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High-repetition-rate pulse-burst laser for Thomson scattering on the MST reversed-field pinch

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ABSTRACT: A new, high-repetition-rate pulse-burst laser system for the MST Thomson scattering diagnostic has operated with 2 J pulses at repetition rates up to 75 kHz within a burst. The 1064 nm laser currently employs a *q*-switched, diode pumped Nd:YVO_4 master oscillator, four Nd:YAG amplifier stages, and a Nd:glass amplifier, with plans for an additional Nd:glass amplifier. The laser can maintain 1.5–2 J pulses in two operating modes: either at a uniform repetition rate of 5–10 kHz (sustained for 5–8 ms), or reach rates of up to 75 kHz in pulse-burst operation (for 10 bursts of 15 pulses each), limited by flashlamp explosion energy and wall loading. The full system, including an additional Nd:glass amplifier, is designed to produce bursts of 2 J pulses at a repetition rate of at least 250 kHz. Custom programmable square-pulse power supplies drive the amplifier flashlamps, providing fine control of pulse timing, duration, and repetition, and allow for pulse-burst operation. The new laser system integrates with the same collection optics and detectors as used by the previous MST Thomson laser: 21 spatial points across the MST minor radius, filter polychromators with 6 to 8 channels (10 eV–5 keV range), avalanche photodiode detectors, and 1 GSample/s/channel digitization. Use of the previous pulse-burst laser continues concurrently with new laser development. Additional notes on optimization of flashlamp simmering will also be covered, showing that an increase in simmer currents can improve pulse-to-pulse energy consistency on both the new and older lasers.

KEYWORDS: Lasers; Plasma diagnostics - interferometry, spectroscopy and imaging

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Contents

1 Introduction

Thomson scattering is an established diagnostic for the measurement of electron temperature, including on the Madison Symmetric Torus (MST) reversed-field pinch (RFP) [1] where Thomson scattering has been important for measuring improved confinement [2] and temperature fluctuations [3]. The typical plasma conditions, light collection system, and detection method used by the MST Thomson scattering diagnostic, described in detail elsewhere [4], requires a 1.5–2 J per pulse light source. The currently operated diagnostic setup on MST utilizes a pair of commercial Nd:YAG 1064 nm lasers modified from single-pulse operation to a pulse-burst operating mode, allowing for up to 15 pulses from each laser (30 total) [5, 6]. By interleaving operation of the two lasers, the 30 pulses can be uniformly spaced at a rate up to 2 kHz, or grouped in bunches of 6 pulses at 25 kHz, with 1 kHz repetition of bursts.

A Thomson scattering diagnostic using tens of pulses at 10 kHz has been demonstrated on a magnetically confined plasma experiment [7]. However, lasers with 1 J pulse energy and high repetition rates have been constructed from common Nd:YAG (yttrium aluminum garnet) components for fluid dynamics research with over 100 pulses at rates up to 1 MHz [8]. Thus we have been developing this Nd:YAG laser technology for application to the MST Thomson scattering diagnostic.

Lessons learned from operating the commercial lasers (hereafter, the “Slow laser”) in pulse-burst mode have been applied to designing and constructing a custom, high repetition laser (“Fast laser”). The new laser integrates with the same collection optics and detectors as used for standard MST Thomson scattering, but with repetition rates of 5–250 kHz. This paper discusses the design and the operation of the partially constructed laser.

2 High repetition laser design

The fast laser consists primarily of a master oscillator, 6 amplifier stages, power supplies for the amplifiers, and a computer control system.

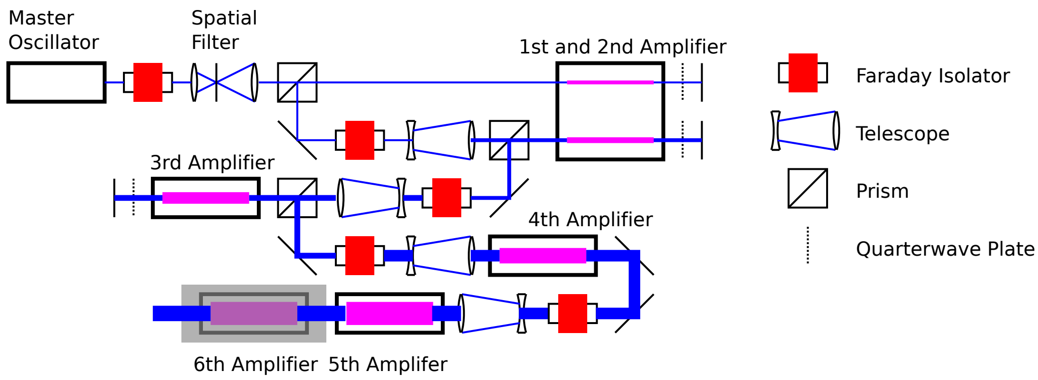

Figure 1. This is a simplified diagram of the high repetition laser, showing all optical components except for some mirrors.

Table 1. The laser rod and flashlamp dimensions for each amplifier. Amplifier 1 and 2 are listed as having half a flashlamp, as the two stages share a single, common lamp. Amplifier 6 has not been installed yet, but is designed as a duplicate of amplifier 5.

Amplifier	Material	Rod diameter (mm)	Lamp Count	Lamp diameter (mm) x length (mm)
1	Nd:YAG	4	1/2	4x67
2	Nd:YAG	6.4	1/2	4x67
3	Nd:YAG	9	2	4x67
4	Nd:YAG	12	4	4x67
5	Nd:glass	16	6	8x250
6	Nd:glass	16	6	8x250

The master oscillator at the head of the laser is a diode pumped Nd:YVO_4, capable of producing pulses at a rate of 5–250 kHz, via an external trigger, with a per pulse energy of $> 5\,\mu$J at 5 kHz to $> 2\,\mu$J at 250 kHz. The master oscillator runs continuously at a set frequency when idle to maintain a stable temperature, but must interrupt pulsing prior to a burst while the amplifiers are pumped. Achieving a stable burst of pulses after this interruption is dependent on fine-tuning of diode pumping via external controls of the diode pump timing and intensity. The output of the master oscillator is spatially filtered.

Following the master oscillator is a series of five flashlamp pumped amplifiers, with plans for a sixth stage that duplicates the fifth amplifier. The first four amplifiers are Nd:YAG, while the last two are Nd:glass. The first three amplifiers are double pass, while the later ones are single pass. The Nd:YAG stages are pumped by 4 mm bore by 67 mm length flashlamps, with a single flashlamp shared by the first two amplifiers, two lamps for the third amplifier, and 4 lamps for the fourth amplifier. The Nd:glass stages uses 8 mm bore by 250 mm length flashlamps, with six lamps each. Figure 1 shows a simplified diagram of the setup, including location of Faraday isolators, while table 1 lists a summary of the amplifier laser rod and flashlamp dimensions.

The flashlamps are powered by programmable power supplies consisting of individual capacitor banks switched by integrated-gate bipolar transistors (IGBT) triggered by computer control. The capacitor banks are charged to a programmed voltage. Additionally, the capacitor banks can be switched between a series and parallel configuration via patch panel. A series configuration provides maximum voltage, 900 V for Nd:YAG stages and 1800 V for Nd:glass stages, allowing for higher repetition rates, while a parallel configuration halves the maximum voltage but allows for longer duration sequences of pulses with less voltage droop. The triggering by computer allows for not only precise control of the start and width of a flashlamp pulse, but for multiple pulses when operating in a pulse-burst mode. The computer control system, along with more details about the master oscillator, have been discussed elsewhere [9].

3 Laser operation

The laser has been operated with the first five amplifiers. Two different operating modes were tested: a uniform pulsing sequence where all pulses are evenly spaced, and a pulse-burst sequence where each burst consists of several pulses with short, equal spacing, then longer pauses between bursts. Pulse-burst mode offers high temporal resolution within bursts, but has gaps between bursts, while uniform pulsing allows uniform measurements over a longer periods at the cost of less temporal resolution. Depending on the phenomena being studied for a given plasma shot, the laser can be quickly reprogrammed to operate in whichever mode is better suited.

In the uniform pulsing operation, the laser was tested up to a rate of 10 kHz while maintaining output pulse energy of > 1.5 J. This rate could be maintained up to 5 ms (a total of 50 pulses), limited by the explosion energy of the flashlamps. [10] Flashlamps are limited to 20% of their explosion energy as a compromise between flashlamp lifetime and maximizing energy. Figure 2 plots the pulse energy from such operation.

Additionally, the figure shows testing of the laser at 5 kHz uniform pulsing over a duration of 5 ms. Based on explosion energy limits, this could be sustained for 9 ms (for a total of 45 pulses). However, as tested and shown in the figure, the power supplies were in series configuration, giving higher possible voltage, but with less capacitance. The 5 kHz and 10 kHz required flashlamps to be at 45% and 50%, respectively, of the maximum series voltage, which would allow for future testing at 90% and 100% of maximum parallel voltage. With four times the capacitance, the voltage droop in the 8 mm bore flashlamps should be reduced considerably on that time scale. Choice of an operating frequency at 5–10 kHz allows for a trade-off between duration of pulsing and temporal resolution.

In pulse-burst mode, the laser was tested up to 75 kHz pulsing within bursts. Burst lengths of 15 pulses per burst were achieved while staying within explosion energy limits on a per burst basis. A maximum of 10 bursts (150 pulses total) can be repeated within a single MST shot, limited by a total energy flux of 200 J/cm^2 on the flashlamp walls [6]. Figure 3 shows the pulse energy over such a sequence of 5 pulses, with the current limit in this case being the number of pulses that can be digitized. The laser has also been tested with 10 bursts without recording the full chain of pulse energy. In both cases, bursting was done at a 1 kHz rate, which represents about 20% duty cycle for measurements (180 μs chain of pulses within each 1 ms, with 820 μs between bursts), while the laser is operating at about 30% duty cycle due to pumping time before each burst. Total electrical energy going into each flashlamps is on the order of 1.2 kJ and 4 kJ for the 4 mm and 8 mm flashlamps respectively. Further optimization of timing values could improve the energy at

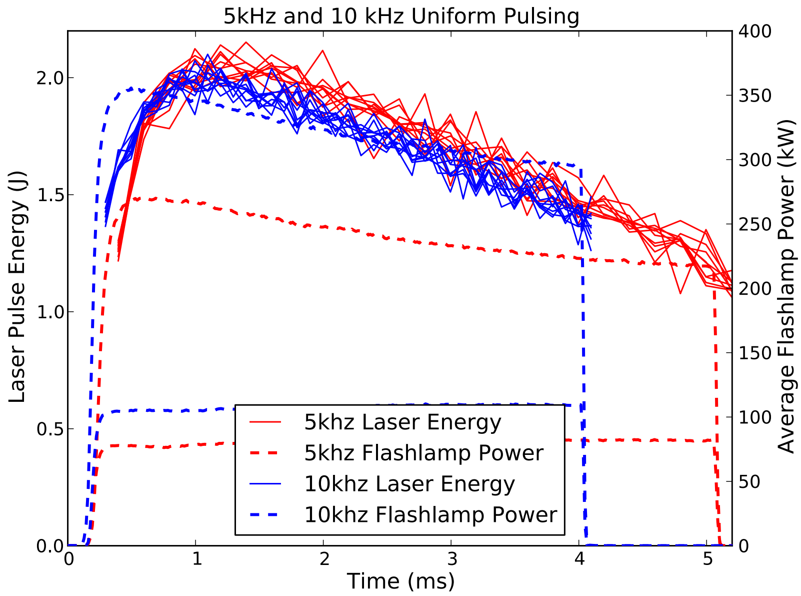

Figure 2. Laser pulse energy and flashlamp power are plotted when operating at a uniform pulse repetition rate of 5 kHz and 10 kHz. The larger flashlamp power curve for each frequency is the average of three of the six 8 mm bore flashlamps in the Nd:glass stage, the smaller curves are an average of the seven, 4 mm bore flashlamps in the Nd:YAG stages. 10 shots worth of laser pulse energies are plotted to illustrate pulse to pulse variability.

the beginning of the bursts, as the energy increases to 2 J pulses later in the bursts demonstrating the amplifiers are capable of pumping up to that level.

Testing at 100 kHz resulted in pulse energies on the order of 1.2–1.5 J with all flashlamps at maximum voltage.

4 Flashlamp optimization

There are four electrical components that drive the flashlamps in parallel (see figure 4): a commercial simmer supply for providing an idle simmer current, a custom triggering circuit for initial breakdown, a constant current supply to increase simmer current, and the capacitor bank for flashing the lamps when firing the laser. While the commercial simmer supply automatically sends out trigger pulses when no current is detected in the lamps, the custom circuit increases the power behind the trigger pulses before sending the pulses to a trigger transformer. Large diode stacks protect the simmer supply and IGBT that switches the capacitor bank from the 15+ kV trigger pulses on the output of the trigger transformer. A smaller stack of transient voltage suppressor (TVS) diodes isolate the trigger transformer from the lower simmer supply and capacitor bank voltages, while providing a current path to suppress any ringing or other voltage transients.

Initially the fast laser was constructed with two different sized simmer supplies, using Analog Modules 867 simmer supplies to provide up to 150 mA of simmer current to the smaller flashlamps in the Nd:YAG amplifiers, and Analog Modules 864 supplies for the larger flashlamps, capable of

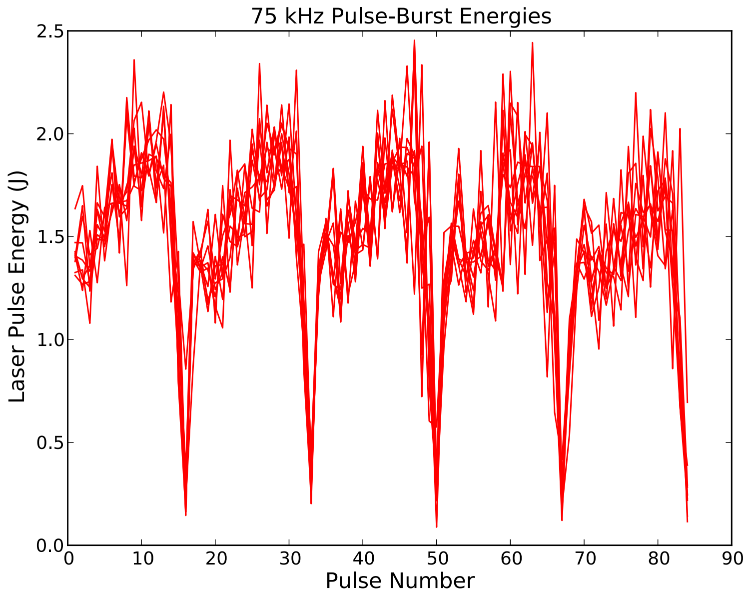

Figure 3. Laser pulse energies for operating in pulse burst mode, with 5 bursts of 15 pulses. The pulses within a burst are at a rate of 75 kHz, while the bursts are at a rate of 1 kHz. An extra pulse after the flashlamps are exhausted, and hence at 0 J, was left in each burst to mark the points between bursts instead of plotting the longer idle time.

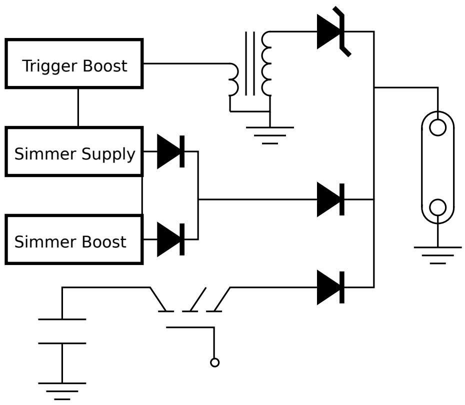

Figure 4. This diagram shows a simplified schematic of the circuits driving the flashlamps in both of MST's Thomson scattering lasers. The capacitor at the bottom is the main capacitor to drive the flashlamps during pulsing, switched by the IGBT. The simmer sources and main IGBT are protected by a 20 kV of diode stacks, while the output of the trigger transformer has 2 kV of transient voltage suppressor diodes.

500 mA, but limited to 250 mA due to the module's power limit. The smaller flashlamp supplies are also used to drive the flashlamps in the slow laser system, a pair of modified Spectron SL858, which consists of four Nd:YAG stages each: an oscillator, pre-amp, and two amplifier stages.

A clear difference in the operation of the pre-amp stage was observed, where the second pulse in a pulse chain experiences a drop of 40% in flashlamp energy, and 30% drop in laser pulse energy, when operating at 500 Hz pulsing rate. As shown in figure 5, the drop recovers after 3–4 pulses

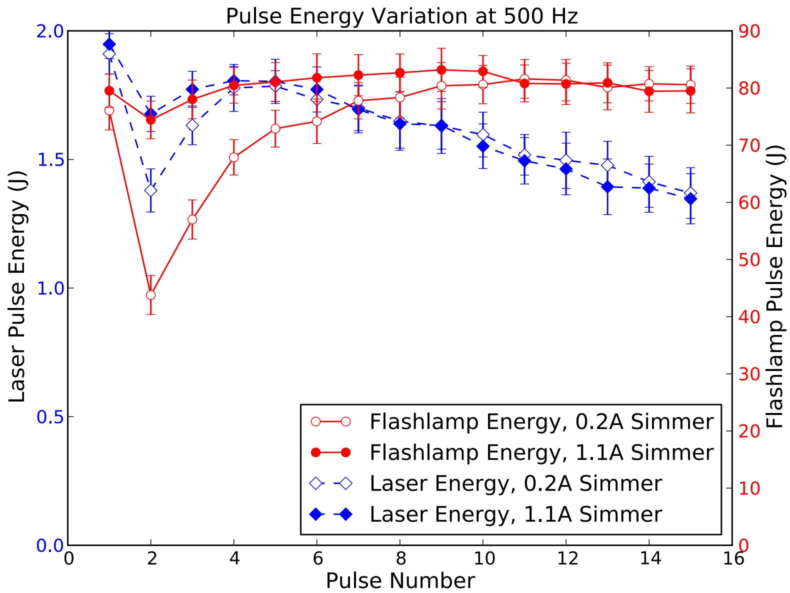

Figure 5. Sequences of 15 pulses at 500 Hz were on the current MST Thomson laser, and the energy of the flashlamp and laser pulses verses pulse position in the sequence are plotted above. When using lower simmer current (0.2 A case shown with open circles and diamonds), a large energy drop in both is seen during the second pulse, before recovery over the following 2–3 pulses. Increasing the current (1.1 A case shown with solid circles and diamonds) removes most of this drop. Error bars show shot to shot variation as the standard deviation of 25 shots at each setting.

before a slower trend of voltage droop and increased current from heating sets in. Operating at a pulsing rate of 1 kHz shows a smaller, 25% drop in flashlamp energy and 15% drop in laser energy. The pre-amp stage uses a 7 mm bore flashlamp, unlike the 4 mm bore in the other stages, which has a higher recommended simmer current. [10]

Tests were conducted to increase the current, first by switching from a model 867 (150 mA) to 864 (500 mA) simmer supply, then by placing two model 864 supplies in parallel to reach 1.1 A. Figure 5 shows the improved pulse chain at higher current, while figure 6 shows the ratio of the first two flashlamp pulse energies as a function of current. A saturation point is observed, beyond which further current does not improve operation.

All power supplies are now being upgraded to increase simmer current to optimize performance of other stages, including on the 8 mm flashlamps used by the Nd:glass stage of the high repetition laser. Instead of using two simmer supplies in parallel, a custom, low-cost, constant current switching power supply is being constructed to run in parallel to other components, as shown as “current boost” in figure 4.Additional current will also lower the voltage across the lamp and improve the amount of current supplied by the power limited 864 modules.

The trigger boost component detects the 350 V trigger from the commercial simmer brick, then produces a higher voltage trigger with adjustable pulse length. Due to loading on the output of the trigger transformer, discovered to be from the capacitance of the large diode stacks used on the large IGBTs and simmer supply outputs to block the trigger pulse, the pulse transformer’s

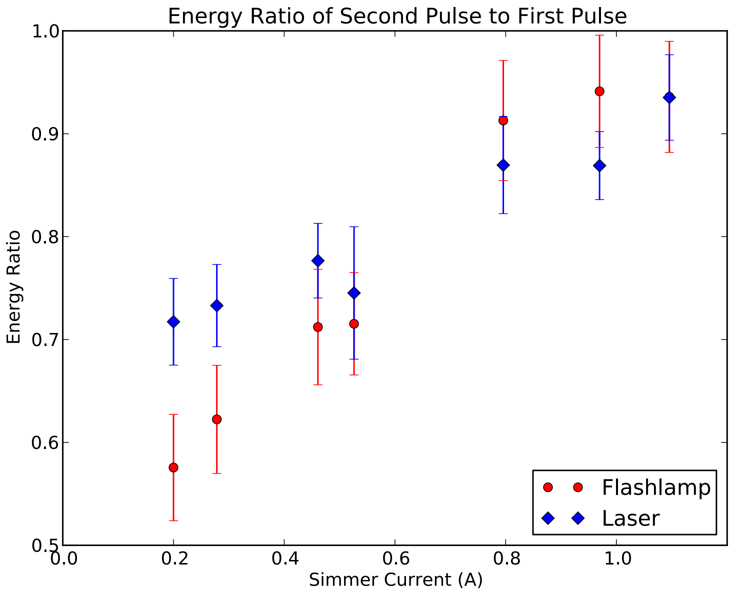

Figure 6. This plot shows the ratio of the second pulse energy to the first pulse energy in a sequence of pulses at 500 Hz, versus several different simmer currents. At low currents, there is up to a 40% drop in flashlamp energy and 30% drop in laser pulse energy, but this saturates to about a 10% drop at higher currents.

voltage specification was not being fully utilized when driven via a 400–450 V source. To improve the robustness of flashlamp starting, the pulse transformer is now overdriven, with a 850 V source switched with a small IGBT into the primary rated for 400 V. Under normal operation, the primary remains below the 400 V limit, but a TVS diode across the primary protects the transformer in potential fault situations.

5 Conclusions and further work

A newer, faster laser for use on MST's Thomson scattering diagnostic has demonstrated operation at uniform pulse up to 10 kHz, and pulse-burst rates up to 75 kHz. The largest improvement of these rates would come from installing an additional Nd:glass amplifier as originally planned. Other shorter term, incremental improvements include fine tuning of timing parameters, and adding a partially reflecting mirror to first amplifier, as it shares a flashlamp with the larger second amplifier.

Improvements to the simmering systems components of the flash lamp power supplies have demonstrate improved pulse-to-pulse energy consistency for the older, slower laser. Work extending these improvements and testing their impact on both the slow and fast lasers is on going.

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