A flexible master oscillator for a pulse-burst laser system

2015 JINST 10 C12008

(http://iopscience.iop.org/1748-0221/10/12/C12008)

Jinst

PUBLISHED BY IOP PUBLISHING FOR SISSA MEDIALAB

RECEIVED: *September 23, 2015*
ACCEPTED: *October 20, 2015*
PUBLISHED: *December 9, 2015*

A flexible master oscillator for a pulse-burst laser system

D.J. Den Hartog[1] and W.C. Young

Center for Magnetic Self-Organization and Department of Physics,
University of Wisconsin-Madison, Madison, WI 53706 U.S.A.

E-mail: djdenhar@wisc.edu

ABSTRACT: A new master oscillator is being installed in the pulse-burst laser system used for high-rep-rate Thomson scattering on the MST experiment. This new master oscillator will enable pulse repetition rates up to 1 MHz, with the ability to program a burst of pulses with arbitrary and varying time separation between each pulse. In addition, the energy of each master oscillator pulse can be adjusted to compensate for gain variations in the power amplifier section of the laser system. This flexibility is accomplished by chopping a CW laser source with a high-bandwidth acousto-optic modulator (AOM). The laser source is a Laser Quantum ventus 1064 diode-pumped solid-state laser with continuous output power variable from 100 to 500 mW. The 1064 nm, 2.7 mm diameter polarized beam is focused into the gallium phosphide crystal of a Brimrose AOM, which deflects the beam by approximately 60 mR when driven by the 400 MHz fixed frequency driver. Beam deflection is controlled by a simple digital input pulse, and is capable of producing deflected pulses of less than 20 ns width at repetition rates much greater than 1 MHz. These deflected pulses from the output of the AOM are collimated and propagated into the laser amplifier system, where they will be amplified to ~2 J/pulse and injected into the MST plasma.

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

[1]Corresponding author.

doi:10.1088/1748-0221/10/12/C12008

2015 JINST 10 C12008

Contents

1 Introduction

Pulse-burst laser systems typically produce a sequential series of laser pulses at high repetition rate (1 kHz to 1 MHz) in bursts that can last many milliseconds. The period between bursts is often long (1–100 seconds), and is determined by the time needed for heat to be removed from the laser gain medium. An alternative name for this type of system is "heat-capacity laser," which makes explicit the use of thermal inertia to obtain a burst of high-power laser operation while avoiding the expense and complication of a high-power laser cooling system. Typical individual laser pulse widths are 1–20 ns with pulse energies that range from a fraction of a joule to several joules. The need for these high brightness pulses (high peak optical power) is often driven by a diagnostic need to record an image or scattering event against an extremely bright background.

Arguably the first Nd:YAG pulse-burst laser system was reported by Knight and coauthors in 1980 [1]. Since then a range of pulse-burst laser capability has been developed at a variety of institutions, the predominant application being laser diagnostics for fluid dynamic measurements [2, 3]. Recent development has emphasized high pulse energy at high pulse repetition rates for long burst durations [4, 5]. Pulse-burst laser technology has also been applied to high-temperature plasma diagnostics, specifically Thomson scattering measurements [6, 7]. A master oscillator, power amplifier (MOPA) configuration has been used to produce 1–2 J pulses at repetition rates up to 200 kHz [8]. However, the diode-pumped Q-switched Nd:YVO_4 master oscillator in this system has several drawbacks. It operates at a preset pulse repetition rate during a burst, pulse-to-pulse energy variation is substantial and difficult to control, and pulse energy and pulse width are functions of the pulse repetition rate. In short, it lacks the flexibility and controllability desirable for pulse-burst MOPA system.

Thus, as a next step in our system development we are implementing the approach of Thurow et al., replacing the Q-switched master oscillator with an acousto-optic modulator (AOM) pulse slicer [9]. The AOM slices pulses from a diode-pumped CW laser, enabling pulse-on-demand operation and variable pulse durations ranging from 10 ns to infinity. This ability to program a burst of pulses with arbitrary and varying time separation between each pulse will maximize extraction

2015 JINST 10 C12008

of stored optical energy from the power amplifier, and provide the flexibility to respond to a broad range of diagnostic and experimental situations.

2 Pulse-burst laser system

The architecture of the custom high-rep-rate pulse-burst laser built for the MST Thomson scattering diagnostic is described in [10]. Since that paper was published, the final Nd:glass amplifier stage has been added to the system. The master oscillator now injects pulses into a power amplifier consisting of four Nd:YAG stages and two Nd:glass stages. The design goal for this system is burst operation at 250 kHz repetition rate with ~2 J pulses.

A schematic illustrating the layout of the new master oscillator system is in figure 1. The diode-pumped CW laser produces a 1064 nm beam, minimum diameter ~2.7 mm, linearly polarized with vertical orientation. The polarization is rotated 90° to horizontal with a halfwave plate (CVI Laser QWPM series). The beam is focused with a $f = +100$ mm bestform lens (CVI Laser BFPL series) to minimum spot size in the crystal of the AOM. The diverging beams (deflected and zero-order) exiting the AOM are re-collimated with another bestform lens. The focal length of the re-collimation lens will be selected to produce a deflected output beam with the combination of beam diameter and beam divergence best matched to the optical characteristics of the power amplifier chain. The deflected beam is produced only when the AOM is energized, and thus is the pulsed beam that is "sliced" from the CW laser beam. These beam pulses are directed through a 4 mm optical isolator (EOT HP-04-I-1064) and on into the first stage of the power amplifier. The zero-order beam is simply dumped.

Orientation of the AOM crystal relative to the incoming beam is critical for proper operation. The required alignment adjustability was achieved by mounting the AOM on a Thorlabs PY005 compact five-axis platform. The optical axis of the AOM crystal must be tilted approximately 30 mR relative to the incoming beam, while at the same time maintaining clear passage of the incoming, deflected, and zero-order beams through the input and output apertures of the AOM crystal.

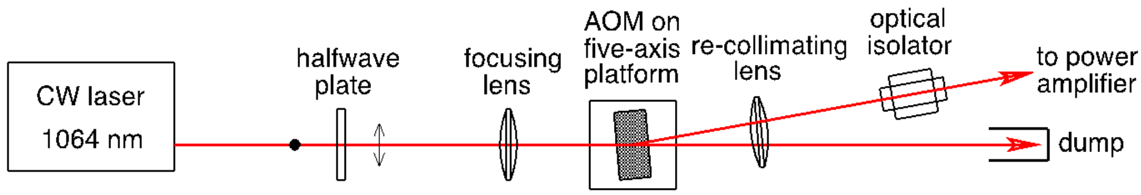

Figure 1. A block diagram illustrating the layout of the new master oscillator system. The tilt of the AOM is exaggerated for clarity.

3 CW laser source

The CW laser source is a diode-pumped solid-state unit, Laser Quantum ventus 1064 with mpc6000 power supply/controller. The laser head is approximately 104 × 174 × 52 mm. Nominal maximum output power is 500 mW, adjustable down to 100 mW. This is not a narrow linewidth laser, as this characteristic is not required for our Thomson scattering diagnostic. The laser operating characteristics most critical for this application are beam power stability and beam optical quality.

The beam power must be stable over a broad range of frequencies in order to avoid fluctuations in the amplitude of the sliced pulses. As a simple example of the importance of this characteristic, suppose the beam power oscillates at a frequency of 0.5 MHz. If pulses are being sliced from this beam at a repetition rate of 1 MHz, there is a high likelihood that the pulse amplitudes will oscillate around a mean, perhaps also varying with a low beat frequency. Similarly problematic is a beam that exhibits random variations in output power, particularly power spikes or dips. A spike, if sliced from the beam, has the potential to be amplified by the power amplifier chain beyond the optical damage threshold. A dip may not deplete the stored optical energy in the amplifier chain, allowing excessive energy to be available to the next pulse sent through the chain, again possibly exceeding the damage threshold. To avoid the problems described above, the laser source was specified to operate with less than 0.2% rms noise fluctuations in beam power over the frequency range 10 Hz to 100 MHz.

The optical characteristics of the beam from the master oscillator in any MOPA system directly influence the quality of the power amplifier output beam. This is true for a system containing an AOM pulse-sliced master oscillator, but in this case the optical characteristics of the CW laser source beam also affect the operation of the AOM pulse slicer itself. In particular, the beam must focus to an acceptable spot size within the AOM crystal, with acceptable divergence out from the focal point, while avoiding high-order mode structure within the beam that could lead to damaging power densities within the crystal. The ideal beam would exhibit a TEM_{00} transverse beam mode, with beam divergence characteristic of a Gaussian beam. Unfortunately, commercially available lasers, even those advertised as having a "Gaussian beam," often deviate from that ideal, particularly in the far-field, so it is generally prudent to characterize a beam before putting the laser into service.

Figure 2 contains transverse beam intensity profiles taken at four distances from the exit of the CW laser source. The lack of structure within the 2D profiles, and the Gaussian shape of the 1D cuts, indicates that this beam is approximately TEM_{00} in both near- and far-field. However, the beam divergence (figure 3) differs from that expected for an ideal Gaussian beam, which has a minimum spot size (the waist) and a single figure for beam divergence, meaning that the beam radius increases linearly past the Rayleigh range. Instead, note that the beam shown in figure 3 has two values of beam divergence: 0.3 mR in the mid-field, and 0.6 mR in the far-field, with the change in divergence occurring at about 600 cm from the laser. The beam waist of approximately 2.7 mm diameter occurs between 100 and 200 cm from the laser; an ideal Gaussian beam with this waist size would have a single value for divergence of ~0.25 mR. This deviation from ideal Gaussian beam characteristics will likely have a negative effect on beam quality in the power amplifier and downstream in the beamline that transports the amplified beam to the plasma. Spatial filtering of the beam may be required if the negative effects become problematic.

Despite this deviation from the Gaussian ideal, the focal spot (figure 4) produced by the $f = +100$ mm lens is acceptable. The spot size of $\sim 70\,\mu$m diameter is within specification for the AOM, and the beam profiles show no evidence of high-order mode structure that could cause potentially damaging concentrations of power within the AOM crystal.

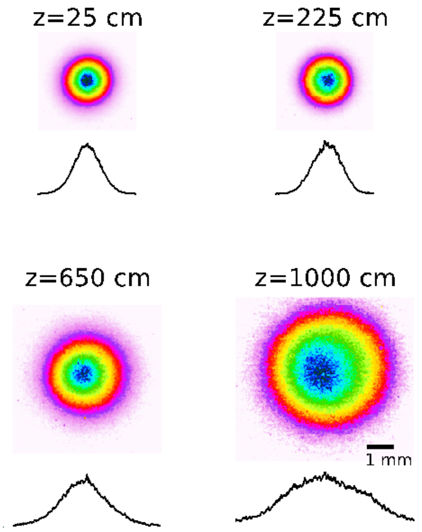

Figure 2. Beam intensity profiles recorded by a DataRay beam profiling camera at various distances from the laser source. The graph below each profile is a 1D cut through the center of each 2D profile.

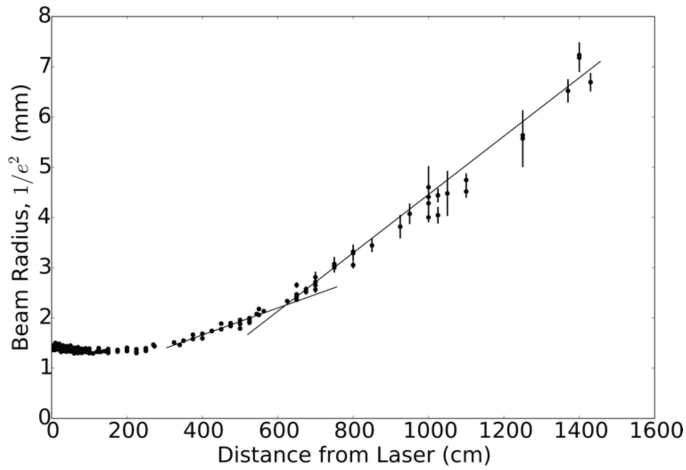

Figure 3. The variation of the 1/e[2] beam radius as a function of distance from the laser source. The two lines illustrate the mid-field divergence (300–600 cm from laser) and the far-field divergence (600–1400 cm from laser).

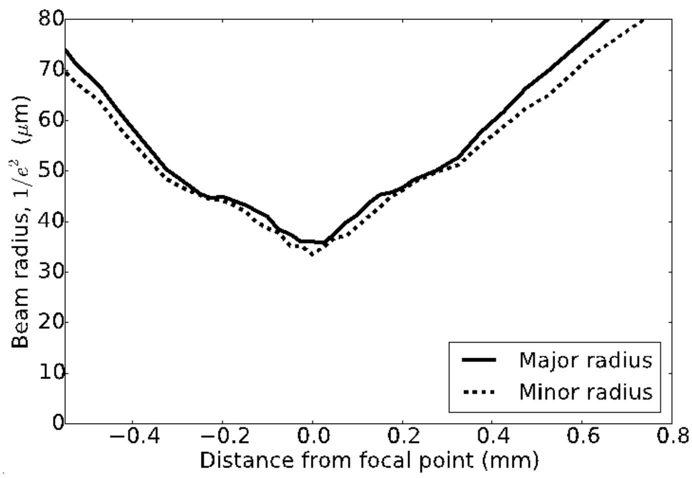

Figure 4. The focal spot variation produced by the $f = +100$ mm lens, with the lens placed approximately 100 cm from the CW laser source.

4 Acousto-optic modulator

The AOM is a Brimrose GPM-400-100-1064, a gallium phosphide crystal with a center frequency of 400 MHz. It is driven by a Brimrose FFA-400-B2-F1.25 fixed frequency driver. This driver has a modulation input, used to turn the driver off and on at frequencies up to 50 MHz. When the driver is not energized, the laser beam proceeds through the crystal undeflected, often called the zero-order beam. When the driver is energized, a deflected beam appears, with the input beam intensity typically split roughly equally between the zero-order and deflected beams.

2015 JINST 10 C12008

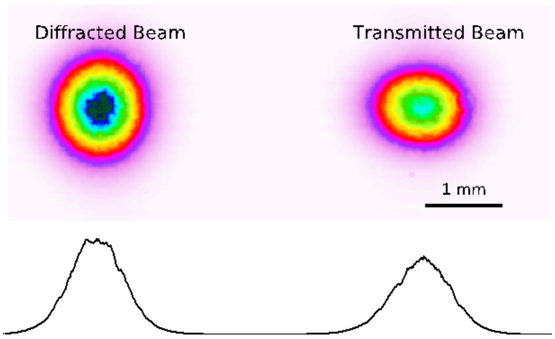

Figure 5. Beam intensity profiles of the diffracted (deflected) and transmitted (zero-order) beam. The graph below each profile is a 1D cut through the center of each 2D profile.

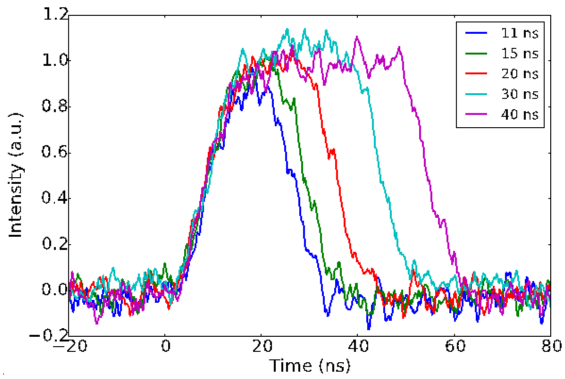

Figure 6. Pulses sliced from the CW laser beam by the AOM. The AOM driver was modulated by an SRS DG535 pulse generator; the time markers identifying each trace are the input pulse width from the DG535. The deflected beam is recorded by a Thorlabs DET025AL with 150 ps rise and fall times. The noise on the traces is a results of the low sensitivity of the detector at 1064 nm.

The operation of an AOM is described in many references, a few of which are listed below [11–13]. In brief, an AOM is activated when an acoustic wave is launched into transparent optical material (glass or crystalline) by a transducer attached to one face of the material. This wave results in a sinusoidal modulation of the density of the material, and thus a modulation of the index of refraction. This index modulation has the characteristics of a grating, so with proper orientation of the laser beam and the axis of acoustic propagation in the material, a large fraction of the incident laser beam will be diffracted into the first-order deflected beam when the acoustic driver is energized. The deflected and zero-order beams are separated by approximately 60 mR by the specific AOM in this system. Figure 5 shows the intensity profiles of these two beams, neither of which exhibit any high-order mode structure.

A key figure of merit for use of an AOM as a pulse slicer is the time required for the driver to establish an acoustic wave in the material, which sets the rise time of the deflected beam, and the time for the acoustic wave to disappear when the driver is turned off, which sets the fall time of the deflected beam. The AO crystal has an acoustic velocity of 6.3 km/s, which results in a predicted rise time of ~7 ns for a 70 μm diameter beam spot in the crystal [12]. The manufacturer specifies a rise time of 7 ns for the driver. The recorded rise time (figure 6) is approximately as expected from a convolution of these two times. The combination of rise time and fall time set the minimum pulse width that can be produced by the pulse slicer. Pulse widths of the deflected beam produced by various input pulse widths to the Brimrose driver are shown in figure 6. Rise and fall times of the sliced pulse are approximately equivalent, and it is straightforward to produce a symmetric 20 ns wide laser pulse for injection into the power amplifier chain. Given the bandwidth of the Brimrose driver, such pulses can easily be produced at repetition rates of 1 MHz, or at repetition rates that vary during a burst. For example, it may be useful under certain circumstances to inject into the power amplifier a burst containing a frequency comb of pulses.

2015 JINST 10 C12008

For input pulses to the Brimrose driver of less than the 11 ns shown in figure 6, the peak amplitude of the pulse begins to drop, the drop being approximately proportional to the reduction in input pulse width. This provides the capability to vary the amount of energy in a sliced pulse while keeping the pulse width below 20 ns (preferable for optimum operation of the Thomson scattering detection system). This capability should be useful in reducing power amplifier pulse energy variation when injecting bursts with varying pulse timing (e.g., a frequency comb).

5 Summary

The new master oscillator system described above, consisting of a CW laser source and pulse-slicing AOM, produces 20 ns wide laser light pulses at MHz repetition rates. These pulses will be injected into the power amplifier chain of the pulse-burst laser system used for high-rep-rate Thomson scattering on the MST experiment. The new master oscillator system has the ability to produce a burst of pulses with arbitrary and varying time separation between each pulse.

Acknowledgments

The authors are grateful for helpful conversations with Walter Lempert and Brian Thurow regarding the design of pulse-burst laser systems. This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Fusion Energy Sciences under Award Number DE-FC02-05ER54814, and by the National Science Foundation under Award Number PHY-0821899.

References

[1] R.C. Knight, R.J. Dewhurst and S.A. Ramsden, *Efficient burst-mode operation of a very high repetition-rate Nd:YAG laser*, *J. Phys.* **E 13** (1980) 1339.

[2] B. Thurow, N. Jiang and W. Lempert, *Review of ultra-high repetition rate laser diagnostics for fluid dynamic measurements*, *Measur. Sci. Tech.* **24** (2013) 012002.

[3] R.B. Miles, *Optical Diagnostics for High-Speed Flows*, in proceedings of *43rd AIAA Fluid Dynamics Conference*, San Diego, U.S.A., 24–27 June 2013 [doi:10.2514/6.2013-2610].

[4] F. Fuest, M.J. Papageorge, W.R. Lempert and J.A. Sutton, *Ultrahigh laser pulse energy and power generation at* 10 *kHz*, *Opt. Lett.* **37** (2012) 3231.

[5] M.N. Slipchenko, J.D. Miller, S. Roy, T.R. Meyer, J.G. Mance and J.R. Gord, 100 *kHz,* 100 *ms,* 400 *J burst-mode laser with dual-wavelength diode-pumped amplifiers*, *Opt. Lett.* **39** (2014) 4735.

[6] D.J. Den Hartog et al., *Pulse-burst laser systems for fast Thomson scattering*, *Rev. Sci. Instrum.* **81** (2010) 10D513.

[7] D.J. Den Hartog, J.R. Ambuel, M.T. Borchardt, J.A. Reusch, P.E. Robl and Y.M. Yang, *Pulse-burst operation of standard Nd:YAG lasers*, *J. Phys. Conf. Ser.* **227** (2010) 012023.

[8] W.C. Young and D.J. Den Hartog, *Operation and beam profiling of an up to* 200 *kHz pulse-burst laser for Thomson scattering*, *Rev. Sci. Instrum.* **85** (2014) 11D808.

[9] B.S. Thurow, A. Satija and K. Lynch, *Third-generation megahertz-rate pulse burst laser system*, *Appl. Opt.* **48** (2009) 2086.

[10] W.C. Young, L.A. Morton, E. Parke and D.J. Den Hartog, *High-repetition-rate pulse-burst laser for Thomson scattering on the MST reversed-field pinch*, 2013 *JINST* **8** C11013.

[11] W. Koechner, *Solid-State Laser Engineering*, Springer, New York, U.S.A. (2006), p. 514.

[12] Gooch & Housego, *Introduction to Acousto-Optic Modulators and Deflectors*, http://www.optoscience.com/maker/gooch/pdf/IntroductionAO.pdf.

[13] Brimrose Corporation of America, *Introduction to Acousto Optics*, http://www.brimrose.com/pdfandwordfiles/aointro.pdf.

2015 JINST 10 C12008