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Thomson scattering at 250 kHz

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ABSTRACT: Several upgrades have been applied to the high-repetition-rate Thomson scattering diagnostic on the MST experiment, having increased the rate and number of electron temperature measurements. The detector portion of the Thomson scattering system requires 1.5-2.0 J, 10-20 ns laser pulses at 1064 nm. A high-repetition-rate laser produces suitable pulses for short 3-4 pulse bursts with only 3 μs pulse spacing. Alternatively, the laser timing can be optimized to maximize the number of pulses in a single burst, producing up to 44 pulses at a rate of 100 kHz. The laser follows a master oscillator, power amplifier architecture. Upgrades to the laser include: a new acousto-optic modulator chopped CW laser based master oscillator, a sixth power amplifier, optimized Nd doping within Nd:glass amplifiers via optical modeling of the pump chamber, and a yet to be installed new cavity reflector. Additionally, a new long wavelength filter has been added to the Thomson scattering diagnostic's polychromator based detector, allowing possible detection of net electron drift.

KEYWORDS: Lasers; Nuclear instruments and methods for hot plasma diagnostics

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Contents

1 Introduction

The Madison Symmetric Torus (MST) [1], a Reversed-Field Pinch (RFP) magnetic confinement experiment, has a well established Thomson scattering diagnostic with plenty of experience utilizing a pulse-burst laser as a light source. By utilizing programmable timing for q-switching and flashlamp power supplies, a pair of commercial lasers could produce 30 pulses of 1.5-2.0 J [2]. These could be grouped into bursts of six pulses with 40 μs separation generated from a single flashlamp pulse, with bursts repeated every millisecond for a total of 5 times. However, even with this measurement rate, events 200 μs or less duration can still require large ensembles to capture temperature evolution [3]. This has motivated the development of a high-repetition-rate laser.

The existing system [4] determines the necessary laser parameters: 1064 nm and at least 1.5 J per 10-20 ns wide laser pulse. The fast laser utilizing some of the same control systems and power supplies as the previous pulse-burst laser, but with a larger configuration. Previous works [5, 6] discuss the early development of this laser and testing a partial implementation utilizing five out of six planned amplifiers.

2 Laser overview and upgrades

The laser follows a master oscillator, power amplifier configuration, as illustrated in figure 1. The power and timing of the master oscillator and amplifiers are programmable by computer, and quickly reconfigurable between shots to allow optimization of different timing sequences suitable for different temperature measurement scenarios.

The first four amplifiers use Nd:YAG rods, with diameters increasing from 4 mm to 12 mm. In total, the Nd:YAG stages have 7 flashlamps with a peak possible pumping power of about 3.5 MW. The laser pulses pass through the first three amplifiers twice.

The final two amplifiers are an identical pair of Nd:glass amplifiers, 16 mm in diameter. These amplifiers use six flashlamps each, of about eight times the volume of the lamps in the Nd:YAG stages. This pumping configuration gives up to 12 MW of pumping power each. While the Nd:YAG

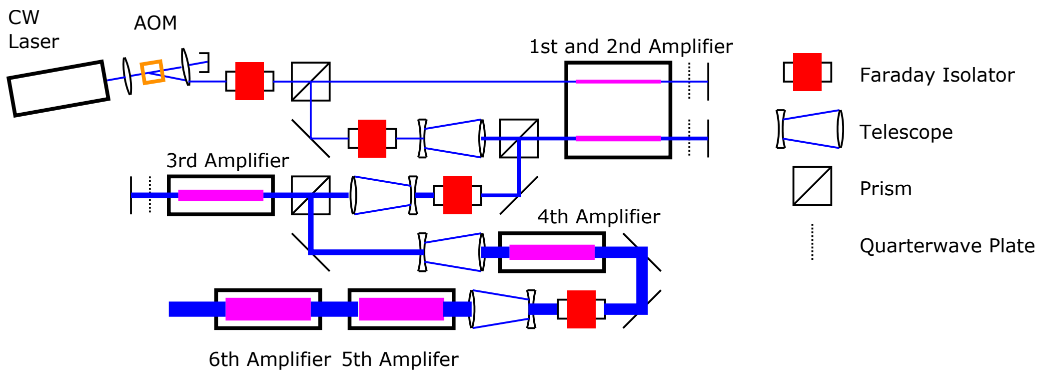

Figure 1. Above is a diagram of current components of the high-repetition-rate laser with most mirrors removed to simplify the diagram.

stages and first Nd:glass amplifiers are the same as previously described in detail, with the exception of Nd concentration discussed below, the sixth amplifier is new.

There are two temporary limitations that impact the performance data discussed in the later part of the paper. Data was taken after experiencing damage to the output face of the sixth amplifier. The beam profile was then modified to have an annular cross-section to limit power deposited into the rod defect. However this reduces the fraction of the Nd:glass rods filled by the laser pulse, limiting extractable energy.

Also, when constructing the sixth amplifier, the plan was to procure a new, high-reflectivity ceramic cavity reflector for both Nd:glass amplifiers. These reflectors were not available yet due to manufacturer delays, likely due to the size of these pumping chambers. The performance data was taken using a Macor reflector in the fifth amplifier and a simple, white acetal copolymer reflector in the sixth amplifier.

2.1 New master oscillator

A new master oscillator has been installed that uses an acousto-optic modulator (AOM) to chop a CW laser.[1] The AOM can be modulated with a bandwidth up to 50 MHz, with a 16 ns FWHM minimum practical pulse width. Pulse energy can be controlled by either producing wider pulse, or supplying shorter trigger pulses that produce a lower amplitude 16 ns pulse.

The previous master oscillator, a commercial, diode-pumped, pulse Nd:YVO_4 laser, had several major limitations. The maximum pulsing rate was 250 kHz. When a chain of pulses began, after some time off to allow for level inversion build-up in the amplifier rods, there would be a rise time of several pulses to achieve maximum pulse energy. Even when at full pulse energy, oscillator pulse to pulse consistency was poor, to the point of being dangerous if the first high energy pulse of a sequence was underpowered, causing the following pulse to remove large amounts of energy from the amplifiers.

The new master oscillator appears to have much better pulse to pulse energy consistency and it has no energy ramp up at a start of a chain of pulses. The largest negative is the much smaller pulse energy. The old master oscillator output was about 300 mW of pulses at 250 kHz, so it had about a

[1]D.J. Den Hartog's paper in the same proceedings goes into detail.

microjoule per pulse. The new master oscillator runs at about 200 mW, before being chopped, and is limited by the maximum power density of the AOM. These pulses have one to two nanojoules each. With the old master oscillator, double passing of amplifier 2 and 3 was found to be unnecessary and removed to simplify the beam path. Double pass was necessary for the new master oscillator to get enough gain before amplifier 4 which can contribute 10+% of the pulse energy. Once double passing was restored, the pulse energies out of amplifier 4 became comparable to the older setup, at the cost of slightly increased complexity.

2.2 Nd:glass doping concentration

Previous early testing [5] of the high-repetition-rate laser found that the laser could produce sufficient energetic pulses even after five or more bursts. This energy was measured close to the output of the fifth amplifier. Later testing [6] found that the beam defocused over the sequence of several bursts, to the point the third burst produced insufficient scattered light for temperature measurements. The behavior was consistent with uneven heating of the laser rods, with more heating of the outer radii of the rod resulting in the rod behaving as a diverging lens. This is in contrast to focusing thermal gradients from cooling of the edges of the rod, which has not been observed as expected due to 100 s thermal diffusion time constant for the Nd:glass rods.

To quantitatively evaluate the thermal gradients within the Nd:glass rod, a simple, physics-based ray tracing code was developed.[2] This code traced rays through a 3D pump cavity while taking into account refraction, specular reflection, and diffuse reflection (both Lambertian reflectance as approximated by a very diffusive ceramic pump cavity, and non-Lambertian diffusion of ground surface of the laser rod). The distribution of deposited heat was then calculated by using a typical spectra [7] for the xenon flashlamps of comparable current density and applying an absorption spectra for similar Nd:glass. Radial light absorption profiles are plotted in figure 2, where the original Nd:glass rods had 2.5% Nd_2O_3 by weight.

The Nd:glass rods were replaced with new rods with 1% Nd_2O_3. This concentration was found to be a balance of reducing the thermal gradients, while not reducing total energy available for pulse amplification. The absorption within the desired pump band was estimated to drop 25%, even though the Nd concentration drops by 60%. In practice, loss of pulse energy was not observed. This was likely due to the loss of energy going into the over pumped rod edge, where the edge of the laser pulse profile is weak.

Early multiple burst tests before the sixth amplifier was installed show greatly improved signal in third burst and usable scatter signal from a forth burst. Further fine tuning testing is required to determine the practical number of bursts. Multiple burst shots have yet to be performed on the six amplifier setup due to the potential extra stress on the damaged rod.

3 Laser performance

After implementation of the above upgrades, the performance of the laser has improved. Two operating modes are considered: maximizing the number of pulses from a single burst and maximizing pulsing rate for a short burst.

[2] A detailed description of this code will be published at a future date.

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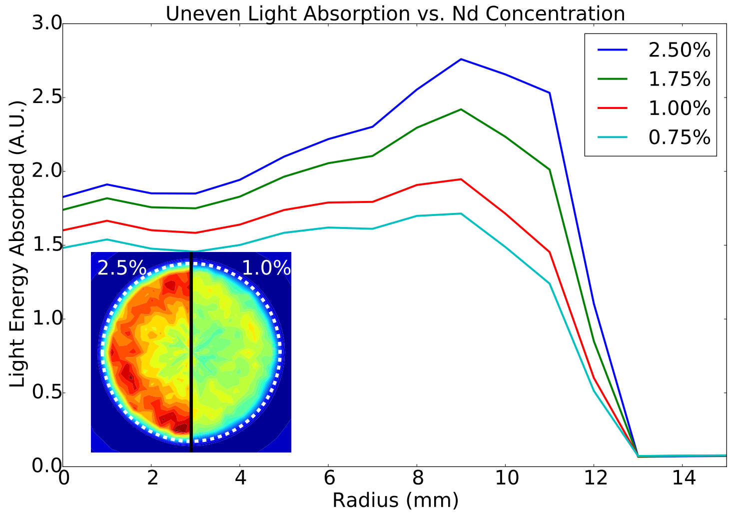

Figure 2. The above plot shows the radial profile of light absorption with a Nd:glass rod with difference concentrations of Nd (Nd_2O_3 by weight). 2D contours of the light absorption for two concentrations are shown in the insert (warm colors for more absorption). The white dashed circle marks the edge of the rod. The original 2.5% rods were replaced with 1% rods.

The best early results for the first mode are shown in figure 3. With a pulsing rate of 100 kHz, 44 pulses exceed the typical 1.5 J needed to get useful scattered light from typical MST plasma. The limiting factor here is the explosion energy of the smaller flashlamps in the Nd:YAG amplifiers. To maintain a reasonable flashlamp lifetime and low failure risk, the energy per burst for each flashlamp is limited to 20% of its explosion energy [8]. For this sequence, the larger Nd:glass stage flashlamps were at about 15% of explosion energy, and further optimization may improve the burst length by finding an operating point where all flashlamps are close to 20%. Previous to the upgrades, this mode was limited to about 25-30 pulses at 75 kHz.

For the second mode, two sequences are shown in figure 4. These shots pump the Nd:glass rods longer before pumping the Nd:YAG rods and pulsing the master oscillator. The stored energy is then released in a small number pulses before the pulse energy quickly drops. This gives 7 pulses and 4 pulses above the 1.5 J threshold for 250 kHz and 333 kHz pulsing respectively. The number of pulses at 250 kHz is comparable to that achieved before the upgrades, however the pulse energy is 20-30% larger, making the sequence suitable for plasmas conditions less optimal for TS measurements.

Both sequences show a ramp up in pulse energy, effectively wasting some energy on pulses too weak for temperature measurements. This is a conservative way of running, with the early pulses helping to prevent build up of enough energy to produce a single, very large pulse. As the upgraded laser becomes better characterized, these pulses may be removed. With the previous master oscillator that would occasionally produce alternating high and low energy pulses, there was a high risk of the first pulse being underpowered, followed by a pulse of 4+ J.

At the time of writing this paper, the laser, with all six amplifiers, has not been used for actual temperature measurements on plasma. However, figure 5 shows temperature measurements at 250

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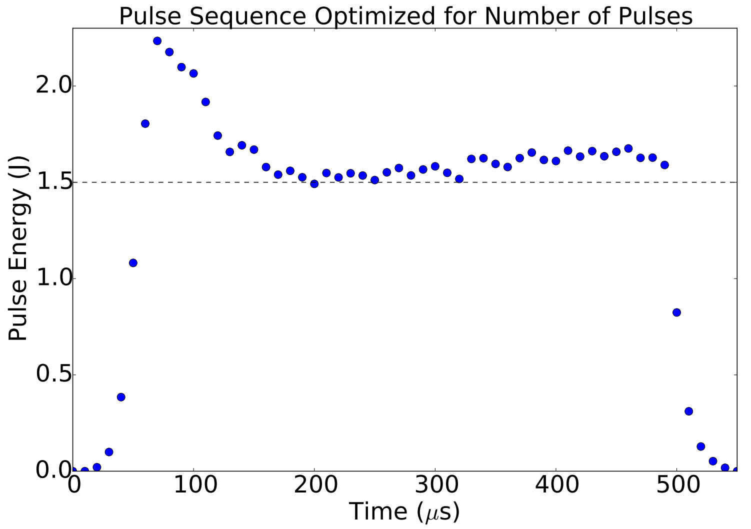

Figure 3. This sequence of pulse energies is the largest number of pulses achieved so far in a single burst: 44 pulses at 100 kHz.

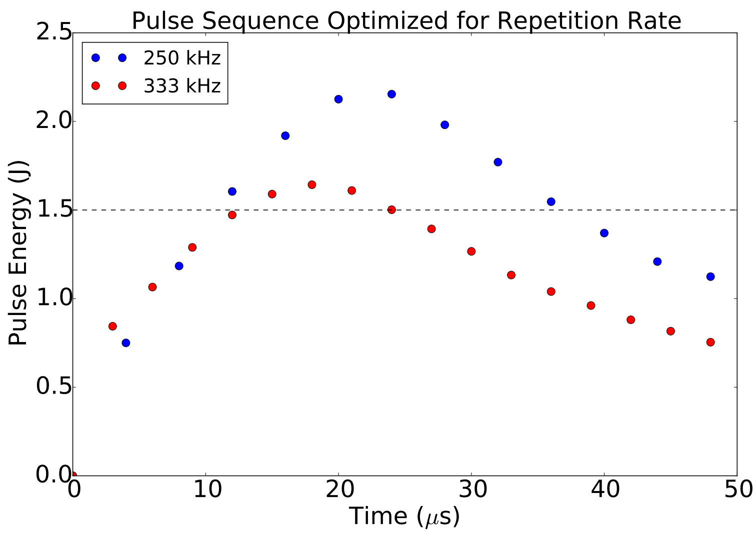

Figure 4. By using the Nd:glass stages for energy storage and increasing their pumping time before pulsing, the pulse sequence can be optimized for fastest repetition rate. The pulse energies plotted here are the current best for 250 and 333 kHz.

kHz from when there were only five amplifiers. This demonstrates that the pulses coming from the laser at these high rates are useful for their intended purpose, and that there should be a lot of potential for a system with an extra amplifier.

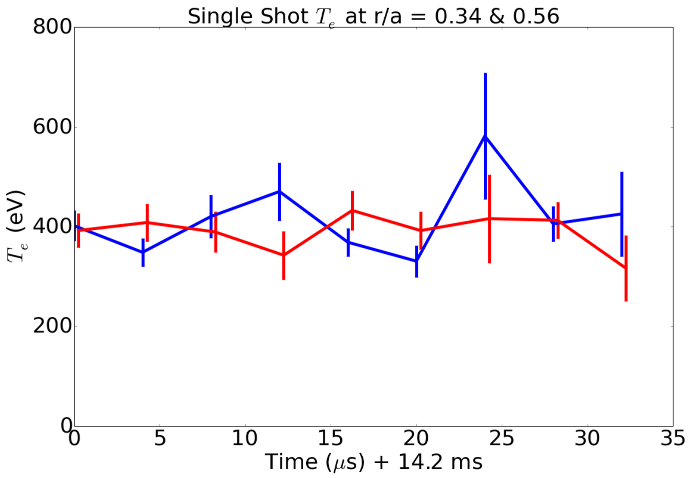

Figure 5. The temperature data from two chords is plotted here to show average to smaller than average error bars for MST TS measurements (10-20%) at 250 kHz. This data was taken when the laser only had five amplifiers installed.

4 Conclusions

The addition of another power amplifier to the laser shows a major improvement in the number of suitable laser pulses produced within a single burst. The number of pulses suitable for temperature measurements has further been increased by optimizing the Nd concentration within the Nd:glass rods, allowing for more bursts in a pulse-burst sequence. Lastly, a new master oscillator has allowed exploring the potential of the MST TS system to go beyond 250 kHz measurement rates.

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