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Operation and beam profiling of an up to 200 kHz pulse-burst laser for Thomson scattering[a)]

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A new, high-repetition rate laser is in development for use on the Thomson scattering diagnostic on the Madison Symmetric Torus. The laser has been tested at a rate of 200 kHz in a pulse-burst operation, producing bursts of 5 pulses above 1.5 J each, while capable of bursts of 17 pulses at 100 kHz. A master oscillator-power amplifier architecture is used with a Nd:YVO_4 oscillator, four Nd:YAG amplifiers, and a Nd:glass amplifier. A radial profile over the pulse sequence is measured by using a set of graphite apertures and an energy meter, showing a change in beam quality over a pulsing sequence. © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4885539]

I. INTRODUCTION

Thomson scattering measurements of electron temperature are critical to magnetically confined fusion experiments, including the Madison Symmetric Torus (MST).[1] Ongoing work on MST includes ensemble modeling and fluctuation analysis,[2,3] where high rate of data capture improves single shot detail and data campaign statistics. Previously, MST's Thomson scattering diagnostic used a pair of commercial lasers modified for pulse burst operation, allowing for 30 pulses per MST discharge. These could be evenly spread at up to 2 kHz pulsing rate, or grouped in bursts of six 25 kHz pulses with bursts repeating every millisecond.

The laser discussed here is being developed as an upgrade to MST's Thomson scattering system,[4] utilizing the same beamline, collection optics, and detection systems.[5] The established systems necessitate a 1064 nm based laser, with minimum pulse energies on the order of 1.5 J. Previous work with this laser has demonstrated multiple bursts of 15 pulses at 75 kHz, or longer single bursts of 40 pulses at 10 kHz, while maintaining the necessary 1.5 J pulse energy.[6] Previous pulse energy results were measured at the immediate output of the laser, while this paper examines pulse energy and beam structure in the far field, as relevant to MST Thomson scattering with well defined scattering volume located approximately 20 m away from the laser.

II. LASER DESIGN

The laser uses a master oscillator-power amplifier architecture.[7] See Fig. 1 for a schematic of the non-mirror laser components.

The commercially sourced master oscillator is a diode pumped, Nd:YVO_4 with externally triggered *q*-switch, and external controls for diode pump intensity and timing. The master oscillator is cycled while the laser system is idle, interrupting to allow pumping of amplifiers. Fine tuning via external timing control has been crucial to optimizing the restart of the oscillator at the start of each burst, both for pulse energy stability and preventing excess energy in the first pulse of a burst. The master oscillator is capable of operating at 5-250 kHz.

Following the master oscillator are four Nd:YAG amplifiers, having rod diameters of 4, 6.4, 9, and 12 mm. These amplifiers use 4 mm bore by 67 mm arc length flashlamps: one shared by the first two amplifier rods, two for the third amplifier, and four for the fourth amplifier. The last amplifier is a 16 mm diameter Nd:glass amplifier, pumped by six 8 mm $\times$ 250 mm flashlamps. Allowances have been made for the future installation of a sixth amplifier, a duplicate of Nd:glass stage. All flashlamps are powered by insulated gate bipolar transistor switched capacitor banks, providing timing control of square pulse lamp firing and allowing for fine-tuning of pulse energies within a burst.

The beam passes through the first amplifier twice, while passing through the remaining amplifiers only a single time.

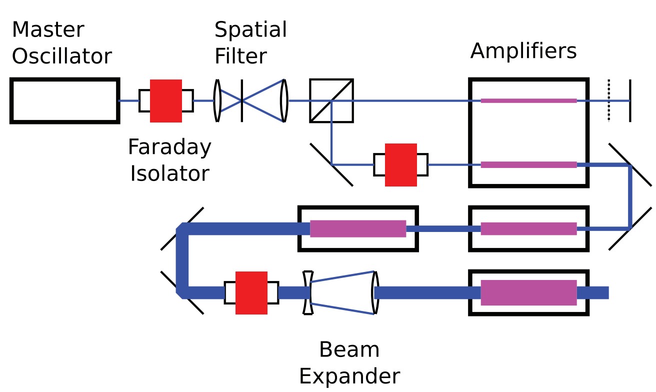

FIG. 1. An overview of the laser components (disregarding additional mirrors). The first amplifier uses a double pass via a quarterwave plate and polarization splitting prism.

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This is a change from the design in previous reported work on this laser,[6] which incorporated a second pass through the second and third amplifier. The far field beam profile of that setup contained a strong annular component, found to be strongly associated with the second passes of the later amplifiers. Removal of the second pass in the second and third amplifier was found to both remove this annular structure, and increase total energy output of the system. The first amplifier still requires a second pass to achieve reasonable amplification, and does not affect the far field beam quality. A likely key difference is that the first amplifier's rod has a wedge shape with a 0.5° tilt of the rod ends, while amplifiers two through four have perpendicular ends. The beamline was further simplified by removal of beam expanding telescopes and instead using the beam divergence to increase beam size between rods. Beam diameter within the laser is adjusted with an initial beam expanding spatial filter, and a single beam expander before the final amplifier is used to control far field focus.

III. LASER OPERATION

Computer control of the master oscillator and flashlamp power supplies allows great flexibility in operating the laser in different sequences as dictated by experimental needs. Changes and optimizations can be made shot-to-shot by loading different timing settings. At lower repetition rates, the laser produces a stream of evenly spaced pulses. Higher repetition rates are achieved by using pulse-burst mode: closely spaced pulses within a burst, with longer pauses between bursts. The flashlamps are fired once for the duration of each burst. The length of each burst, and hence the number of pulses within each burst at a given rate, is limited by the explosion energy of the flashlamps,[8] while the total number of bursts within a single shot is limited by total heat loading of the flashlamp walls.

Fig. 2 shows pulse energies of the laser operating at 200 kHz for three bursts, spaced out by 1 ms (see Sec. IV for method of pulse energy measurement). The plot includes a decay in pulse energies after the end of flashlamp discharges, as the master oscillator continues running through the end of the burst and when idle to improve pulse energy stability for following bursts. Within the first two bursts are 5 pulses of sufficient average energy for MST Thomson scattering (> 1.5 J). The amplifier rods are being used to store energy in this operating mode, and the rate that pulses drain that stored energy limits the number of pulses at usable energy. This is the highest repetition rate currently capable of producing more than two pulses per burst of usable energy. While only a small number of total pulses per shot, a few closely spaced pulses are useful for high frequency correlation measurements. Currently, there are significant pulse-to-pulse energy variations due to limited energy stability of the master oscillator. While the average energy exceeds 1.5 J per pulse, each individual shot can have pulses with up to 50% variation in energy, although typically more than 75% of the pulses remain above the threshold.

A burst at 100 kHz pulsing is shown in Fig. 3 and a series of three bursts with 75 kHz pulsing are shown in Fig. 4. The limiting factor for burst length here is flashlamp explosion energy, while the limit for number of bursts is currently the droop in pulse energy. At these settings, up to 12 bursts could be created before reaching the wall-loading limit. The number of bursts at the higher repetition rates will more likely be limited by the voltage droop within the capacitors powering the flashlamps. Here, the droop in pulse energy is much more so than the droop in power supplied to flashlamps, and could be the result of defocusing discussed in Sec. IV. With the current configuration and optimization, the 75 kHz repetition rate was found to have the highest number of usable pulses from multiple bursts, while the 100 kHz achieves the highest number of pulses in a single, faster burst at the loss of usable energy in multiple bursts.

IV. BEAM PROFILING

This laser is operated under the assumption that temperature gradients are not formed in the amplifier rods during

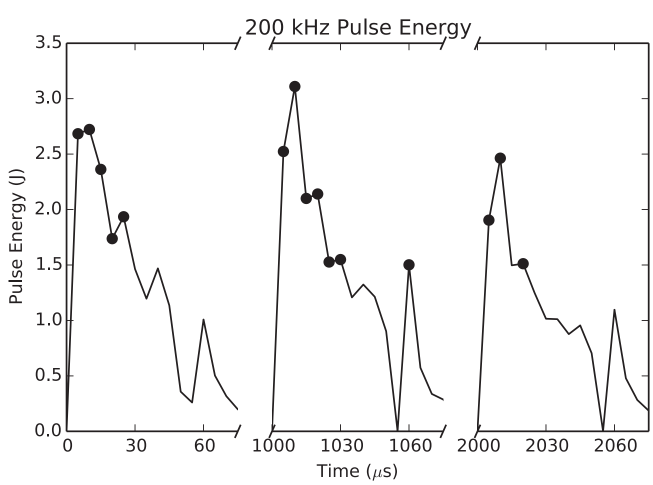

FIG. 2. This plot shows the pulse energies averaged over five shots with 200 kHz pulsing, and three bursts at 1 kHz. Dots indicate pulses with more than 1.5 J. Note that the long time between bursts was removed to clarify the plot.

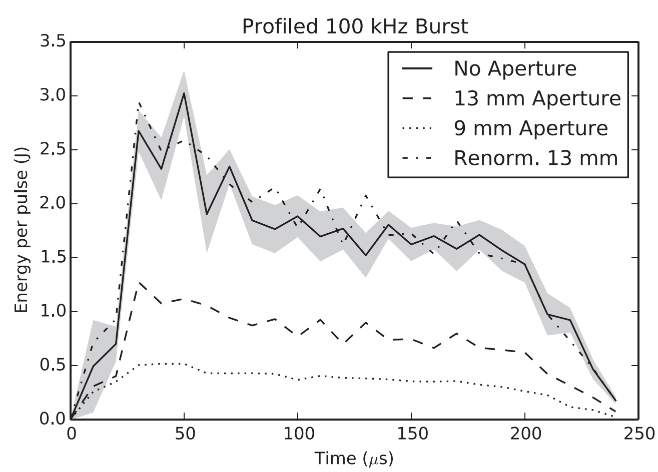

FIG. 3. This plot shows the average pulse energies over a burst of 100 kHz pulses, with and without apertures. A grey patch shows the standard deviation of shot-to-shot variation for the full pulse energy case. The dashed and dotted curves show pulse energies when restricted by a graphite disk aperture, while the dashed-dotted curve is the 13 mm aperture energies rescaled to show it has the same shape as the full energy trace.

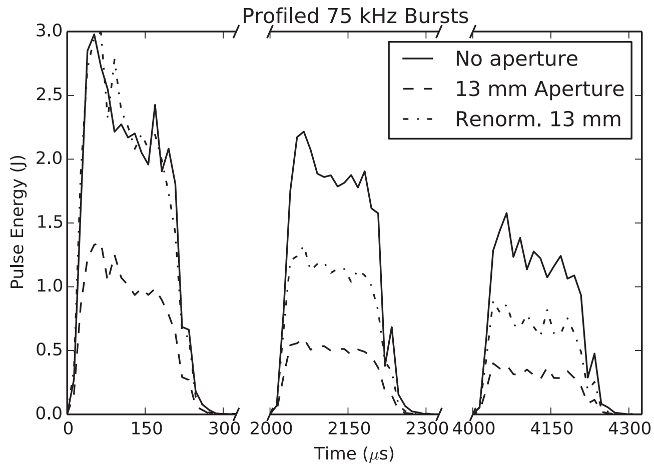

FIG. 4. This plot shows the pulse energy when operating with multiple bursts at 75 kHz pulsing, 0.5 kHz burst rate. The dashed-dotted curve is a rescaling of the 13 mm aperture energies showing that the ratio of full beam to 13 mm aperture energies is constant within bursts, but changes after the first burst.

a burst sequence. Thermal conduction estimates imply that a typical burst sequence is too short for thermal gradients to build up in the laser rods, while the 2-4 min laser off period between burst sequences gives enough time to completely cool the rods.[4] Measuring that the beam profile in the far field does not change over a sequence of pulses helps confirm the lack of thermally induced changes in beam focusing.

A series of 2 mm thick graphite disks with different sized holes were used as a set of fixed sized apertures on the laser running at full power. These were mounted in pairs in a twin filter wheel mount separated by 25 mm, to provide extra collimation. After the beam was passed through the aperture pair, the pulse energy was measured by use of a Litron photodiode based pulse energy meter (Mode LPM250-4-F). The analog output was digitized at 1 GSample/s, numerically integrated, and then compared to the calibrated total energy displayed on the meter. The measurements were taken with the apertures and energy meter (separated by 50 cm) on the laser table at the end 15 m path beyond the last amplifier, while the scattering volume within the MST plasma is located at a distance of approximately 22 m from the end of the last amplifier. Measurements labeled as without an aperture were taken using the same setup and an empty position in the filter wheel, which limits the beam to a 25 mm diameter, as compared to the 20 mm beam diameter for a single pulse.

Figs. 3 and 4 also show average pulse energies with apertures applied to the same pulse sequences. Both figures also include a trace of the masked beam energies that has been rescaled to match the initial pulse energies in the sequence, to allow comparison of the shape with the full energy trace. Within a single, high repetition rate burst, the ratios between the different parts of the beam vary by less than 5%.

However, as seen in Fig. 4, a large change in the ratio occurs between the first and second burst, suggesting a defocusing of the beam. Varying the time between two bursts from 1 to 5 ms does not change the drop in pulse energy or amount of defocusing. Tests with a 2 ms long 10 kHz burst show that the defocusing occurs on a timescale of 0.5-1.0 ms. A 10 kHz burst uses less pumping power than a 100+ kHz burst, but the total applied energy to the flashlamps over the bursts is comparable.

A possible source of this defocusing may be uneven pumping or heating of the Nd:glass laser rod. When an unamplified master oscillator beam is monitored after passing through the system, a significant change in the profile is noticed a couple of minutes after enabling the simmering of flashlamps within the fifth amplifier, implying there is uneven heating of the rod from the 30+ W each lamp dissipates while simmering. The same uneven heating could also occur during full power flashing of the lamps, explaining why the time between bursts, and hence flashlamp firing, does not affect the beam profile and why an effect is seen on a timescale two orders of magnitude below thermal conduction times for the laser rods.

V. SUMMARY

Operation of the laser has been demonstrated at 200 kHz producing pulse energies usable by the Thomson scattering diagnostic on MST. Longer bursts have been demonstrated at slower repetition rates, increasing the number of usable pulses.

Large changes in the beam profile and pulse energies are observed between burst, and despite the capability to pump the system for at least 10 bursts, the laser pulse energy drops off too far by the second or third burst. Measurements suggest this is not from bulk heating and edge cooling of the laser rods, but from uneven heating. A high priority for further work will be evaluating the design of the fifth amplifier's pumping chamber to ensure even heating of the laser rod. If the droop in pulse energy could be made more comparable to droop in applied flashlamp power, considerably more burst could be achieved. Installation of a sixth amplifier would also increase the burst durations and pulse energy.

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