Initial operation of a pulse-burst laser system for high-repetition-rate Thomson scattering[a)]

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(Presented 17 May 2010; received 12 May 2010; accepted 31 May 2010; published online 1 October 2010)

A pulse-burst laser has been installed for Thomson scattering measurements on the Madison Symmetric Torus reversed-field pinch. The laser design is a master-oscillator power-amplifier. The master oscillator is a commercial Nd:YVO_4 laser (1064 nm) which is capable of Q-switching at frequencies between 5 and 250 kHz. Four Nd:YAG (yttrium aluminum garnet) amplifier stages are in place to amplify the Nd:YVO_4 emission. Single pulses through the Nd:YAG amplifier stages gives energies up to 1.5 J and the gain for each stage has been measured. Repetitive pulsing at 10 kHz has also been performed for 2 ms bursts, giving average pulse energies of 0.53 J with $\Delta E/E$ of 4.6%, where ΔE is the standard deviation between pulses. The next step will be to add one of two Nd:glass (silicate) amplifier stages to produce final pulse energies of 1–2 J for bursts up to 250 kHz. © *2010 American Institute of Physics.* [doi:10.1063/1.3466901]

I. INTRODUCTION

Thomson scattering has proven to be a successful diagnostic for electron temperature and density on fusion devices.[1] On the Madison Symmetric Torus[2] (MST), the Thomson scattering diagnostic system is capable of providing high quality data[3] using two commercial Nd:YAG (yttrium aluminum garnet) lasers [Spectron (Rugby, UK) SL858]. In a recent upgrade, replacement of the Pockels cell drive circuits and flashlamp drive system allows pulse repetition rates between 1 and 25 kHz by interleaving the two lasers.[4] Pulse energies from these lasers are typically around 2 J at 1064 nm. A multipoint collection system is installed which allows 21 simultaneous radial measurements to be performed in a single discharge.[5]

To supplement this, a new "pulse-burst" laser has been installed and is currently being tested. Goals for this laser are to achieve a burst of up to 200 pulses with energies around 1 J at repetition rates between 5 and 250 kHz. The existing detection hardware and electronics do not require any upgrades for operation with the new laser. Extension of the beam path to the MST vessel will be accomplished by removing one of the turning mirrors from each of the Spectron lasers. Switching between the two laser systems will be possible by replacing the mirrors. Details of the pulse-burst laser are described as follows: Sec. II is an overview of the laser system, Sec. III outlines the laser control system, and Sec. IV covers the initial tests that have been performed.

II. SYSTEM OVERVIEW

Most of the design details of the pulse-burst laser are described elsewhere,[6] so only a brief description is given here. In particular, reference to Fig. 1 of Den Hartog *et al.*[6] will aid understanding of the following description. The laser system is a master-oscillator power-amplifier design[7,8] which employs a diode-pumped Nd:YVO_4 laser [CrystaLaser (Reno, NV) QIR-1064–1250-YV] as the master oscillator. The output beam of the Nd:YVO_4 laser has a beam diameter of about 1 mm and pulse energies ≥ 2 μJ at 1064 nm. External control of the master oscillator requires three inputs: an analog input for the level of pumping by the laser diodes and two digital inputs for turning on the pump diodes as well as the Q-switch. The output beam of the master oscillator is spatially filtered, which reduces its pulse energy by a factor of 50, but improves the 2.2 mrad initial divergence to 330 μrad.

There are six planned flashlamp-pumped amplifier stages, the first four of which are presently operational. Details of the amplifier stages are shown in Table I. A Nd:glass amplifier identical to the fifth stage is planned after the performance of the fifth stage has been carefully evaluated. As shown,[6] the initial beam undergoes five stages of beam expansion resulting in a final diameter of 16 mm. The laser system is installed on a Newport (Irvine, CA) RS2000 optical table with I-2000 series vibration isolators.

Energy is stored for the flashlamps using 16 000 μF electrolytic capacitors rated at 450 V. To accommodate the 900–1800 V necessary to drive the flashlamps and provide sufficient energy storage to reduce the voltage droop, the capacitors are wired in a series-parallel configuration. Each flashlamp is driven by its own set of capacitors, and the applied voltage and current is monitored by the laser control system described in Sec. III. Switching of the capacitors is performed through the use of insulated-gate bipolar transistors.

The flashlamp power supply control system (FLPSCS) developed at the Physical Sciences Laboratory at the Univer-

[a)]Contributed paper, published as part of the Proceedings of the 18th Topical Conference on High-Temperature Plasma Diagnostics, Wildwood, New Jersey, May 2010.

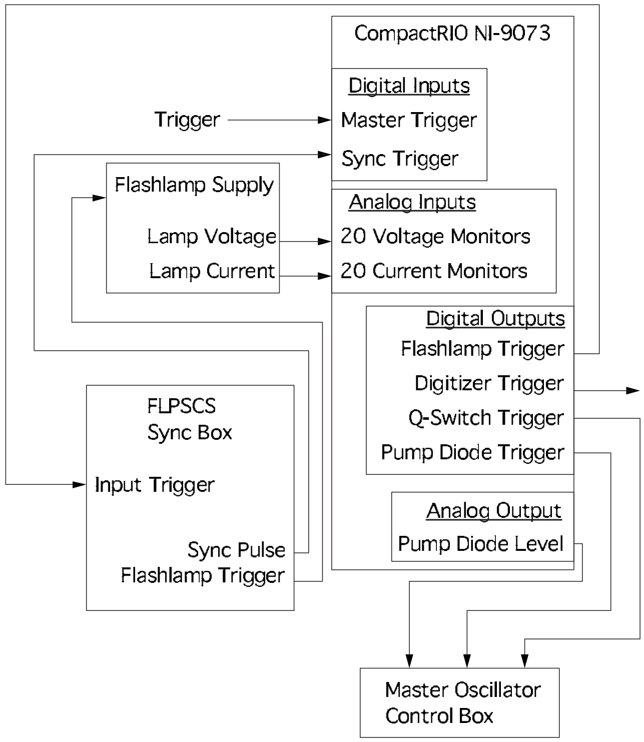

FIG. 1. Laser timing control with CompactRIO NI-9073.

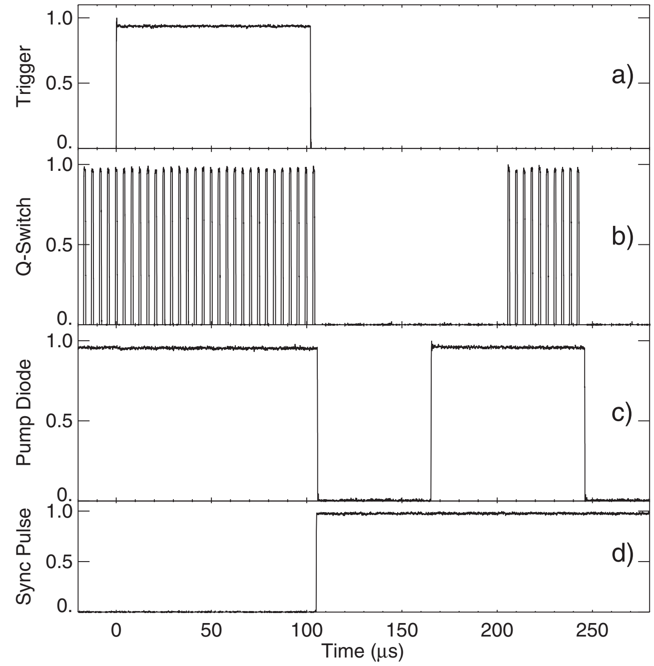

FIG. 2. Laser control trigger pulses: (a) master trigger, (b) Q-switch trigger from cRIO operating at 250 kHz, (c) pump diode control from cRIO, and (d) sync pulse from the FLPSCS.

sity of Wisconsin-Madison is how the flashlamp pulse width, delay, and applied voltage are controlled. Details of this system are described in more detail elsewhere.[6] Programming of the FLPSCS is accomplished through two RS-232 ports from a personal computer.

III. LASER CONTROL SYSTEM

A. Modes of operation

In a typical MST discharge, the equilibrium lasts 20–30 ms. Throughout this, the pulse-burst laser is expected to operate in two distinct modes. In one mode, a low frequency ($\leq$50 kHz) pulse train will be up to 20 ms long. For this, the flashlamps will be energized for the full 20 ms while the Q-switch operates at the pulse frequency. In the other mode, the flashlamps will be pulsed repetitively throughout the discharge at ~1 kHz for 300 μs, while the Q-switch delivers 10 to 30 pulses at a much higher frequency (up to 250 kHz). The latter mode will be particularly useful for electron temperature and density fluctuation measurements, while the former will be useful for fast equilibrium changes.

TABLE I. Summary of amplifier stages.

Stage	Material	Diameter (mm)	N_{lamps}	Flashlamp arc diameter × length (mm^2)
1	Nd:YAG	4	1[a]	4×67
2	Nd:YAG	6.4	1[a]	4×67
3	Nd:YAG	9	2	4×67
4	Nd:YAG	12	4	4×67
5[b]	Nd:glass	16	6	8×250
6[c]	Nd:glass	16	6	8×250

[a]These stages share a single flashlamp within a single pumping chamber.
[b]This stage is installed, but not yet operational.
[c]This stage has not been installed.

B. Timing

As stated in Sec. II, external control of the master oscillator requires one analog and two digital inputs. To accommodate this, a National Instruments (Austin, TX) CompactRIO-9073 integrated system is used with an analog output module (NI-9263) and two digital input/output modules (NI-9401). The NI cRIO-9073 has a reconfigurable field-programmable gate array that operates at a 40 MHz clock cycle and has room for eight different modules. In addition, the flashlamp voltage and currents are monitored using five analog input modules (NI-9201) for the CompactRIO. Each analog input module has eight channels, 12-bit resolution, and has a sampling rate of 62.5 kHz per channel.

Synchronization of the flashlamps with the master oscillator is made possible by a component of the system called the synchronization box (or sync box), which is part of the FLPSCS and provides a 15 V reference pulse (called the sync pulse) once initialization of the flashlamp timing sequence has begun. The sync pulse is used to trigger the master oscillator through the CompactRIO. Figure 1 shows how the CompactRIO triggers the FLPSCS and then uses the sync pulse to trigger the master oscillator.

The manufacturer recommends keeping the $Nd:YVO_4$ laser crystal at a stable (warmed-up) temperature for energy stability of the master oscillator. For a single burst of a few (ten to 30) pulses, the stable temperature is not achieved. To remedy this, the master oscillator is operated as demonstrated in Fig. 2. Prior to a burst, the laser is run continuously at the desired pulse frequency for at least five minutes. When

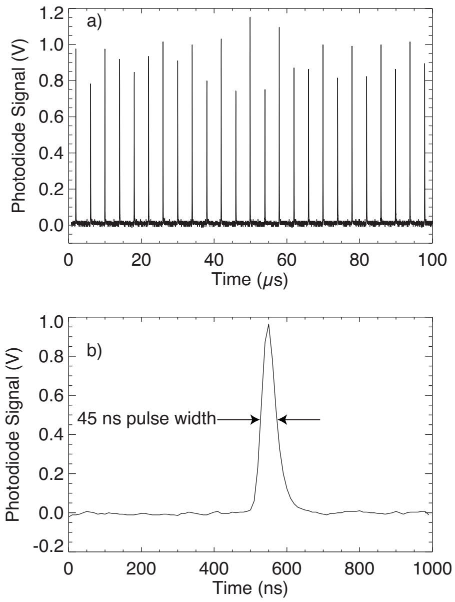

FIG. 3. Operation of the Nd:YVO_4 master oscillator: (a) at 250 kHz, a single burst of 25 pulses as detected by an InGaAs photodiode and a single pulse; (b) with a 45 ns full width at half maximum.

a burst is triggered through the CompactRIO master trigger input [Fig. 2(a)] at $t=0$, the Q-switch [Fig. 2(b)] turns off along with the pump diode [Fig. 2(c)] after receiving the sync pulse from the FLPSCS [Fig. 2(d)] at $\sim$100 μs. The laser diode is turned off while the Q-switch is off in order to prevent excess heating of the oscillator crystal. After some time ($\sim$60 μs here), the laser diode is turned back on and the Q-switch resumes pulsing after an additional delay ($\sim$40 μs here). Multiple bursts are accomplished by repeating the turning on/off of the Q-switch and the pump diode as triggered by the sync pulse. After a discharge, the master oscillator will run continuously at the desired pulse frequency to maintain the thermal equilibrium of the crystal. It should be noted that the Q-switch and pump diode delays shown in Fig. 2 were chosen for figure clarity, not optimization.

IV. INITIAL LASER OPERATION

Several tests have been performed to characterize the laser system. Testing of the Nd:YVO_4 master oscillator's energy stability was performed using a InGaAs biased photodiode detector [Thorlabs (Newton, NJ) DET10C]. The energies of single pulses amplified through stages 1–4 have been measured using a Litron (Rugby, UK) LPM250–4F-B energy meter and the gain of each stage has been determined. Additionally, energy measurements of multiple Q-switched pulses at 10 kHz have been performed.

Numerical integration of the photodiode's output voltage signal is expected to be proportional to the pulse energy. A set of 25 pulses at 250 kHz is shown in Fig. 3(a). For these pulses, the energy stability $\Delta E/E$ is 5.2% as calculated using five-point Newton–Cotes integration on the photodiode signal, where ΔE is the standard deviation between laser pulses. A single pulse is shown in Fig. 3(b), which has a full width at half maximum of 45 ns. The pulse width decreases with

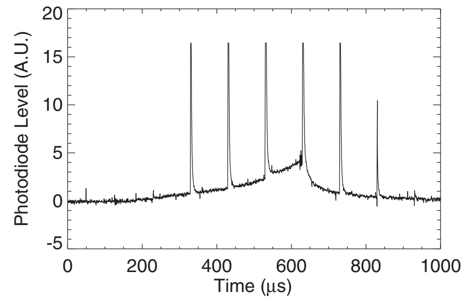

FIG. 4. Photodiode output showing laser pulses on top of amplified spontaneous emission from the first two amplifier stages.

the Q-switching frequency for this laser, so 45 ns is the widest pulse width expected. As originally purchased, the measured pulse width of the Nd:YVO_4 laser operated at 250 kHz was $\sim$70 ns.[6] The manufacturer subsequently rebuilt and realigned the laser with consequent reduction of the pulse width to 45 ns.

Initial operation of the first amplifier stage resulted in self-lasing due to an optical cavity between the polarizing beam-splitter cube and the 0° reflecting mirror (a setup necessary for a double pass through the amplifier rod). This was eliminated by rotating the cube and realigning the master laser beam. Further testing shows that there is amplified spontaneous emission (ASE) from each laser rod, as shown in the photodiode output in Fig. 4. In the data shown, a laser pulse is sent through the first two amplifier stages which are pumped for 500 μs. The flashlamp turns on around $t=120$ μs, after which the ASE is shown by the gradual rise in the baseline until $\sim$620 μs when the flashlamp turns off. Six amplified (10 kHz) laser pulses are the 100 μs spaced peaks in the data. Additional measurements show that the instantaneous power level of ASE is less than 5% of the unamplified laser pulse power from the master oscillator. This percentage increases with amplifier stage, as the rod diameter and number of flashlamps increases.

Initial results (described below) indicate that the observed level of ASE is not a problem. Single pulses with energies up to 1.5 J have been measured through the fourth amplifier stage after subtracting the contribution due to ASE. Numerical integration of the energy monitor's analog output $f(t)$ is broken up into three intervals in order to determine the pulse energy

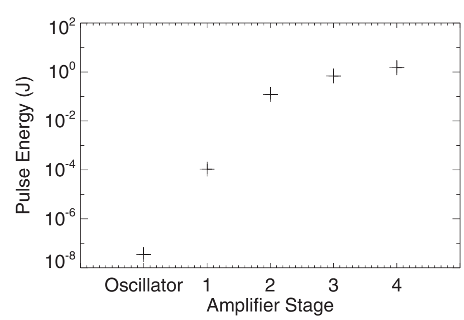

FIG. 5. Single pulse energies as measured at the various amplification stages. The master oscillator pulse is 35 nJ after spatial filtering and is amplified to 1.5 J after the final Nd:YAG stage.

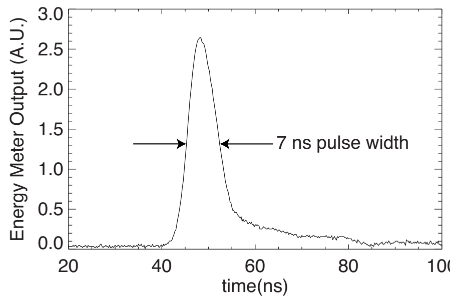

FIG. 6. Output pulse from the Litron energy meter of a 1.5 J amplified pulse showing a 7 ns pulse width (full width at half maximum).

$$\int_0^{t_L} f(t)dt = \int_0^{t-\varepsilon} f(t)dt + \int_{t_0-\varepsilon}^{t_0+\varepsilon} f(t)dt + \int_{t-\varepsilon}^{t_L} f(t)dt, \quad (1)$$

where t_L is a time window chosen to be much longer than the flashlamp pulse, t_0 is the time of the Q-switched laser pulse, and $2\times\varepsilon$ is the width of the laser pulse. The integral over the interval $[t_0-\varepsilon, t_0+\epsilon]$ gives the contribution of the laser pulse I_{pulse} to the total energy measured by the energy meter E_{total}, while the rest of the integral I_{ASE} is the contribution due to ASE. The energy of the amplified pulse is then taken to be

$$E_{\text{pulse}} = \frac{I_{\text{pulse}}}{I_{\text{pulse}} + I_{\text{ASE}}} E_{\text{total}}. \quad (2)$$

Using this technique, the energy of a pulse through each Nd:YAG amplification stage has been measured and is shown in Fig. 5. For these data, the flashlamps in amplifier stages 1–3 are charged to 680 V and deliver a peak current of 640 A over a 150 μs pulse (21% of the flashlamp explosion energy). The flashlamps on the fourth amplifier stage are charged to 640 V and have a peak current around 540 A over the same pulse width (18% of the flashlamp explosion energy). A single amplified pulse with an energy of 1.5 J is shown in Fig. 6 with a full width at half maximum of 7 ns. Burn paper spots of the amplified pulse looks uniform and circular, with no noticeable hot-spots. The voltage and current traces from the output of the flashlamp power supply control system are measured by a NI-9201 analog input module. Presently, data for amplification through the fifth (Nd:glass) stage are not available. Laser alignment through the fifth stage has not been performed because the installed rod does not have the required 4° cut on the rod faces; it is a "dummy" rod for testing purposes.

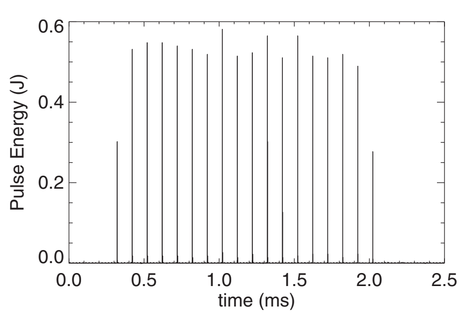

FIG. 7. Eighteen amplified pulses at 10 kHz measured by a Litron energy meter. Ignoring the first and last pulse, the average pulse energy is 0.53 J and the relative deviation $\Delta E/E$ is 4.6%.

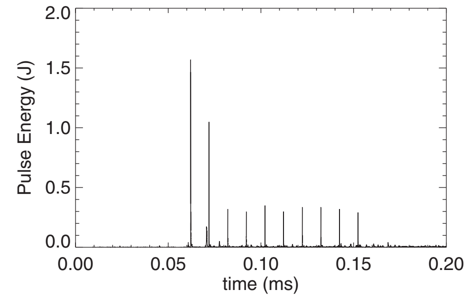

FIG. 8. Ten amplified pulses at 100 kHz measured by a Litron energy meter. Ignoring the first two pulses, the average pulse energy is 0.32 J and the relative deviation $\Delta E/E$ is 6.6%.

To demonstrate repetitive pulsing of the laser, 18 pulses were sent from the master oscillator at a repetition rate of 10 kHz through the four Nd:YAG amplifier stages. The output from the energy meter is recorded by a digital storage oscilloscope, shown in Fig. 7. The flashlamps were fired at $t=0$ for a duration of 2 ms, with a charging voltage of 390 V and peak current of 275 A, which is 15% of the explosion energy. Ignoring the first and last pulse, the average pulse energy is 0.53 J with a relative deviation $\Delta E/E$, calculated from the variance is 4.6%. An additional test was performed to achieve 100 kHz Q-switching for ten pulses (Fig. 8). Optimization of the pulse to pulse energy uniformity was not performed due to time constraints.

The next steps in the commissioning of this laser system are described as follows. Further testing of the fifth amplification stage is required. Optimization of the flashlamp charging voltages, Q-switch timing for stable, and repetitive pulsing must be performed. The laser beam path needs to be extended to the MST vessel.

ACKNOWLEDGMENTS

The authors would like to thank Mike Borchardt, Adam Falkowski, Josh Reusch, and Ming Yang from the Thomson Scattering group at MST for their help. Mikhail Reyfman and David Deicher from the electronics shop have also provided valuable assistance. In addition, the efforts of Jack Ambuel and Phil Robl of the Physical Sciences Laboratory at the University of Wisconsin-Madison are also recognized. This work was supported by U.S. Department of Energy Grant No. DE-FC02-05ER54814 and National Science Foundation Grant No. PHY 0821899.

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