**Laser and Optical System for Laser Assisted Hydrogen Ion Beam
Stripping at SNS**

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Abstract

Recently, a high-efficiency laser assisted hydrogen ion (H-) beam stripping was successfully carried out in the Spallation Neutron Source (SNS) accelerator. The experiment was not only an important step toward foil-less H- stripping for charge exchange injection, it also set up a first example of using megawatt ultraviolet (UV) laser source in an operational high power proton accelerator facility. This paper reports in detail the design, installation, and commissioning result of a macro-pulsed multi-megawatt UV laser system and laser beam transport line for the laser stripping experiment.

Keywords: Laser; Hydrogen ion; Laser stripping; Charge exchange injection; Spallation Neutron Source

I. Introduction

Advancements in laser technology have dramatically expanded the applications of lasers to high energy physics [1]. Today, lasers have been used in a broad range of particle accelerators from test stands to operational facilities. A number of important applications with different levels of technical readiness have been demonstrated including beam diagnostics [2], photo-injectors [3], Compton scattering-based light sources [4, 5], and laser driven electron acceleration [6, 7]. Recently, a laser assisted hydrogen beam stripping method was developed at the Spallation Neutron Source (SNS) [8]. The laser stripping technique has the potential to make it possible to stack high-intensity proton beam with no restrictions of beam loss and radiation activation at high beam intensities. Following a successful proof-of-principle demonstration [9] using a Q-switched laser, a more advanced experiment, or a proof-of-practicality experiment was recently proposed by SNS [10] and funded by U.S. Department of Energy (DOE) High Energy Physics Program. The goal of the project is to demonstrate high-efficiency H^- beam stripping at an operational accelerator setting. A typical neutron-production H^- beam at SNS is bunched in a macropulse (burst-mode) structure where each macropulse consists of 30-ps micro-pulses repeating at 402.5 MHz.

Laser stripping imposes a number of challenges on both laser technology and laser operation. First, high efficiency stripping requires lasers with high peak and high average powers in the ultraviolet wavelength regime as well as a complicated macropulse structure, which cannot be obtained using conventional chirped pulse amplification (CPA) technology [11]. Such lasers are not available in the current laser market and demand the development in macropulse amplification technology. Second, high radiation in an operational high power proton accelerator puts significant restrictions on the control/operation of the laser system. Besides, high intensity UV laser beam also introduces risks to accelerator operation, such as the laser induced breakdown on the vacuum windows. In most the above-mentioned applications [2-7], high power lasers have been installed near electron accelerator beamlines where radiation concerns were much insignificant compared to proton accelerators.

1 In this paper, we describe the design and performance of a macropulse laser system that
2 provides picosecond pulses with multi-MW peak power at 355 nm. The pulses are
3 repeating at 402.5 MHz and are bunched into a burst mode structure with variable
4 macropulse durations and frequencies. The general design concept can be adapted to any
5 temporal beam structures in most accelerators. We also describe the implementation of
6 laser transport line (LTL) that delivers UV beam over a 60-meter long complicated beam
7 path with remote control/monitor of laser parameters. The LTL delivered UV beam to the
8 laser stripping location at a 70% efficiency and survived high radiation doses induced by
9 megawatt proton beam accelerator. A laser parameter scalability to the full-cycle laser
10 stripping, i.e., 1 ms macropulse at 60 Hz, is also discussed.

12 **2. Macropulse UV Laser**

13 *2.1 Laser parameter requirement*

14 The SNS laser stripping scheme consists of three steps: First, H^- ions are converted to H^0
15 by stripping off the first electron in a magnetic field; then H^0 atoms are excited from the
16 ground state ($n = 1$) to an upper level, i.e. $n = 3$, by a laser; finally the excited states H^{0*}
17 are converted to H^+ by stripping the second electron in a second magnetic field [8]. The
18 bandgap energy between the ground state and the $n = 3$ state is 12.1 eV which
19 corresponds to a laser wavelength of 102.6 nm. Although some lasers, e.g. excimer lasers,
20 are emitting at the close wavelengths, those lasers are usually operating at continuous-
21 wave (CW) mode with relatively low power. Meanwhile, by taking advantage of the fact
22 that the hydrogen atoms are moving at a relativistic speed, it was shown in [12] that the
23 necessary photon energy to excite H^0 atoms can be greatly reduced. In the case of SNS
24 linear accelerator, the H^- beam reaches a kinetic energy close to 1 GeV (the
25 corresponding H^- ions and H^0 atoms speed are near 87% of the light speed), the
26 wavelength of the laser light in the H^0 atom rest frame can be lowered to around 355 nm
27 if the laser and H^0 beams interact with each other at a certain angle. Such a wavelength
28 can be readily achieved by tripling the frequency of an Nd:YAG laser that is one the most
29 popular high power pulsed light sources.

1 While the three-step laser stripping concept [12] was proposed several decades ago, a
2 fundamental technical challenge was to deal with the Doppler broadening of the
3 hydrogen absorption linewidth due to the finite momentum spread of the H^-/H^0 beam.
4 Danilov [8] proposed an efficient method to excite all the hydrogen atoms nearly
5 simultaneously by using the Doppler dependence of the hydrogen rest-frame laser
6 frequency. By preparing a diverging laser beam, the interaction angle between the laser
7 and particle beams continuously changes across the hydrogen beam path and accordingly
8 the frequency of the light in the H^0 atom rest frame decreases as the angle increases. The
9 diverging laser beam introduces an effective frequency “sweep” as the hydrogen beam
10 traverses the laser interaction region, which assures that all atoms with different energies
11 will be excited.

12 Figure 1(a) shows the calculated stripping efficiency as a function of the laser peak power.
13 Obviously, the stripping efficiency rapidly grows in proportional to the laser power at
14 low power levels while saturates quickly when the laser peak power exceeds 1 MW. The
15 stripping efficiency also depends on the laser beam divergence angle in the interaction
16 plane (assumed in the horizontal plane) and the laser beam size in the perpendicular
17 (vertical) plane, as shown in Fig. 1(b). To obtain stripping efficiency of 90% and above,
18 we need to prepare a UV laser beam with a peak power of 1 MW, typical (horizontal)
19 divergence angle (RMS) around 0.5 mrad and (vertical) beam size around 0.2 mm (RMS).

20 Temporal structure of the laser beam is another important factor. To minimize the
21 (average) laser power requirement, the laser beam needs to have the same temporal
22 structure as that of the ion beam. The baseline H^- beam of the SNS accelerator has a 1 ms
23 pulse length and a repetition rate of 60 Hz. Each macropulse contains micro-pulses
24 bunched by the SNS RFQ at a frequency of 402.5 MHz. For the laser stripping
25 experiment, the pulse width of the micro-pulses is compressed to ~ 27 ps (FWHM).

26 The goal of the present experiment is to verify the practicality of laser stripping by
27 demonstrating that all individual micro-pulses within a macropulse can be simultaneously
28 stripped at $\sim 90\%$ efficiency using a properly designed macropulsed UV laser. The
29 macropulse duration is set at 10 μ s in the current experiment. The macropulse duration
30 can be expanded to 1 ms by changing the pump scheme in the proposed amplifier system.

Maintaining the MW peak power over 1 ms is beyond the capability of the present laser technology. On the other hand, by using the power recycling optical cavity, the proposed laser stripping technology is scalable to full-cycle H- beam. A discussion on the scalability will be given in the later part of this paper.

2.2 Macropulse laser system

Figure 2 shows a schematic of the stripping laser system. The laser adopts a master oscillator power amplifier (MOPA) configuration. Primary segments include a fiber seed laser, a macro-pulse generator, multiple-stage Nd:YAG amplifiers, and two harmonic conversion crystals. The seed laser, i.e., the master oscillator, is an actively mode-locked fiber laser pumped by 1480 nm diode lasers. The gain medium is a Ytterbium-doped fiber which supports generation of laser light around 1064 nm. The laser wavelength is controlled via a temperature tuned fiber Bragg grating (FBG) with a tuning factor of 13.3 pm/°C. The temperature of FBG is stabilized at $36.0 \pm 0.05^\circ\text{C}$ so that the corresponding wavelength 1064.45 nm maximizes the Nd:YAG amplifier gain. The laser cavity (fiber loop) is also temperature stabilized and the default cavity length corresponds to a round-trip frequency of ~ 4.43 MHz. An electro-optic modulator (EOM) modulates the loss in the laser cavity for the active mode-locking. The phase lock loop circuit in the laser provides a control signal to adjust the cavity length through a piezo-transducer (PZT) so that its round-trip frequency matches a sub-harmonic of the pulse repetition frequency. Fig. 3 shows the measured pulse width as a function of (a) the bias voltage (V_b) of the EOM and (b) phase loop control voltage (V_{ph}) of the seed laser. Stable mode locking is obtained over a quite large range of both parameters. The pulse width shows a sensitive dependence on V_b , which provides an efficient way of pulse width tuning within 55 – 85 ps. The radio-frequency (RF) modulation signal on the EOM is synchronized to an external timing signal at 402.5 MHz with a synchronization accuracy of about 1 ps. The seed laser also has a built-in fiber amplifier which brings the seed laser output power to ~ 200 mW.

The infrared (IR) light pulses from the seed laser have a very low peak power (~ 10 W). To generate MW peak power at 355 nm required by the laser stripping, an amplification factor of $\sim 10^6$ on the IR pulses from the seed laser is needed. In this work, the

1 amplification is performed in a burst mode by using solid-state amplifiers. Both the
2 macropulse generation and amplification are conducted in free space. An acousto-optic
3 modulator (AOM) is employed to generate macropulses with adjustable pulse durations,
4 repetition rates, and most importantly arbitrary pulse shapes. The macropulse shaping
5 capability is crucial to combat the effects of gain saturation in the amplifier chain. Since
6 the pulse being amplified is short compared to the lamp pulse, the first part of the pulse
7 envelope sees the highest gain and the gain is depleted as the pulse envelope passes
8 through the amplification rods. To achieve a flat macropulse of the UV light, the
9 macropulse of the seed light is controlled so that the front of the pulse envelope has less
10 energy than the end of the pulse envelope, thus compensating for this gain depletion. The
11 AOM is driven by a voltage controlled RF amplifier at a fixed frequency close to the
12 resonance frequency (41 MHz) of the crystal while the amplitude of the RF signal is
13 controlled by an arbitrary waveform generated on a computer. For the present stripping
14 experiment, the laser is operated at 10- μ s macropulse mode. Fig. 4(a) shows a typical
15 macropulse waveform of the UV beam with the peak power of ~ 2 MW. The
16 corresponding control voltage waveform on AOM is shown in Fig. 4(b).

17 Our custom-built macropulse amplifier has three stages. Each stage consists of a pair of
18 identical Nd:YAG rods with the diameters of 5-, 6-, and 9-mm for amplifier stages 1, 2,
19 and 3, respectively. Both the 5-mm and 6-mm amplifiers are single flash lamp pumped
20 with the first rod pumped from the top and the second rod pumped from the bottom. The
21 9-mm amplifiers are pumped by two flash lamps from sides. In each amplifier stage,
22 there are two compensation optics between the two rods: a negative lens for thermal
23 lensing compensation and a quartz rotator for thermal birefringence compensation. The
24 amplified IR macropulses are converted to the UV light using a 25 mm long LBO
25 doubler and a 30 mm long LBO tripler. More details of the amplifier can be found in the
26 previous paper [13]. The amplifier was designed to generate 1 MW (peak power) UV
27 pulses bunched in 10- μ s@10-Hz macropulses. We have implemented a number of
28 improvements in recent years. Maximum gains of the first two amplifier stages have been
29 achieved after proper optics realignment and insertion of an additional isolator between
30 5- and 6-mm rods. The image relay optics and spatial optical filters have been redesigned
31 to maximize the amplifier output power while maintaining high beam quality. The

1 improvements boosted the maximum peak power of the UV pulses to ~ 3.5 MW, more
2 than three times the design specification.

3 Figure 5 shows the IR micro-pulses measured using a high bandwidth photo-detector
4 (New Focus 1444). A typical micro-pulse waveform is shown in the inset box. The pulse
5 width varies from 55 to 85 ps and the temporal jitter is about 1 ps. Accurate information
6 of the UV pulse width is important in the optimization of pulse energy in the
7 amplification. We have developed a multifunctional optical correlator to measure the
8 pulse width of the UV beam without using any external reference pulse [14]. The
9 correlator measures both auto-correlation between IR pulses and cross-correlation
10 between IR and UV pulses using the same nonlinear optical crystal. We were able to
11 perform a detailed characterization of the UV beam at a variety of amplifier parameters.
12 Fig. 6 shows the measured UV pulse width as a function of the IR pulse width. We also
13 calculated the UV pulse peak power using the measured UV pulse width and UV
14 (average) power. While the UV pulse width is nearly proportional to the IR pulse width,
15 the peak power shows a nonlinear inverse dependence on the pulse width. This is because
16 the harmonic generation efficiency depends on the intensity of the incoming light. As a
17 result, when the seeder pulse width is narrowed from 84 to 54 ps, the UV pulse width
18 changes from 58 ps to 34 ps and the peak power of the UV light increases from 1.2 MW
19 to 3.1 MW.

20 The UV beam quality is mainly determined by the incoming beam size to the 9-mm
21 amplifier and the entire amplification factor (particularly the setting of the last amplifier).
22 To optimize the beam quality, we set up the 5- and 6-mm amplifiers at their maximum
23 voltages (~ 1.4 kV) while limiting the 9-mm amplifier to relatively low voltages (1.15 –
24 1.25 kV). Fig. 7(a) shows a near-field profile of the UV beam at ~ 2 MW and Fig. 7(b)
25 shows the far-field profile. The laser beam shows a TEM_{00} Gaussian mode in the far-field
26 and the M^2 factor is measured to be ~ 1.3 in both horizontal and vertical directions. The
27 M^2 factor increases when the peak power exceeds 3 MW.

29 **3. Optical Setup for Stripping Experiment**

30 *3.1 Laser transport line*

1 Operating lasers in a proton accelerator facility always faces concerns of radiation
2 induced damage. Although in the previous laser stripping experiment [9] the laser was
3 located in the linac beam dump area, the accelerator was operating with beam powers at
4 the kilowatt level at the time. As the SNS accelerator was ramping up the proton beam
5 power, the residual radiation levels grew rapidly. It was experimentally verified that the
6 laser system (mainly the electronics parts) did not survive more than a few hours even in
7 a relatively lower radiation area. Currently, SNS is routinely operating at the 1 MW
8 proton beam power level. At this power level, the radiation doses are several orders of
9 magnitude higher than before. In particular, radiation in the Ring injection area reaches
10 tens of kilo-Rads.

11 To protect the laser from radiation induced damage, we located the macropulse laser
12 system in the Ring Service Building (RSB) and built an LTL to deliver the laser beam to
13 the stripping chamber. The RSB is about 10 meters above the beam line and shielded
14 from the accelerator tunnel through a 20-meter thick concrete wall. The only available
15 penetrations between the RSB and tunnel are 6-inch penetration chases which were
16 originally designed as cable chases. A schematic of the LTL is shown in Fig. 8. It consists
17 of three parts: the first part transports the laser beam from the laser table to the entrance
18 of the penetration hole in the RSB, the second part is a 70-ft long cable chase, and the last
19 part relays the laser beam from the exit of the penetration chase to the stripping chamber
20 location in the Ring/HEBT tunnel areas. The entire LTL is enclosed in aluminum tubes
21 and the entrance/exit of the LTL are sealed with 4-inch vacuum viewport windows that
22 are AR-coated at 355 nm. The enclosure is important to eliminate air flow caused by
23 pressure/temperature difference between the RSB and accelerator tunnel.

24 Although the total length of the LTL is only about 60 meters, due to the existing
25 accelerator beam line, electronic and mechanical equipment, the available space for the
26 LTL is extremely limited and the resulting LTL has a very complicated path configuration
27 as shown in Fig. 8. A total of 8 mirrors have to be used to relay the beam in 8 different
28 planes. Table I lists the parameters of each relay mirror. Note that mirrors reflect light at
29 different angles varying from $\sim 6^\circ$ to $\sim 50^\circ$ are used due to the space limitation. All
30 mirrors are 3-inch dielectric mirrors with high-reflection (HR) coating at 355 nm over a

1 wide range of reflection angles ($5^\circ - 53^\circ$). In addition, most of mirrors are very difficult
2 to access due to radiation/electrical concerns. Therefore, all relay mirror mounts except
3 the first two are equipped with a pair of pico-motor driven actuators for remote beam
4 steering and a compact analog camera for beam position monitor. Two examples of the
5 mirror box implementation are shown Fig. 9.

6 Many conventional laser transport lines employ the image relay approach where beam is
7 focused and collimated between two relay mirrors. This approach turns out to be
8 impractical in the present environment due to the limitation of space for lens mount, lack
9 of control and accessibility. Instead, we chose an approach of propagating a collimated
10 laser beam through the entire LTL without image relay. A series of LTL simulations were
11 carried out on the optical table in the laser lab by using multiple reflections on 8 mirrors
12 to make up a path length close to 60 meters. Using LTL simulations, we compared
13 different telescope settings for beam collimation and studied the transmission efficiency
14 and final beam quality for each case. The optimal transmission performance is obtained
15 when the laser beam is focused close to the final destination. In this case, the laser beam
16 is collimated to have beam diameters of about 10-12 mm ($1/e^2$) along the LTL. The
17 transmission efficiency was estimated to be around 75%. Major beam losses come from
18 the absorption/scattering on the mirror surfaces and loss of high-order modes of the laser
19 beam during the propagation through the LTL.

20 *3.2 Stripping experiment optics*

21 The laser stripping experiment is carried out at ~ 20 meters upstream of the SNS ring
22 injection area. As described in the previous section, successful stripping requires a
23 narrow parameter range in laser beam size, divergence angle, and interaction angle
24 between the laser and ion beams. In addition, to avoid possible optical breakdown on the
25 vacuum windows, the minimum beam sizes on the entrance and exit vacuum windows
26 have to be limited. Fig. 10 shows a schematic of the optical setup around the stripping
27 chamber. The telescope consists of a lens pair ($f_1 = -100$ mm and $f_2 = 200$ mm) and the
28 spacing between the two lenses is controlled by a stepper motor. The location and
29 spacing of the telescope controls the beam size and divergence angle at the interaction
30 point. Limit switches are implemented at each end of the motor to restrict the beam sizes

1 on the vacuum windows. The interaction angle is controlled by a steering mirror and a
2 second stepper motor. The entrance and exit windows are located at ~ 40 inches from the
3 focused point of the laser beam by using extension tubes. Laser beam positions are
4 monitored before and after the stripping chamber using two Gigabit Ethernet cameras
5 (Cam1 and Cam2 in Fig. 10). The laser power is monitored also by an Ethernet accessed
6 power meter.

7 Table II summarizes the major laser parameters measured before the stripping experiment.
8 The laser beam is interacting with a 1 GeV H- beam at 37.5° . At the interaction point, the
9 designed laser beam has a full-width half-maximum (FWHM) beam divergence angle of
10 1.2 mrad and a FWHM beam size of 0.5 mm. The transmission efficiency was measured
11 to be near 70% which is close to our lab simulations.

12 *3.3 Laser operation and control*

13 Like many other experiments in the accelerator facilities, laser stripping experiments are
14 conducted in the central control room, which requires high level of automation and
15 remote access/manipulation of laser and optical parameters. Table III lists major
16 electronic chassis and computers used in the operation. Most controls are realized in the
17 extensible display manager (EDM) screen during the laser stripping experiment.

18 The customized macropulse laser amplifier has a sophisticated graphic user interface
19 (GUI) software that allows the users to operate the laser through a computer. Using the
20 accelerator network, one can remotely turn on/off the laser operation, change amplifier
21 settings, switch between different macropulse modes, and monitor the status of amplifiers
22 and optical crystals. The laser power is also remotely controlled using a motor driven
23 rotational stage to control an optical wave plate. There are two levels of temporal
24 synchronization. The micro pulses generated in the seed laser are synchronized to the
25 402.5 MHz RF timing of the SNS accelerator. The phase difference can be remotely
26 tuned using a computer controlled digital phase shifter with a precision of 0.1 degree
27 (corresponding to ~ 0.7 ps). The laser macropulse is timed to the accelerator according to
28 a beam position monitor near the stripping chamber and its phase is also computer
29 controlled to nanosecond accuracy.

Beam steering in the LTL is implemented using 7 pairs of pico-motor actuators. The Thorlabs open-loop actuators have a very high radiation tolerance and are controlled by a single computer. The same computer also controls two stepper motors in front of the stripping chamber (Fig. 10) to change the laser beam size/divergence angle at the interaction point.

Laser beam positions along the LTL are monitored using Watec analog cameras toward the surface of the mirror. The tiny cameras were chosen since they have reasonably high radiation tolerance, and are easy to install in a limited space. All images are displayed on a monitor next to the laser table to facilitate the alignment. The laser beam positions right before and after the stripping chamber are monitored by two CMOS cameras (Allied Vision GC 750). Both cameras are synchronized to the 10 Hz macropulse timing and the captured images are sent back to the computer through Ethernet network. The images are then analyzed to extract the centroid position which is used to feedback control the piezo-transducer (PZT) mirror mounted right before the LTL on the laser table. The feedback control is very effective in the reduction of slow (<1 Hz) drifts of the laser beam through the LTL [15].

Finally, the laser power after the stripping chamber is measured by a power meter. The measured power determines the actual laser pulse energy in the stripping chamber by taking into account the losses in vacuum windows.

4. Discussions

The present laser stripping experiment has been successfully conducted using a 10-us laser macropulse. A stripping over 10 mini-pulses of the H⁻ beam has been observed with the maximum stripping efficiency close to 99%. Details of experimental results are reported in [16]. Here we briefly discuss the scalability of the present laser stripping scheme to a full-cycle H⁻ beam, e.g. 1-ms@60-Hz in the case of SNS neutron production operation.

It is clear that the flash lamp pumping scheme in the present laser amplifier is the major limiting factor of the macropulse structure. Typical flash lamps limit the repetition rate to 30 Hz and the pulse duration to ~ 200 μ s. The flash lamp limitation can be resolved by

1 using a diode pump scheme. A commercially available 3-stage diode-pumped solid-state
2 laser amplifier can generate multi-millisecond macro pulses [17]. A less obvious limiting
3 factor, however, is the strong dependence of the achievable UV light power on the
4 macropulse duration. In our experiment, we observed that the achievable peak power of
5 the IR pulses rapidly dropped below 1 MW when the macropulse duration was increased
6 beyond a few tens of microseconds. In this case, the peak power of the UV pulses after
7 harmonic conversion is at the 10 kW level, which is two orders of magnitude lower than
8 the required power for laser stripping.

9 On the other hand, since the cross-section number in the photon-particle interaction in the
10 laser stripping process is extremely small, the power loss of the laser light is negligible.
11 The laser power can be recycled if the laser stripping is located in an optical cavity.
12 External optical cavities have been routinely applied to recycle the power from single-
13 frequency lasers or mode-locked lasers which have pico-/femto-second pulses repeating
14 at tens of MHz to GHz. However, for a burst-mode laser, due to a very small duty factor
15 and low repetition rate of the burst, it is impossible to generate an effective error signal
16 within the short duration of the burst. In such a case, the conventional cavity locking
17 technique will fail and a different cavity locking method is demanded. At SNS, we
18 proposed a double-resonance optical cavity (DROC) scheme and developed a robust
19 locking scheme to realize cavity enhancement of burst mode laser pulses. In the prototype
20 experiment, we have shown how a Fabry-Perot based DROC can be simultaneously
21 locked to an infrared (IR) and its third-harmonic ultraviolet picosecond pulses using a
22 frequency shift technique. We have experimentally demonstrated that such a cavity can
23 be applied to enhance burst-mode UV laser pulses with arbitrary burst lengths and
24 repetition rates [18]. The cavity enhancement of UV macropulses was achieved with an
25 enhancement factor of 50. By using diode-pumped solid state amplifier and optical cavity
26 enhancement technology, it is promising to scale the present laser parameters to fulfill the
27 requirement of the full-cycle stripping experiment.

28 29 **5. Conclusion**

1 We have described the design and commissioning of a macropulse laser system and its
2 transport line for the laser assisted H⁻ beam stripping experiment conducted at the proton
3 accelerator of the Spallation Neutron Source. The macropulse laser has a MOPA
4 configuration and consists of a mode-locked picosecond pulsed seed laser and a burst-
5 mode Nd:YAG laser amplifier. We have achieved UV pulses with the pulse widths
6 varying between 34 to 54 ps and a maximum peak power over 3.5 MW. A laser transport
7 line is installed to deliver the UV beam to the laser stripping chamber. The LTL has
8 capabilities such as a remote control and monitor of laser parameters including phase
9 delay, beam power, beam size, beam divergence, and interactions angle. A transmission
10 efficiency of 70% has been achieved. A successful stripping with > 90% efficiency has
11 been demonstrated over a 10 μ s macropulse by using the developed laser and optical
12 system [16]. We have also discussed the scalability of the present experiment to the
13 parameters required for the full-cycle laser stripping.

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Figure captions

Figure 1 Stripping efficiency as a function of (a) laser peak power and (b) laser beam size and divergence angle.

Figure 2 Schematic of macropulse laser system. EOM: electro-optic modulator, AOM: acousto-optic modulator, PZT: piezo-electric transducer, $\lambda/2$: half-wave plate, SPF: single-mode polarization-maintaining fiber, SF: spatial filter, SHG: second-harmonic crystal, THG: third-harmonic crystal.

Figure 3 Seed laser parameter investigation results. (a) Pulse width vs. EOM bias voltage; (b) Pulse width vs. phase control voltage of mode-lock loop. ‘U’ indicates parameter regions where stable mode-lock cannot be obtained.

Figure 4 (a) 10- μ s macropulse waveform. (b) Control waveform on AOM.

Figure 5 A typical IR micro pulse waveform detected by a fast photodiode. The inset box shows zoom-in pulse shape of a micro pulse.

Figure 6 UV pulse width and peak power vs. IR pulse width measured by the multi-functional optical correlator.

Figure 7 Spatial profiles of UV beam. (a) Near-field and (b) far-field patterns.

Figure 8 Schematic of LTL. (a) LTL in the RSB is linked to (b) LTL in the Ring through a 20-meter long chase indicated by A - A' in the figure. M1 – M8 are mirrors for relay.

Figure 9 Examples of optics boxes in the laser transport line.

Figure 10 Optical setup around the laser stripping chamber in the accelerator tunnel.

Table I LTL Components

Mirror	Description	Reflection angle	Propagation length (cm)
Mirror #1	LTL Box #1 (RSB) No camera, No picomotor	52°	110
Mirror #2	LTL Box #2 (RSB) No camera, No picomotor	45°	527
Mirror #3	LTL Box #3 (RSB) Pico-motors (2), camera	45°	122
Mirror #4	LTL Box #4 (RSB) Pico-motors (2), camera	35°	2339
Mirror #5	LTL Box #5 (Ring tunnel) Pico-motors (2), camera	5.6°	50
Mirror #6	LTL Box #5 (Ring tunnel) Pico-motors (2), camera	16.9°	311
Mirror #7	LTL Box #6 (Ring tunnel) Pico-motors (2), camera	50.3°	135
Mirror #8	LTL Box #7 (Ring tunnel) Pico-motors (2), camera	45°	2439

Table II Parameters of Stripping Laser

	Required	Delivered
Macro-pulse length	10 μ s	12 μ s
Micro-pulse width	> 30 ps	30 – 50 ps (adjustable)
Peak power	1.5 MW	4.0 MW (at pulse width 35 ps)
LTL transmission efficiency	> 60%	70%
Maximum power at IP	> 1 MW	2 MW @ 33 ps
Horizontal beam divergence (4σ) at IP	1.6 – 2.6 mrad	2.3 – 3.0 mrad
Vertical beam size (4σ) at IP	1.0 – 1.4 mm	1.1 mm
Pointing stability at the IP		± 0.10 mm (H) x ± 0.11 mm (V)
Maximum peak laser intensity on entrance vacuum window	≤ 100 MW/cm ²	57.9 MW/cm ² *
Maximum peak laser intensity on exit vacuum window	≤ 100 MW/cm ²	78.6 MW/cm ² *

*These values were measured on 1 MW peak laser power. At the end of the experiment, the laser power was raised to 2 MW. No laser induced breakdown was observed over 8 hours of influence.

1 **Table III Control electronics**

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Control Unit	Description
IOC 1	Laser control (remote on/off, amplifier voltage setting)
IOC 2	Laser power control 6 steering mirrors Interaction angle control Laser beam divergence angle control Laser beam size control Horizontal position control
IOC 3	Laser beam pointing stability feedback control using PZT driven mirror
IOC 4	Laser beam position sensing using GigE cameras
IOC 5	Laser power monitor after the stripping chamber

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Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

Figure 10

Figure

Figure 1

Figure 2

Figure 3

(a)

(b)

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

Figure 10