Pulse-burst laser systems for fast Thomson scattering (invited)[a)]

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Two standard commercial flashlamp-pumped Nd:YAG (YAG denotes yttrium aluminum garnet) lasers have been upgraded to "pulse-burst" capability. Each laser produces a burst of up to 15 2 J Q-switched pulses (1064 nm) at repetition rates of 1–12.5 kHz. Variable pulse-width drive (0.15–0.39 ms) of the flashlamps is accomplished by insulated gate bipolar transistor (IGBT) 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 record the dynamic evolution of the electron temperature profile and temperature fluctuations. To further these investigations, a custom pulse-burst laser system with a maximum pulse repetition rate of 250 kHz is now being commissioned. © *2010 American Institute of Physics.* [doi:10.1063/1.3475723]

I. INTRODUCTION

The Thomson scattering plasma diagnostic system on the Madison Symmetric Torus (MST) reversed-field pinch (RFP) was originally equipped with two standard commercial Nd:YAG (YAG denotes yttrium aluminum garnet) laser systems (Spectron SL858).[1] This type of flashlamp-pumped laser system is common and similar systems are available from several manufacturers. Typically these lasers are used in Thomson scattering systems to deliver either a single pulse of light during a plasma discharge, or are operated to produce a train of pulses at a repetition rate $\leq$100 Hz.[2–4] We have upgraded our lasers such that each can now produce a burst of up to 15 ~2 J pulses, at repetition rates up to 12.5 kHz, with the ability to balance burst length and repetition rate to best suit experimental needs. The optical head of each laser was left unchanged, except for the addition of a 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. Immediately below is a brief description of the Thomson scattering system on MST, followed by a brief description of the laser system as originally configured and operated. The bulk of the paper describes the upgrades made to the laser system and the new operational capabilities. Section II summarizes the new pulse-burst laser system being built for addition to the Thomson scattering system on MST.

The design, calibration, and operation of the Thomson scattering diagnostic on MST is described in detail elsewhere,[1,5,6] so only an overview will be provided here. During typical operation, the two Nd:YAG lasers each produce ~2 J pulses at 1064 nm. The lasers are remotely located from the MST experimental bay in an environmentally controlled room, and are directed to the plasma via a remotely controlled beamline. Thomson-scattered light is collected from 21 spatial points across the minor radius of MST and transported via fiber optic to an array of filter polychromators with avalanche photodiode detectors. The signal from each detector is digitized at 1 Gsample/s for 500 ns around each laser pulse to record both the Thomson-scattered signal and background light before and after the signal. Measurement range is 10 eV–1.5 keV (and greater than 10 keV for a subset of the filter polychromators), for densities greater than $\sim 3\times 10^{18}$ m^{-3}. The entire scattered signal recording chain (polychromators, detectors, digitizers, etc.) is capable of recording scattered light pulses at a repetition rate greater than 1 MHz, thus the only factor preventing higher Thomson scattering measurement rates is the repetition rate limit of the laser sources.

The optical head of each Nd:YAG laser consists of an oscillator with Pockels cell Q-switch, preamplifier, and double-rod amplifier (Fig. 1). 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

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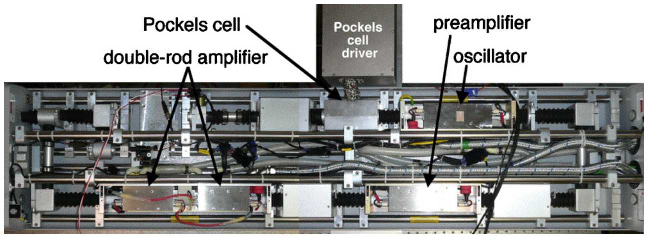

FIG. 1. (Color online) An overhead view of the Nd:YAG laser head.

flashlamp.[7] The capacitance and inductance were approximately matched to the impedance of the flashlamp arc to produce a fixed-width damped sine pulse with a full width at half maximum 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. 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.

II. LASER UPGRADES AND 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 $\sim$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 $\sim$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.

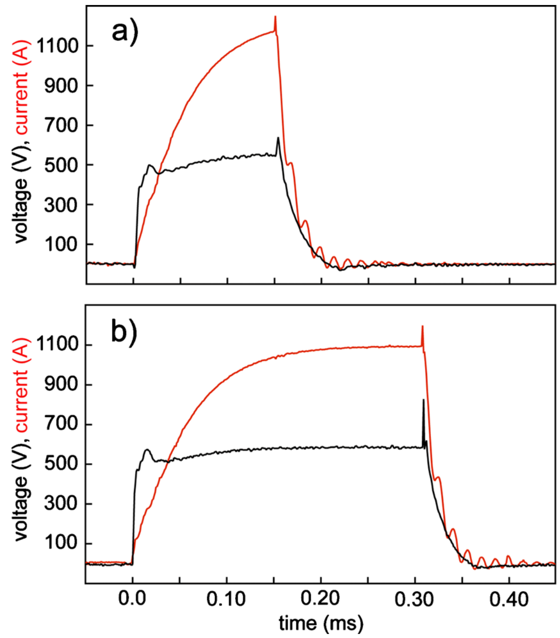

FIG. 2. (Color online) Voltage (black trace) and current (gray/red trace) applied to the largest flashlamp in the laser head to produce (a) one of fifteen 0.15 ms pulses and (b) one of five 0.31 ms pulses.

As part of the new pulse-burst laser development project, we have designed and fabricated a modular flashlamp drive system based on insulated gate bipolar transistor (IGBT) switching of large electrolytic capacitor banks.[8] As configured to drive the flashlamps in the Nd:YAG laser head, this 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. In order to avoid damaging voltage transients across the IGBT, the electrical layout of this system minimizes inductance of the high current connection between the capacitor bank and IGBT, and between the IGBT and flashlamp.

The most typical mode of the operation is to drive the laser flashlamps with a burst of fifteen 0.15 ms pulses at a repetition rate of 1 kHz.[9] A detail of one of the fifteen pulses is shown in Fig. 2. The Pockels cell is switched near the end of each flashlamp pulse to produce a train of fifteen $\sim$2 J pulses from each laser.[9] Usually the pulse trains from each of the two lasers in the MST Thomson scattering system are interleaved to produce a burst of thirty pulses at an effective 2 kHz repetition rate. Thomson scattering measurements of electron temperature using this mode of laser operation are shown in Fig. 3. Note that electron cyclotron emission measurement of electron temperature does not work in the low field RFP plasma in MST because the plasma is typically overdense ($\omega_{pe} > \omega_{ce}$), thus this type of Thomson scattering operation is the only way to track the dynamic evolution of the electron temperature profile.

This burst of laser pulses is repeated every few minutes, coincident with the duty cycle of MST plasma production. Since the burst production duty cycle is low ($\sim$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. This

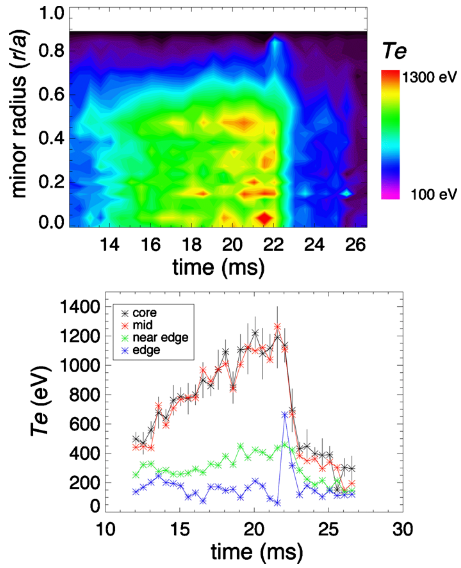

FIG. 3. (Color online) Thomson scattering measurement of electron temperature evolution during an improved confinement discharge. Both upper and lower plots are illustrations of the same data. Temperature in the core volume of the plasma steadily rises during the improved confinement period and then drops rapidly as the period ends.

pulse-burst laser programming is a type of heat-capacity laser operation.[10–12] Heat-capacity laser operation is characterized by a burst of pulses of limited duration, tens of ms in this case. During the burst, the entire volume of the laser rod is evenly heated by the flashlamp pump pulses,[7] rising steadily in temperature as the burst progresses and the waste heat from the pump pulses accumulates. The temperature rise is relatively uniform throughout the rod volume, so thermal gradients in rod remain small and beam distortion due to index gradient effects also remains correspondingly small. Heat is completely removed from the rod after each burst.

Heat-capacity laser operation is intermediate between single-shot high energy operation in which every laser pulse starts with a completely equilibrated gain medium, and steady-state operation (e.g., continuous train of pulses) in which cooling while pumping establishes thermal gradients in the gain medium. Typically substantial effort in optical correction and compensation is required to counteract the index gradient effects arising from steady-state operation. This level of effort is usually not required for heat-capacity laser operation, thereby substantially simplifying the laser design.

The time required to establish a temperature gradient in the smallest rod in our NdYAG laser heads is long compared to the burst length. The figure of merit useful to quantify this statement is the one-dimensional approximation of the thermal diffusion time across the rod radius

$$\Delta t \approx \frac{\rho c}{\kappa} r^2,$$

where ρ is the 4.56 $\mathrm{g/cm^3}$ density of YAG, c is the 0.59 J/g °C heat capacity of YAG, and κ is the 0.1 $\mathrm{W_{th}/cm}$ °C thermal conductivity of YAG.[13] For a YAG rod with $r=3$ mm, the thermal diffusion time is 2.4 s, much greater than the burst length. This approximation of the thermal diffusion time assumes effective cooling of the rod edge, therefore the time to establish thermal gradients in a rod will be lengthened if it is thermally isolated from its surroundings. The modeling results reported in Ref. 14 also indicate that the index gradient effects on pulse energy and beam divergence should be small for these short bursts.

A practical limit to the peak temperature of the rod at the end of a burst is 100 °C, the boiling point of unpressurized cooling water. Around this temperature, the lower lasing level of the active Nd ion in the rod also begins to be thermally populated from the ground state.[11] The rods in our laser should be well under this limit at the end of a burst, using the approximation that half the electrical energy delivered to the flashlamp arc is radiated, and a substantial fraction of that radiant energy is absorbed by the flow tubes and other surfaces in the pumping chamber.

In addition to the burst of fifteen 0.15 ms pulses, 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. A detail of one of the five pulses is shown in Fig. 2. 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.[9] 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 and correlating them with magnetic mode rotation in MST.[15]

In practice, the operational limits of this laser system are set by the explosion energy and wall loading limits of the flashlamps.[9] 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. At this limit we expect a lifetime of greater than 10^5 pulses. The need to produce ~2 J laser pulses sets the required flashlamp power input, 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 $\mathrm{W/cm^2}$ for liquid-cooled flashlamps with clear fused quartz walls of 1 mm thick. 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 $\mathrm{J/cm^2}$. This operational maximum limits the number of flashlamp pulses in a burst; the longer a flashlamp pulse, the fewer a burst can contain.

Several months of operational experience producing greater than 10^4 pulses suggests that the pulse-burst programming described above is conservative; in particular it appears that the number of flashlamp pulses in a burst can be increased. As a starting point, we plan to double the number of pulses in a burst (e.g., 30 pulses instead of 15) during the next major MST experimental campaign.

Besides actually pulsing the flashlamps, the drive system is required to perform another key function: starting and sustaining a simmer discharge in the flashlamps.[7] 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 ($\sim 1\ \mu$s) high-voltage (≥ 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.

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 Ref. 8 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.

As a next step beyond the laser upgrades described above, a custom pulse-burst laser system is now being commissioned. This new laser is designed to produce a burst of up to 200 approximately 1 J *Q*-switched pulses at repetition frequencies of 5–250 kHz. The master oscillator is a compact diode-pumped $Nd:YVO_4$ laser, intermediate amplifier stages are flashlamp-pumped Nd:YAG, and final stages will be flashlamp-pumped Nd:glass (silicate). The YAG amplifier stages of this system are complete and work well, and the first Nd:glass stage is undergoing testing (Fig. 4).[16]

Although the laser systems described in this paper are limited to a burst length of a few tens of milliseconds, this is not an intrinsic limit of heat-capacity laser design. For example, the Solid-State Heat-Capacity Laser (SSHCL) program at Lawrence Livermore National Laboratory has built and operated a diode-pumped Nd:YAG laser capable of 10 kW average power operation for 5 s, with a two-times diffraction limited, wavefront corrected beam.[17] The gain media are $10 \times 10 \times 2\ \mathrm{cm}^3$ slabs of transparent ceramic Nd:YAG.[12] This laser is relatively compact, fitting on a single large optical table. With some refinement and extension, this type of laser system could be adapted to serve as the source for a Thomson scattering diagnostic on a large fusion research experiment, producing electron temperature profiles at a rate of 10–100 kHz for several seconds.

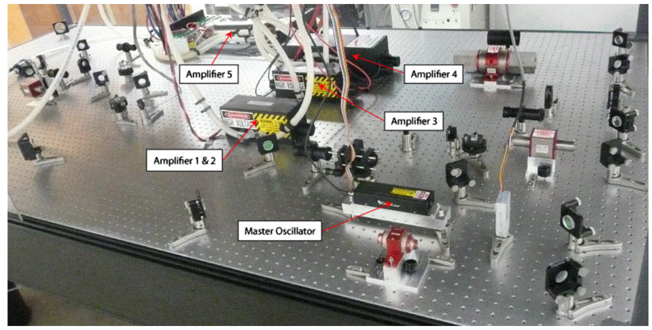

FIG. 4. (Color online) Optical table layout of high-repetition-rate pulse-burst laser system being commissioned for addition to the MST Thomson scattering system.

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