LASER SYSTEM FOR THE SNS LASER STIRPPING EXPERIMENT

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Abstract

This paper reports the development of a macro-pulse mode laser system capable of providing 30-50 ps/402.5 MHz UV pulses with multi-megawatt peak power. The laser operates at a 1 ms/60 Hz macro-pulse mode and will be used in the laser assisted hydrogen ion (H⁻) beam stripping at Spallation Neutron Source.

INTRODUCTION

The Spallation Neutron Source (SNS) accelerator complex utilizes charge-exchange injection to stack a high-intensity proton beam in the accumulator ring for short-pulse neutron production. A foil-less charge exchange injection method was researched at SNS by using a laser assisted H⁻ beam stripping scheme [1]. Following a proof-of-principle experiment using a Q-switched laser, a new experiment is being prepared to demonstrate laser stripping over a 10-us macro-pulse [2].

In this report, we will describe the design and measurement results of the laser system for the next stage laser stripping experiment. The laser system adopts a master oscillator power amplifier (MOPA) configuration and contains an actively mode-locked fiber seeder, macro-pulse generator, multiple-stage Nd:YAG amplifiers, harmonic converters, and control electronics. The laser system generates 30-50 ps ultraviolet (UV) pulses at 402.5 MHz repetition rate with multiple megawatt peak power. The measurement results of laser spectrum, spatial/temporal waveforms and their parameter dependence will be described.

SYSTEM DESCRIPTION

The laser parameters are determined by laser-hydrogen interaction physics and the linac operation condition at SNS [1]. First, the energy gap between the ground and excited states in the hydrogen atom, beam energy and the interaction geometry at the accumulation ring requires a laser with UV emission. The peak power of micro-pulses needs to be ~1 MW to achieve a sufficient stripping efficiency. The temporal structure of the laser system must match the bunch structure of the SNS accelerator which has a pulse width of ~30 ps at a repetition rate of 402.5 MHz. The micro-pulses are further bunched into a macro-pulse with up to 1 ms duration at a repetition rate of 60 Hz. The ideal (minimum laser power requirement) condition would be that the laser beam has an identical temporal structure with the ion beam.

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A macro-pulse mode laser system has been designed by ORNL and Continuum, Inc. to meet the above requirements [3]. The laser adopts a master oscillator power amplifier scheme contains an actively mode-locked fiber laser, three-stage Nd:YAG amplifiers, a wavelength conversion stage that converts the infrared radiation from the laser to the UV beam, and an electronic RF and control system that allows full remote-control of the laser. Fig. 1 shows a schematic diagram of the laser system.
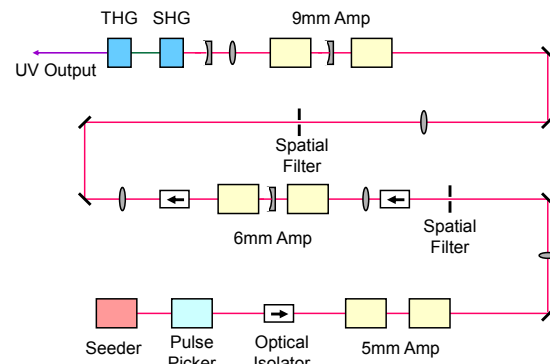

Figure 1: Diagram of the macro-pulse laser.

The master oscillator is an actively mode-locked fiber laser pumped by 980 nm diode lasers. The gain medium is Ytterbium-doped fiber which supports generation of picosecond pulses at λ=1.064 μm. The laser cavity has a round-trip frequency of ~ 4.43 MHz that depends on the cavity length. An electro-optic modulator (EOM) modulates the loss in the laser cavity to support the active mode-locking. Synchronization of the laser oscillator with the linac is accomplished by driving the EOM with a 402.5 MHz signal that operates the superconducting acceleration cavities of the SNS linac. The synchronization accuracy of the picosecond pulses with regard to the electronic radio-frequency (RF) oscillator is approximately 0.5 ps rms. The phase lock loop circuit in the laser provides a control signal to adjust the cavity length through a piezo-transducer (PZT) mirror so that its round-trip frequency matches a sub-harmonic of the laser repetition frequency. The oscillator output is pre-amplified by a YDFA. The laser wavelength is stabilized by a fiber grating and the wavelength can be controlled through a temperature adjustment of the grating.

Prior to the YAG amplifiers, the output light from the YDFA is injected into an acousto-optic modulator (AOM) through a PM fiber for macro-pulse generation and shaping. The AOM is driven by a voltage controlled RF amplifier at a fixed frequency close to its resonance (41 MHz). The macro-pulse shape is controlled with a wave

shaper program through a Stanford DS345 synthesized function generator. When the driver is triggered, the control waveform generated on a Continuum graphical user interface (GUI) is converted to voltages and applied to the voltage controlled RF amplifier which in turn controls AOM. The amplitude of the RF signal determines the amount of seed light directed into the amplification chain. Through controlling the RF pulse profile, one can achieve an arbitrary pulse shape out of the end of the amplifiers. The main purpose of having the shaping capability is to combat the effects of gain saturation in the amplifier chain. The pulse being amplified is short compared to the lamp pulse. The first part of the pulse envelope therefore sees the highest gain and the gain is depleted as the pulse envelope passes through the rods. To achieve a flat macro-pulse of the UV light, the macro-pulse of the seed light is controlled so that the front end of the pulse envelope has less energy than the end of the pulse envelope, thus compensating for this gain depletion.

The amplifier includes three amplification stages which contain 5 mm, 6 mm, and 9 mm Nd:YAG heads, respectively. Each amplification stage consists of two YAG rods and two pieces of compensation optics between the rods: a negative lens for compensation of thermal lensing in the heads and a quartz rotator for compensation of the thermal birefringence from the heads. A Pockels cell is installed after the 5 mm heads and the delay time between the Pockels trigger and the flash lamp is properly adjusted to prevent the laser from generating too much forward propagating amplified spontaneous emission (ASE) that will rob the gain from the main pulse. A Faraday isolator is inserted between 6 mm and 9 mm amplification stages to eliminate light reflection. Relay imaging lenses and spatial filter pinholes are installed between amplification stages to control the beam profile. Finally, a φ5-mm apodizer is installed before the 9 mm amplifiers to optimize the spatial profile of the laser output.

The wavelength conversion part contains a pair of lenses for beam collimation, a 25 mm long LBO crystal for the second harmonic generation, and a 30 mm long LBO crystal for the third harmonic generation. The 1064/532/355 lights are separated by a couple of dichroic mirrors. Due to the limited space, no dispersion compensation optics is used between the doubler and the tripler. The group velocity mismatch is estimated to cause a few picoseconds of pulse broadening which is acceptable for our application.

The timing of the entire system (pulse picker, Pockels cell, flashlamp discharge timing) is controlled by a multiple-channel delay generator to achieve synchronization of both macro-pulses and micro-pulses of the laser to the H⁻ beam. The flashlamp discharge timing for each amplifier is adjusted to achieve an optimum amplification performance. The macro-pulse duration of the present laser system is limited to 20 µs due to the pumping scheme and the wavelength conversion efficiency. To achieve longer macro-pulses, diode

pumping has to be used and the peak power has to be reduced.

PERFORMANCE MEASUREMENT

Wavelength and Optical Spectrum

The wavelength of the seed laser is controlled by a fiber Bragg grating. By changing the temperature of the grating, the laser wavelength can be tuned from 1064.3 to 1064.6 nm. In the experiment, the temperature is stabilized so that the wavelength stabilizes at 1064.5 nm which matches the maximum gain of the amplifier.

Optical spectrum has been measured by an optical cavity with a free spectral range of 402.5 MHz. The linewidth cannot be resolved with the cavity bandwidth. However, due to the harmonic mode-locking scheme, a frequent mode hopping at multiple integers of 4.43 MHz was observed. A modified seed laser has been home-made to generate similar pulse structures with no mode-hopping [4]. Using the new seed laser, the development of a beam recycling optical cavity is in progress [5].
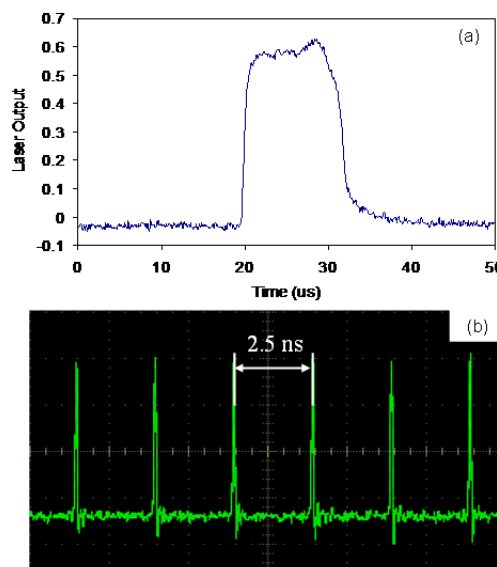
Temporal Waveform

Figure 2: Waveforms of macro-pulse and micro-pulses.

The macro-pulse width and shape are tuned by controlling the RF waveform of the AOM. A typical 10-us macro-pulse waveform is shown in Fig. 2(a). A fast photodetector (New Focus 1444 with the rise time 18.5 ps) is used to measure the waveform of the IR light. Fig. 2(b) shows the micro-pulse waveform displayed on a high bandwidth oscilloscope (Agilent 86100D). The pulse jitter was measured to be less than 1 ps.

Spatial Profile

The UV beam is collimated with a telescope so its beam waist forms at about 12 meters from the laser. Fig. 3 shows the far-filed profile of the beam measured around

the beam waist. The full width far-field angle is about 80 urad. The beam quality is evaluated from the beam sizes measured around the beam waist and the result indicates the beam is close to the diffraction limited.
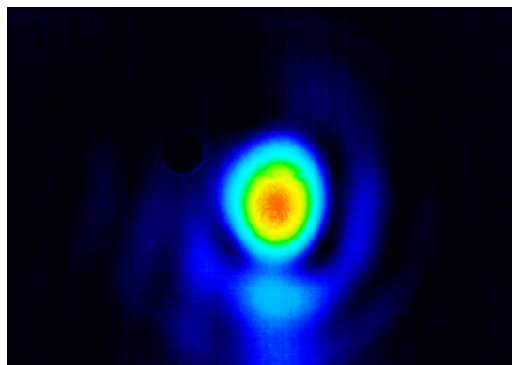

Figure 3: Far-field profile of the UV beam. Scattering spots are high order modes.
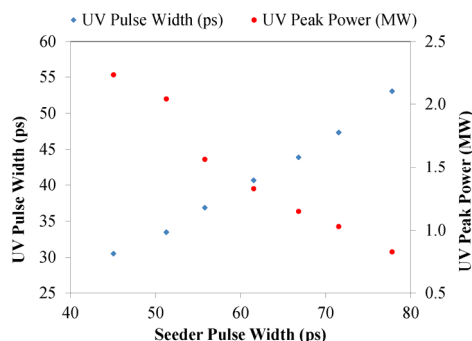
Pulse Width and Peak Power

Figure 4: UV beam pulse width and peak power as functions of the IR seed laser pulse width.

The maximum IR power is achieved by appropriately increasing the IR beam size to match the rod diameter of the final stage amplifier. The UV power depends on the IR power, the beam size on the crystal, and is also strongly correlated with the pulse width. We observed a slow drift of the pulse width due to the shift of the bias voltage of the EOM and phase voltage of the phase locker in the seed laser.

The pulse width of micro-pulses of both IR and UV lights are measured by a home-made multi-functional optical correlator [6]. The pulse width of the seed laser can be tuned by adjusting the bias and/or phase voltages of the mode-locking circuit. The UV peak power is inversely proportional to the pulse width. Fig. 4 shows the measured UV pulse width and peak power as a function of the seed laser pulse width.

CONCLUSION

A macro-pulse laser system is designed and commissioned to generate high repetition rate picosecond UV pulses with MW peak power. The laser parameters including spectrum, temporal waveforms, beam quality, and pulse width have been measured. The laser parameters are suitable for the laser assisted H⁻ beam stripping at the Spallation Neutron Source.

ACKNOWLEDGMENT

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