LASER APPLICATIONS: H^- BEAM PHOTO-DETACHMENT AND "PUSH BUTTON" DIAGNOSTICS

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Abstract

The laser based nonintrusive H^- beam diagnostics and laser assisted H^- beam stripping technologies have been developed at the Spallation Neutron Source (SNS). This paper reviews the present status of the SNS laser based diagnostics and the recent R&D progress on the fiber transmission of laser pulses and power enhancement optical cavity which are intended to be used in diagnostics and laser stripping.

INTRODUCTION

The Spallation Neutron Source (SNS) has made major effort on the laser based nonintrusive diagnostics and laser stripping since the design phase of the accelerator. Figure 1 shows an outline of the laser application systems implemented in the SNS accelerator complex. At the superconducting linac (SCL), multiple laser wire stations measure horizontal and vertical profiles of the H^- beam [1,2]. At the high energy beam transport (HEBT) line, a laser transverse emittance scanner has been installed which allows measuring the phase space of the 1 GeV, 1 MW H^- beam right before the accumulation ring [3]. At the medium energy beam transport (MEBT) line, a laser based longitudinal profile monitor has been designed [4]. Finally, a laser assisted H^- beam stripping experiment is being prepared at the ring [5].

In this paper, we will give a general review of the above laser applications at SNS. We will first report the present status of the operational laser based diagnostics including the SCL profile monitor system and the HEBT emittance measurement system. We will then describe the recent progress on the experiments of fiber transmission line and dual wavelength power recycling optical cavity.

LASER WIRE BASED TRANSVERSE PROFILE/EMITTANCE MONITOR

System Configuration

The SNS laser wire system consists of 9 SCL profile monitors and a HEBT emittance scanner. Figure 2(a) shows a layout of the system. The 9 profile monitors cover from the beginning to the end of the SCL. A schematic illustration of the laser wire measurement station is shown in Fig. 2(b). When the H^- beam interacts with the laser light, a small portion of the ions illuminated by the laser pulse are ionized to H^0 and the liberated electrons are separated from the ion beam by a bending magnet and collected by an electron detector installed next to the interaction chamber. The measurement of the resulting electron density leads to the determination of the negative ion density. By scanning the incident laser beam in horizontal or vertical directions, profiles of the ion beam along the correspondent axis can be obtained.

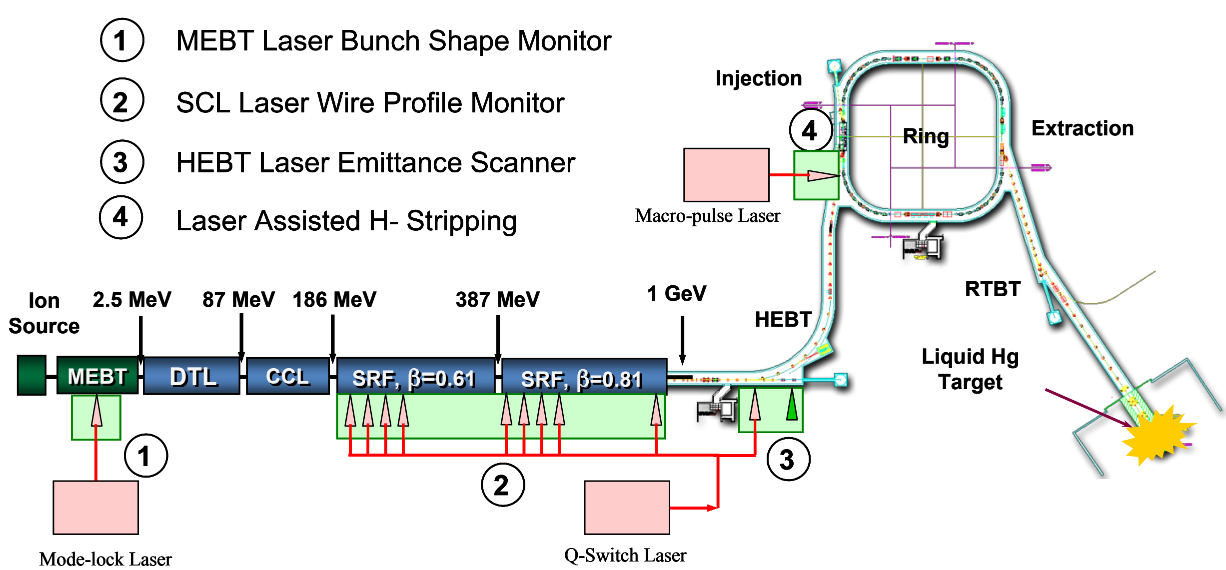

Figure 1: Layout of laser based beam instrumentation systems at the Spallation Neutron Source.

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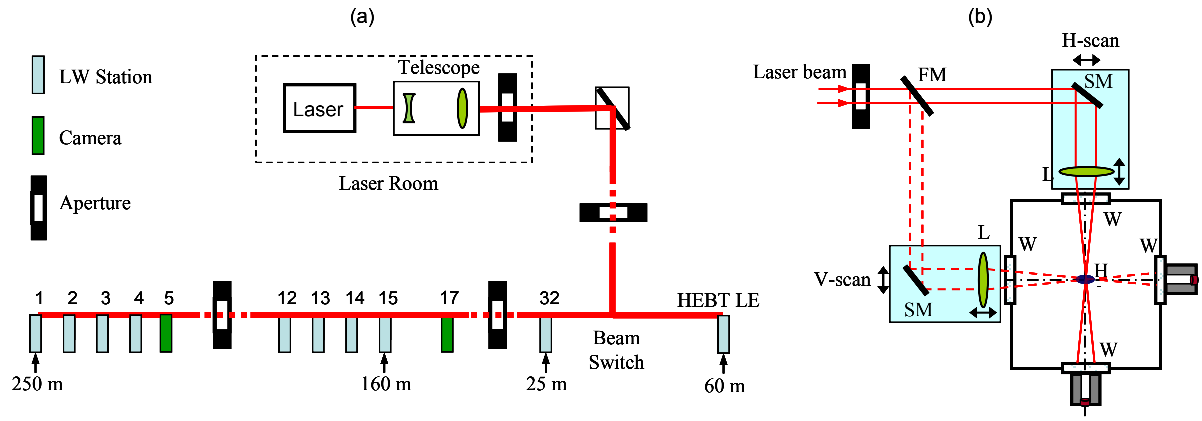

Figure 2: (a) Layout of SCL laser wire and HEBT laser emittance measurement systems. (b) Optics setup of individual laser wire scan station. Numbers indicate cryomodules and distances are from the laser room. LE: laser emittance; FM: flipper mirror; M: mirror; SM: scan mirror; L: lens; W: vacuum window.

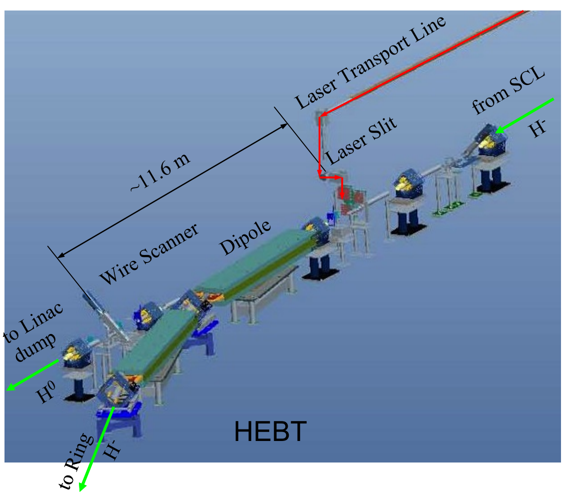

Figure 3: HEBT laser emittance monitor system.

The HEBT emittance monitor is an extension of the laser wire system in terms of the laser beam transport line. The emittance measurement setup is located about 40 meters away from the beginning of the HEBT beamline. As shown in Fig. 3, the setup consists of two parts: a laser wire scanner (laser slit) and a conventional metallic wire scanner. The laser wire scanner is installed right before the first of eight 11.25° C-type dipoles which turn the H^- beam to the accumulator ring. These dipoles also separate the neutralized hydrogen beam (H^0) created by the laser from the main beam trajectory and direct the H^0 beam to the linac dump beam line. A metallic wire scanner is installed in the linac dump beam line, about 11.6 meters downstream of the laser wire station. The wire scanner measures the distribution of the H^0 beam released from the laser slit. Since the laser wire only interacts with a very tiny portion ($\sim 10^{-7}$) of the ion beam and the wire scanner is interacting with an off-line H^0 beam, the entire measurement is effectively nonintrusive and can be conducted parasitically during neutron production.

All of the 9 SCL profile monitors as well as the HEBT emittance monitor are using a single Q-switched Nd:YAG laser as the light source. This laser is capable of producing a maximum pulse energy of 1.5 J with a 7 ns pulse width and a 30 Hz pulse rate. The high peak power is needed to achieve a sufficient signal-to-noise ratio. The laser is located outside the linac tunnel to avoid radiation damage and the laser beam is delivered to each profile monitor through an enclosed laser transport line (LTL). Since the light propagation distance is as much as 250 meters and the laser and LTL are at different building foundations, even a small drift can cause the laser beam to miss the downstream optics. One of the most challenging issues in the implementation of a stable profile scan is the stabilization of the laser beam. We have developed an active feedback control algorithm by steering the laser beam with a PZT driven mirror. By using the feedback, the achieved mirror stability at low frequencies is better than 5 μrad, which corresponds to only ±1.25 mm at the furthest measurement station [6].

Status of SCL Laser Wire System

The SCL laser wire system was the most sophisticated laser based diagnostics developed at SNS and has been brought to operational use since 2010. The profile measurement has been actively used for emittance evaluation and SCL modelling study. Recent progress includes the multi-station parallel scan and software platform improvement. After a series of experimental tests, profile scans at all 9 SCL laser wire stations can now be simultaneously conducted. To realize this parallel scan, not only was the laser transport line appropriately modified so that each measurement station obtains a roughly equal portion of the laser power from the single light source, the phase delay between the laser pulse and the ion beam pulse was also carefully designed to ensure the short laser pulse (~ 7 ns) encounters the pulsed ion beam at each laser wire station. The parallel scan made it possible to obtain all 18 profiles from the 9 locations of

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the SCL within as short as 5 minutes, which is very useful for beam physics study at SCL.

Laser Wire Transfer Line

Label	Description	Retract	mm	Insert	Command		
LW_01	Station 01		-0.037		Rtn Lim	Set Pt	Ins Lim
LW_02	Station 02		0.042		Rtn Lim	Set Pt	Ins Lim
LW_03	Station 03		-0.058		Rtn Lim	Set Pt	Ins Lim
LW_04	Station 04		0.138		Rtn Lim	Set Pt	Ins Lim
LW_12	Station 12		-0.016		Rtn Lim	Set Pt	Ins Lim
LW_13	Station 13		0.069		Rtn Lim	Set Pt	Ins Lim
LW_14	Station 14		-0.021		Rtn Lim	Set Pt	Ins Lim
LW_15	Station 15		-0.016		Rtn Lim	Set Pt	Ins Lim
LW_32	Station 32		0.021		Rtn Lim	Set Pt	Ins Lim
LW_EMIT	Beam Block		0.000		Rtn Lim	Set Pt	Ins Lim

Figure 4: EDM screen of laser wire system.

The laser wire software was originally composed on the Labview platform. To facilitate its operational use, the laser wire user interface was changed to EDM screen for EPICS from 2011 and was therefore integrated into the standard platform of the SNS beam instruments. Figure 4 shows an EDM operator screen of the laser wire (including the HEBT laser emittance) system. From this screen, the user can pick one, multiple, or all 9 laser wire profile monitors at the same time. Although theoretically the laser emittance measurement can be included as one station of the parallel scan, currently we run laser wire and laser emittance measurements separately. Figure 5 shows typical EDM screens of 4 profile measurements that were conducted in parallel on a 1MW neutron production H^- beam.

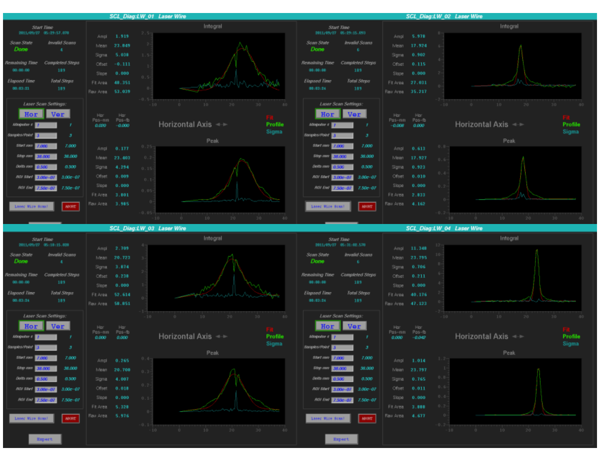

Figure 5: An example of multi-station parallel scan of laser wire measurement.

Status of HEBT Laser Emittance System

The HEBT emittance measurement system was installed during the winter shutdown of 2010 - 2011. During the summer shutdown of 2011, a number of modifications were made to the system. The single wire was replaced by a flat bundle of 10 identical wires to increase the number of detached electrons from the wire scanner. The hardware update has improved the signal-to-noise ratio by an order of magnitude. In addition, the data analysis software has been optimized to improve the measurement speed, accuracy, and dynamic range.

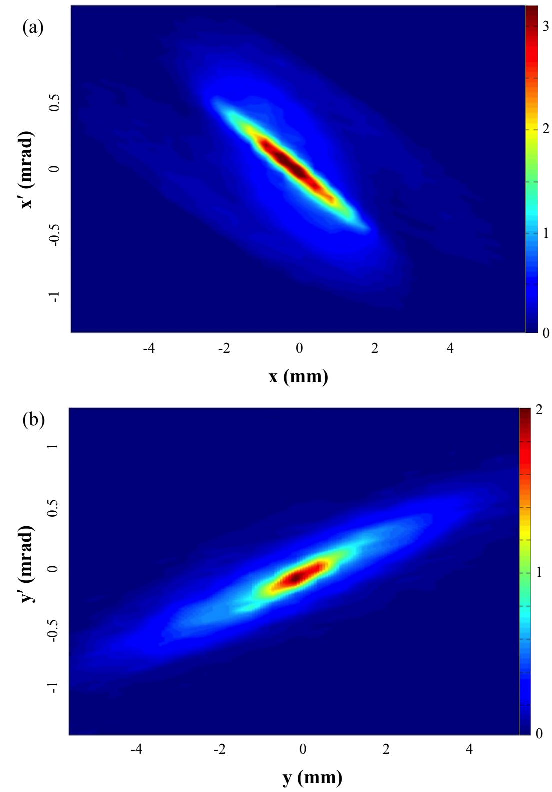

Figure 6: An example of emittance measurement.

A typical emittance measurement result is shown in Fig. 6. The updated measurement reveals fine structure in the phase space density, which would have been impossible to see with the previous system. The measured emittance of 0.46 mm·mrad is close to the design value. We have performed a self-consistency check by integrating the output of the emittance measurement over the angle and comparing it with the beam profile measured directly from the laser wire. The two results agree with each other at a high accuracy. The angle resolution of the measurement is better than 0.1 mrad. The measurement time consists of the motion of the stepper motor and the data analysis. Currently we measured the speed of the motor to be about 0.5 sec/step while the data analysis takes about 35 msec/sample. The measurement time for Fig. 6 was about 10 minutes for each axis, which is comparable to that of the conventional emittance measurement instruments.

R&D for Laser Applications

Fiber Transmission of Picosecond Laser Pulses

Short pulsed laser beam was proposed to measure the longitudinal H^- beam profile at the MEBT of SNS accelerator [4]. In the same way that the transverse profile is obtained by scanning the laser beam across the ion

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beam, the longitudinal bunch shape of the ion beam can be reproduced by scanning the laser phase with respect to the linac timing. A preliminary experiment was demonstrated by using 2.5 ps 80.5 MHz laser pulses from a mode-locked Ti:Sapphire laser. The experiment suffered from heavy laser beam instability due to mechanical vibration and temperature drift in the free space beam transport line. Using fiber-optic delivery of the laser beam offers several advantages over conventional free-space beam delivery system. First, the laser beam position at the measurement site is not affected by mechanical vibration or temperature drift along the transmission line. This is of importance when sub-millimeter measurement accuracy is required. Next, alignment is greatly simplified because the fiber output can be made as a single, portable unit and beam can be delivered along a complex path. This also avoids the access of the transmission line during operation, which is often prohibited in many applications. Last, a fiber-optic delivery system completely eliminates the exposure of high power light beam in the transmission line.

We have conducted experimental investigations on the transmission of picosecond laser pulses through a large mode area (LMA) polarization maintaining fiber [7]. Figure 7 shows a schematic of the experimental setup. The laser pulses have 80.5 MHz repetition rate and kilo-watts peak power which are suitable for longitudinal profile measurement of the H^- beam at SNS. The launching condition, coupling and transmission efficiency, output beam quality, pulse width broadening and timing jitter of the picosecond laser pulses propagating through a 30 m optical fiber are investigated.

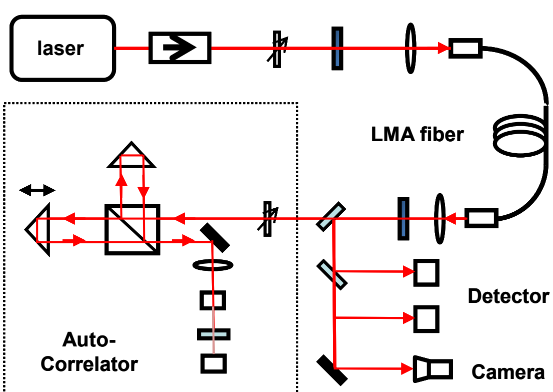

Figure 7: Experiemntal setup and pulse width broadening measurement results of the pulse tranmission through a LMA opticla fiber.

The fiber output beam quality strongly depends on the launching condition. We found that the incidence beam with ~30 µm diameter and ~50 mrad divergence angle generated an ideal single-mode guidance, providing a nearly diffraction-limited output beam with M^2 = 1.23 (1.03) along (perpendicular to) the fiber polarization direction. Over 85% of the overall transmission efficiency through a 30 m fiber has been achieved for a broad range of incident peak power levels of up to 3 kW. The pulse width of the fiber output was measured with a home-made autocorrelator using a type-II second harmonic generation crystal. The dependence of the pulse width on the laser power agrees well with the numerical result of the theoretical modeling. At over 500 mW transmitted power, the fiber output beam has a pulse width of about 11.6 ps and a beam diameter of less than 400 µm at a working distance of 600 mm, which fulfills the requirement for future measurement. The timing jitter after fiber transmission is insignificant. The fiber transmission system has been implemented at SNS.

Power Enhancement Optical Cavity

The SNS accelerator complex utilizes charge-exchange injection to "stack" a high-intensity proton beam in the accumulator ring for short-pulse neutron production. A laser-assisted "foil-less" charge exchange injection method was proposed by Danilov et al. [8] using a three-step scheme. This scheme works as follows: First, H^- ions are converted to H^0 by stripping off the first electron in a magnetic field; then H^0 atoms are excited from the ground state (n = 1) to the upper levels (n ≥ 3) by a laser, and the excited states H^{0*} are converted to H^+ by stripping the second electron in a second magnetic field.

In a proof-of-principle experiment [5], a third harmonic beam from a Q-switched laser was used for stripping. The stripping efficiency reached 90% using a 30 Hz, 6 ns pulsed laser beam with a peak power of ~1 MW at 355 nm. A simple multiplication of the above peak power and the duty factor of the SNS beam (6%) yields an average laser power of tens of KW at 355 nm to strip the entire H^- beam. Similar numbers are obtained for other proton ring facilities. Obviously, this average power requirement is too large to make the device practical. In recent years, an optical R&D effort has been made to overcome the above laser power challenge [9].

In general, the photon-hydrogen interaction results in a negligible loss to the photon number due to the tiny cross sections. It is therefore expected that the average laser power requirement can be significantly reduced by recycling the laser beam with a power build-up optical cavity and allocating the laser-particle beam interaction inside the cavity. Optical cavity technology has been well developed for low-power, infrared, and often for continuous laser beams. However, in our case, the cavity needs to work on high intensity picosecond UV pulses operating at a macropulse mode with a very small duty factor, which imposes a technical challenge on the cavity stabilization and operation.

A ring cavity has been designed to recycle the pulsed UV beam. The cavity consists of two flat mirrors and two concave mirrors [9,10]. Figure 8 shows a schematic of the cavity setup. Since the UV output from the macropulse laser has only a 10 µs pulse duration at a repetition rate of 10 Hz, it is difficult to generate an effective error signal and to stabilize the cavity with PZT. Instead, we use the auxiliary IR beam extracted directly from the seed laser to lock the optical cavity. The IR beam reflection from the

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coupler shows sharp intensity drops when the cavity is resonant with the input light. The error signal is generated using the Pound-Drever-Hall (PDH) scheme by phase modulating the input IR light at 20 MHz.

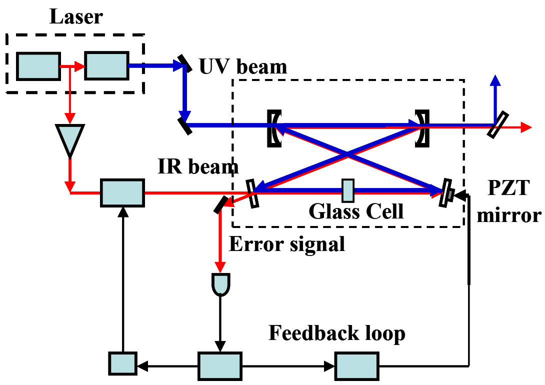

Figure 8: Schematic of the dual wavelength power recycling optical cavity.

While the cavity locking was readily achieved with the PDH stabilization scheme, the mode hopping of the seed laser can easily trigger a locking failure. We implemented the re-search and re-lock functions of the servo controller by using the cavity transmission signal as a reference. Another challenge is the phase shift between the resonance of UV and IR beams that is caused by the optical path difference of UV and IR beams such as through the coating film and the air dispersion (if not in vacuum). A piece of optical glass with adjustable thickness was installed inside the cavity to match the phases between the two wavelengths. By controlling the temperature of the glass, we have properly matched the optical paths between the two beams and successfully achieved cavity lock to both wavelengths. The enhancement factors of up to 100 can be achieved. Currently we are working on the improvement of coupling efficiency.

CONCLUSION

Laser based nonintrusive beam profile and emittance measurement have attracted increasing attention since they have little risk of causing equipment damage and can be conducted at operational particle beam parameters, i.e., particle beams with high beam current, long pulse duration and/or high repetition rates. Owing to a decade long research and development, SNS has acquired significant infrastructure and expertise on laser based beam instrumentation. We have implemented the world-first large scale, operational laser wire system. Profile and emittance measurements have been conducted on 1 MW, neutron production beam. Laser based longitudinal profile monitor is being developed at SNS MEBT using optical fiber transmission. Macropulse laser system and power enhancement optical cavity have been actively developed for the next-stage laser assisted H^- beam stripping experiment.

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