-pumped laser system is common, and similar systems are available from several manufacturers. As delivered by the manufacturer, our lasers were capable of \( \geq 2 \) J single pulse, or \( \approx 1 \) J pulses at 50 Hz rep rate. This paper describes the upgrades made to enable each laser to produce a burst of up to fifteen \( \approx 2 \) J pulses, at rep rates up to 12.5 kHz, with the ability to balance burst length and rep rate to best suit experimental needs. The optical head of each laser was left unchanged, except for the addition of programmable Pockels cell drive. The major change was replacement of the flashlamp power supplies with a flexible modular system that controls all aspects of flashlamp operation. This paper begins with a brief description of the laser system as originally configured and operated, then describes the upgrades made and the new operational capabilities.

The optical head of each laser consists of an oscillator with Pockels cell Q-switch, pre-amplifier, and double-rod amplifier. Each rod is pumped by a single flashlamp, thus the optical head contains four individual linear flashlamps. As delivered by Spectron, the flashlamps were driven with a standard critically damped inductor/capacitor single mesh pulse-forming network; in other words, a charged capacitor bank was discharged by a fast switch (a thyristor) into an inductor in series with the flashlamp [2]. The capacitance and inductance were approximately matched to the impedance of the

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flashlamp arc to produce a fixed-width damped sine pulse with a FWHM of about 100 μs. The Pockels cell Q-switch was opened past the peak of the flashlamp pulse to produce a single 2 J, 9 ns laser pulse. This was repeated every few minutes to coincide with the plasma production cycle of the MST device. Thus, with two lasers, it was possible to obtain two Thomson scattering measurements every few minutes.

While this data was valuable, it was extremely difficult to measure the evolution of, or fluctuations in, the plasma electron temperature during the approximately 20 ms equilibrium period of a single MST plasma discharge. Such data could only be acquired by taking large ensembles of measurements from many MST discharges. This was costly and tedious, and was compromised by the imperfect reproducibility of MST discharges. Thus there was substantial motivation to modify our laser system to produce a short burst of pulses at a high repetition rate, but with burst production required only every few minutes. Fortunately, this combination of requirements did not require investment in an expensive custom laser system, but could be met by two relatively straightforward upgrades of the existing commercial lasers.

2. Laser upgrades and modes of operation

The first upgrade made to the lasers was replacement of the original manufacturer’s Pockels cell drive circuit with a Pockels cell driver manufactured by Bergmann Messgeräte Entwicklung KG. This driver enables precise on/off control of the Pockels cell (Cleveland Crystals Impact 10), and is able to repeat the on/off sequence every ~30 μs. This upgraded driver provided two immediate advantages. First, it dramatically reduced the pulse of high frequency electrical noise previously recorded during a laser pulse by all sensitive detectors in the vicinity of the laser. Second, it enabled the production of two Q-switched laser pulses from a single flashlamp pulse. The first pulse was produced by switching the Pockels cell slightly prior to the peak of the flashlamp pump pulse, then switching again 100 μs later to produce the second pulse. By raising the capacitor voltage in the flashlamp pulse-forming network pulse energy was maintained, and two ~2 J pulses were produced per laser. This doubled the data acquisition rate for the Thomson scattering diagnostic, but was still short of continuous data acquisition during the 20 ms equilibrium period of an MST discharge.

The second upgrade made to the lasers was larger in scope and entailed replacement of the original flashlamp drive system. While a simple inductor/capacitor pulse-forming network is an efficient way to convert electrical energy into light, it does not allow easy variation of the flashlamp pulse width, pulse energy, or pulse repetition rate. As part of a larger laser development project, we have designed and fabricated a modular flashlamp drive system based on IGBT (insulated gate bipolar transistor) switching of large electrolytic capacitor banks [3]. The system is described in the reference, so only those details relevant to operation of this laser system will be covered here. In essence, this flashlamp drive system applies an approximately square voltage pulse (adjustable up to 900 V capacitor charge) of variable width (0.15–0.39 ms) at a repetition rate up to 1 kHz. Each flashlamp is driven with a separate power supply containing 32 mF of capacitance. The most typical mode of operation is to drive the laser flashlamps with a burst of fifteen 0.15 ms pulses at a repetition rate of 1 kHz (figure 1). The Pockels cell is switched near the end of each flashlamp pulse to produce a train of fifteen ~2 J pulses from each laser (figure 2). Usually the pulse trains from each of the two lasers in the MST Thomson scattering system are interleaved to produce a burst of thirty pulses at an effective 2 kHz repetition rate. This sequence is repeated every few minutes, coincident with the duty cycle of MST plasma production. Since the burst production duty cycle is low (~0.01 Hz), the laser rods and pumping chambers are completely cooled between each burst. This means that each burst starts with a cold cavity with no thermal gradients in the laser rods. The thermal diffusion time constants for the rods range from one to several seconds, therefore any thermal gradients that develop in the rod during the 15 ms burst should be negligible. The modeling results reported in [4] also indicate that the index gradient effects on pulse energy and beam divergence should be small for these short bursts. Some of the drop in laser pulse energy as the burst progresses (figure 2) could be an index gradient effect, but most of the drop is probably due to changes in flashlamp pump light output during the burst.
Another typical mode of operation is to drive the laser flashlamps with a burst of five 0.31 ms pulses at a repetition rate of 1 kHz. The Pockels cell is switched three times: 0.145, 0.225, and 0.305 ms after the start of each flashlamp pulse. The 0.08 ms between Pockels cell switches allows the laser rod to re-pump, and thus produces a burst of three ~2 J pulses at a repetition rate of 12.5 kHz (figure 3). By operating both lasers in this mode and interleaving the pulses, the system produces five bursts of six ~2 J pulses; the pulse repetition rate within a burst is 25 kHz, and the burst repetition rate is 1 kHz. This mode of operation is useful for recording electron temperature fluctuations with a bandwidth up to about 10 kHz.

The operational limits of this laser system are set by the explosion energy and wall loading limits of the flashlamps [5]. The explosion energy characterizes the electrical energy applied to the flashlamp that is likely to cause single-pulse catastrophic failure. A single-pulse explosion constant is generally supplied in flashlamp data sheets; the explosion energy then scales as the square root of the pulse width. The flashlamps in the system described in this paper are operated at a maximum of approximately 15% of the explosion energy (table 1). At this limit we expect a lifetime of >10⁵ pulses. The need to produce ~2 J laser pulses sets the required flashlamp power input (figure 1), thus the practical effect of this explosion energy operational maximum is to limit a single flashlamp pulse to a width of 0.39 ms.

Flashlamp manufacturers typically suggest a time-averaged wall loading of 200 W/cm² for liquid-cooled flashlamps with clear fused quartz walls of 1 mm thickness [5]. Application of this limit to pulse-burst operation is not immediately apparent since the power loading within a burst is large, but then the time between bursts is long enough to ensure that all heat is removed from the flashlamps. As a starting point, the flashlamps have been operated such that the burst-integrated heat load is kept well below 200 J/cm² (table 1). This operational maximum thus limits the number of flashlamp pulses in a burst; the longer a flashlamp pulse, the fewer a burst can contain. Several months of operational expe-
rience producing $>10^4$ pulses suggests that the operational parameters in table 1 are conservative; in particular it appears that the number of flashlamp pulses in a burst can be increased.

**Table 1.** Laser system operational modes and example operational parameters for the a) largest, and b) smallest flashlamps in the system. The largest flashlamp pumps the pre-amplifier, the smallest pumps one of the rods in the double-rod amplifier. Both are krypton flashlamps, one with 7 mm bore and 93 mm arc length, the other 4 mm bore and 53 mm arc length.

| Number of laser pulses extracted from each flashlamp pulse | Number of flashlamp pulses in 1 kHz burst | Flashlamp pulse width (ms) | Fraction of explosion energy in single pulse a) | Fraction of explosion energy in single pulse b) | Burst-integrated wall loading (J/cm²) a) | Burst-integrated wall loading (J/cm²) b) |
|----------------------------------------------------------|----------------------------------------|---------------------------|-----------------------------------------------|-----------------------------------------------|------------------------------------------|------------------------------------------|
| 1                                                        | 15                                     | 0.15                      | 6%                                           | 8%                                           | 50                                       | 68                                       |
| 2                                                        | 7                                      | 0.23                      | 8%                                           | 10%                                          | 40                                       | 49                                       |
| 3                                                        | 5                                      | 0.31                      | 10%                                          | 14%                                          | 41                                       | 54                                       |
| 4                                                        | 3                                      | 0.39                      | 12%                                          | 15%                                          | 32                                       | 38                                       |

Besides actually pulsing the flashlamps, the drive system is required to perform another key function: starting and sustaining a simmer discharge in the flashlamps [5]. If the simmer discharge is not present when the IGBT applies the drive system voltage to the flashlamp electrodes, the flashlamp arc discharge will not start. Initiation of the simmer discharge requires application of a short (~1 µs) high-voltage ($\geq 10$ kV) trigger pulse to the flashlamp. In the initial design of the drive system the primary of the trigger transformer was driven with a pulse of fixed width and voltage. Unfortunately the resulting high-voltage pulse was insufficient to reliably initiate the simmer discharge. The solution was to produce an adjustable width input pulse with a small IGBT, and optimize the pulse width to match the characteristics of the trigger transformer as loaded by the flashlamp.

3. Summary

In addition to greatly extending the capability of the MST Thomson scattering diagnostic, a major advantage of the system described in this paper is the relative simplicity of implementation and operation. A number of solid-state pulse-burst laser systems have been previously built (see [3] for brief descriptions), but they have all been custom systems, with limited operational flexibility. In contrast, for the system described in this paper, $Q$-switch and flashlamp parameters are independent and programmable, and enable production of a burst of pulses tailored to experimental needs. In addition, any of a large variety of commercial solid-state laser optical heads could be used as the basis of such a laser system, substantially reducing development and construction effort.

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References

[1] Reusch J A, Borchardt M T, Den Hartog D J, Falkowski A F, Holly D J, O’Connell R and Stephens H D 2008 Rev. Sci. Instrum. 79 10E733
[2] Koechner W 2006 *Solid-State Laser Engineering* (New York: Springer)
[3] Den Hartog D J, Jiang N and Lempert W R 2008 Rev. Sci. Instrum. 79 10E736
[4] Stone D H and Rotondaro M D 1992 Appl. Opt. 31 1314
[5] PerkinElmer *High Performance Flash and Arc Lamps* ([www.perkinelmer.com/opto](http://www.perkinelmer.com/opto)), Heraeus Noblelight *The lamp book* ([www.heraeus-noblelight.com](http://www.heraeus-noblelight.com))