LASER BASED DIAGNOSTICS FOR MEASURING H^- BEAM PARAMETERS

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Abstract

In recent years, a number of laser based H^- beam diagnostics systems have been developed in the Spallation Neutron Source (SNS). This talk reviews three types of laser based diagnostics at SNS: the laser wire profile monitors at superconducting linac (SCL), the laser transverse emittance scanner at high energy beam transport (HEBT), and the laser bunch shape monitor at medium energy beam transport (MEBT). Measurement performance will be reported and major technical challenges in the design, implementation, and operation of laser based diagnostics at accelerator facilities will be addressed.

INTRODUCTION

Measurement of beam profile and emittance is important for beam matching and control of beam loss and residual activation in high-brightness particle accelerators. Recently, nonintrusive profile measurement instruments such as laser based profile monitors have attracted increasing attention since they have almost no 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.

At the Spallation Neutron Source (SNS), three types of laser based diagnostics have been actively studied. Figure 1 shows the layout of the system. At the superconducting linac (SCL), we have commissioned 9 laser wire stations to measure horizontal and vertical profiles of the H^- beam along a 230-m acceleration line. At the high energy beam transport (HEBT) line, a laser transverse emittance scanner has been installed which allows measuring phase space of 1 GeV, 1 MW H^- beam right before the accumulation ring [1-3]. At the medium energy beam transport (MEBT) line, a laser bunch shape monitor has been tested and the designed setup is under construction.

In this paper, we will describe the system configuration of the above laser based H^- beam diagnostics systems. Particular attention will be given to the laser optics requirement, measurement performance, and key technical issues in the design and operation of laser based diagnostics at accelerator facilities

PRINCIPLE OF LASER BASED H^- BEAM DIAGNOSTICS

The mechanism of the laser based H^- beam diagnostics is rooted in the physics of photo-ionization. When the H^- beam interacts with photons at sufficient energy, a certain number (typically up to a few percent) of the ions illuminated by the laser pulse are ionized and the detached electrons are separated from the ion beam by a bending magnet or an electrostatic deflector and collected by an electron detector (typically a Faraday cup) 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, profiles of the ion beam along the scan direction will be obtained.

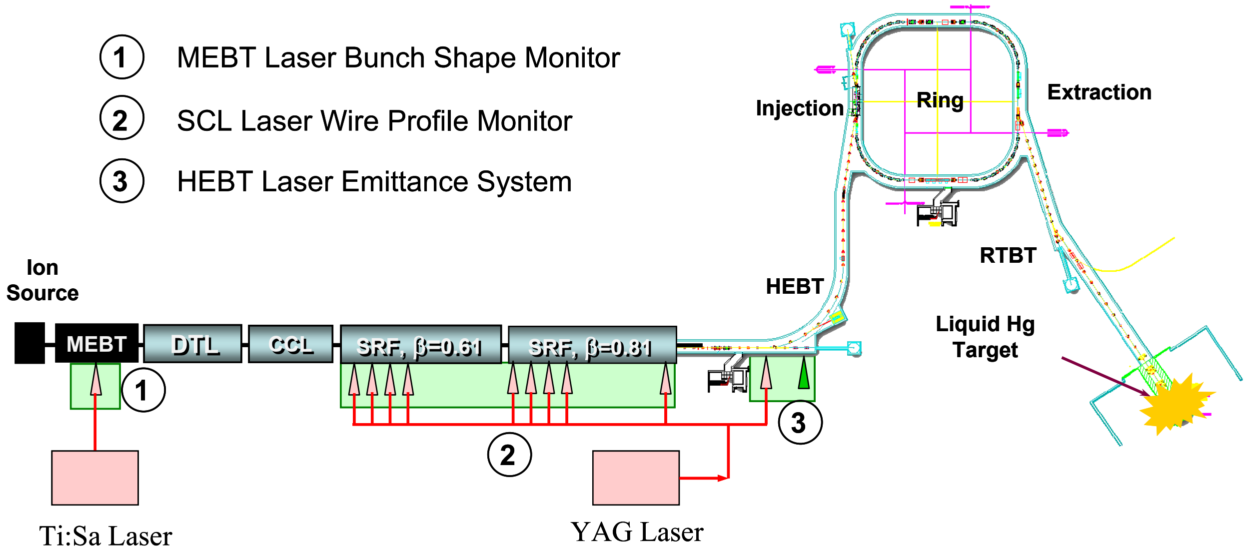

Figure 1: Layout of laser based H^- beam diagnostics systems at the Spallation Neutron Source.

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SCL LASER WIRE PROFILE MONITOR

System Configuration

The SNS SCL consists of 23 cryomodules with each cryomodule housing 3 or 4 superconducting cavities to accelerate the H$^-$ beam. The 230-meter long SCL is the longest section of the SNS accelerator complex and accelerates the H$^-$ from 200 MeV to 1 GeV. To track the H$^-$ beam profiles along the SCL, the SCL beam line was designed to have a laser profile monitor after each cryomodule. Currently, a total of 9 profile monitors have been commissioned with the first 4 stations located after each of the first 4 cryomodules, the next 4 stations after cryomodules 12 through 15, and the last station at the end of the SCL. The light source is located outside the linac tunnel and the laser beam is delivered to each profile monitor through an enclosed laser transport line (LTL).

The optics setup of the measurement station is shown in Fig. 2. The laser beam enters a vacuum chamber through a vacuum window (laser port) and intercepts the ion beam near its focused point. The focusing lens has a focal length of 200 mm and is placed as close as possible to the vacuum windows so that the laser beam size remains large when it passes through a vacuum window, which reduces the chance of laser-induced damage on the window. The focused laser beam can also increase the spatial resolution of the measurement and minimizes the effect of unwanted reflections. After the interaction, the laser beam passes through the back window of the vacuum and hits the beam dump. A photodiode is installed at the center of the beam dump to receive a small portion of the laser beam to provide an indication signal of laser beam presence. For the ion beam profile scan, the laser beam is translated across the ion beam. This is accomplished by translating the final steering mirror. The key point is that both the steering mirror and lens are mounted and translated together. This design maintains the relationship between the lens and the incident beam throughout the profile scan.

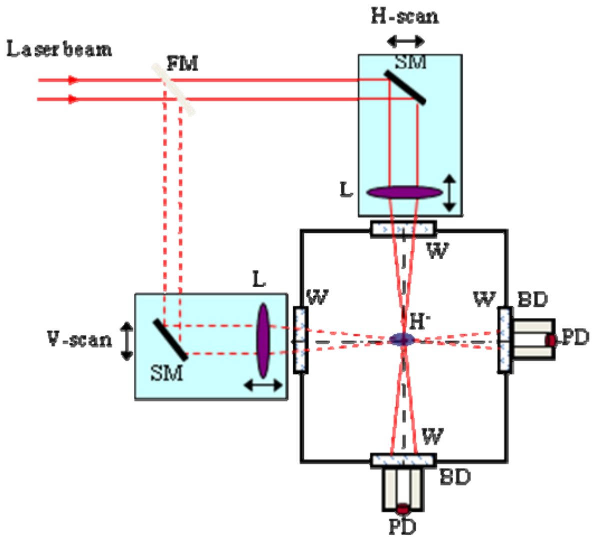

Figure 2: Optics setup of the laser wire measurement station. LTL: laser transport line, M: mirror, L: lens, FM: flipper mirror, W: vacuum window, BD: beam dump, PD: photodiode.

Profile Measurement Performance

The profile of the H$^-$ beam in the SCL has been measured at all 9 stations (serially). The measurement was conducted on a 60-Hz, neutron production beam with an average power of 1 MW. Figure 3 summarizes the measured horizontal and vertical profiles along the SCL during a neutron production period with a beam power over 1 MW. The marks in the graph are the measurement data while the lines represent the Gaussian fitting curves. Profile parameters, e.g., beam size, beam center position,

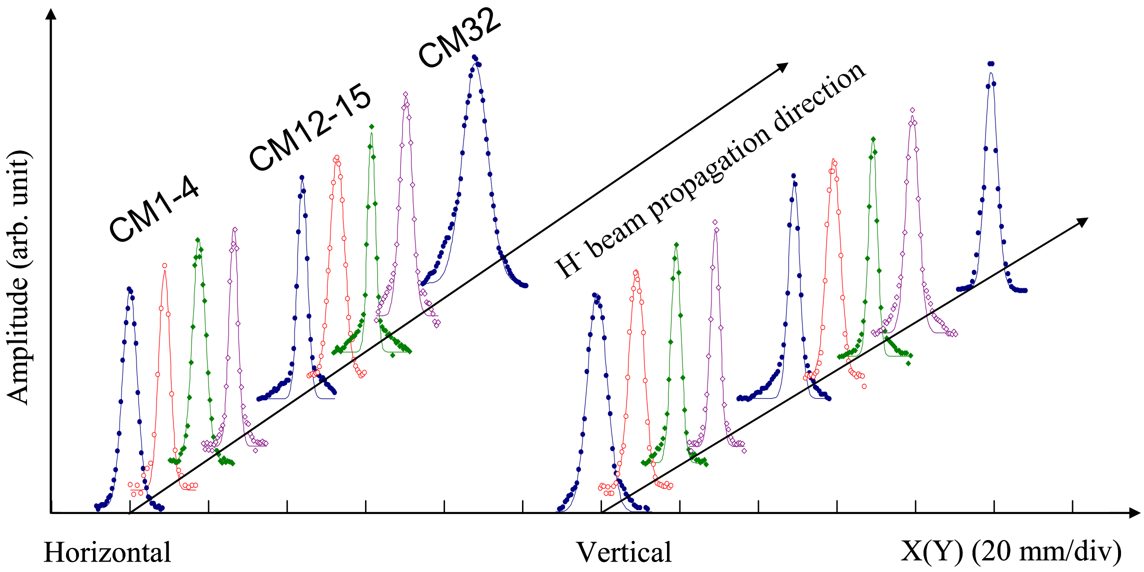

Figure 3: Profiles of H$^-$ beam along the SCL measured during 2010. Marks are measured data and solid lines are Gaussian fitting curves. CM: cryomodule in the SCL. The measurement was conducted on full power (1 MW) neutron production beam.

and the amplitude, are estimated from the Gaussian fitting curve. Our measurement shows that the beam size before exiting the SCL is less than half of that at the entry of the SCL, while showing large variations during the acceleration path. The measured beam parameters have been applied to transverse beam matching in SCL [4]. Work on the SCL model development by utilizing the laser wire measurement results is ongoing. The SCL laser wire system is currently in operational use. Further improvements include simultaneous scan of profiles at multiple stations to increase the yield.

The profile measurement performance has been investigated against laser and ion beam parameters. The measured profile shape, beam size, and beam center position show very little variation versus the change of the laser power, spatial beam jitter, and the ion beam position. The results demonstrate that the reliable measurement has been achieved with the implemented laser profile monitor system [2]. We estimated the measurement sensitivity to be about 0.03 pC which corresponds to about 10^{-4} of the total charge of a ~ 38 mA H^- beam within a 10 ns time period. The dynamic range of the measurement was measured to be about 300 but this number is probably limited by the light scattering/reflection from the vacuum wall.

HEBT LASER EMITTANCE SCANNER

Measurement of transverse emittances at the SNS HEBT is of essential importance for both the evaluation of the existing 1GeV/1MW H^- beam and the planning for the upgrade project which aims at a beam energy/power of 1.4GeV/3MW. The HEBT emittance measurement system is divided into two sections: a laser based scanning slit in the beam path and a wire scanner in the linac beam dump line for the emittance profile measurement. In this way, we can measure the transverse emitttances of an operational H^- beam right before the accumulation ring at a parasitic manner.

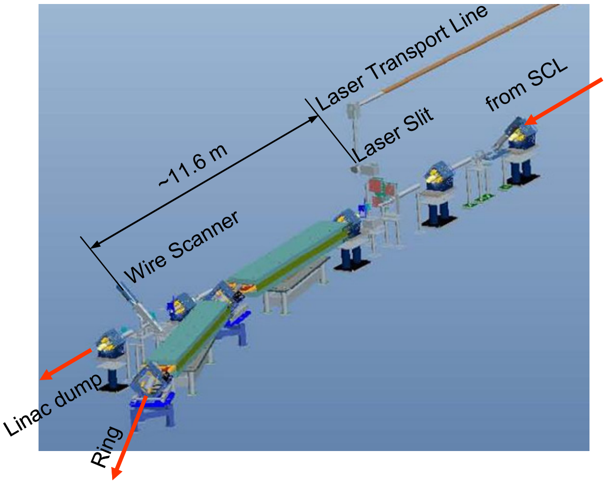

Figure 4: Schematic of HEBT laser transverse emittance scanner.

The current laser emittance measurement setup uses the same light source of the SCL laser wire system. Figure 4 shows a diagram of the system. The laser wire scanning slit is located about 45 meters away from the laser source. The scanning station has an identical design to that of the laser wire system. The laser beam has a diameter of about 2 cm on the surface of the focusing lens which consequently focuses the laser beam to a narrow slit with a diameter of a few tens of micrometers. The wire scanner is about 11.6 meters away from the laser slit. The neutralized H^0 beam is intercepted with a 50 um diameter titanium wire and the stripped electrons are detected by a Faraday cup through a collection magnetic field, similar to the detection in the laser wire stations.

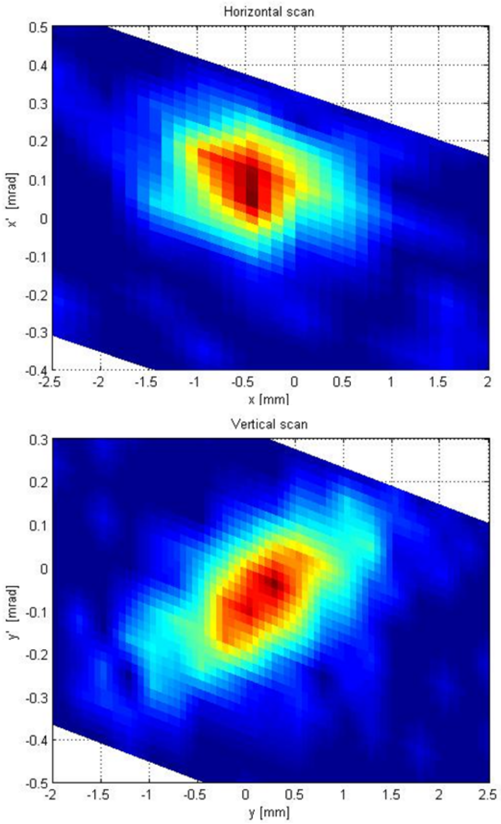

Figure 5: Laser emittance measurement results.

The entire system was completed during the winter shutdown period of 2011. The system has been tested using the H^- beam at different power levels up to the operational power. In a typical measurement, we park the wire scanner at a certain position and scan the laser beam across the region of interest. The output from the Faraday cup after the wire scanner is recorded for each point. A preliminary measurement result is shown in Fig. 5. A self-consistency check has been run to verify the reliability of the measured emittance. The present detection scheme imposes a constraint on the thickness of the wire and therefore limits the number of liberated electrons. Future work is needed to improve the detection efficiency and the dynamic range.

MEBT LASER BUNCH SHAPE MONITOR

The laser bunch shape monitor (LBSM) measures the longitudinal profile of an H^- beam in almost the same way that a sampling oscilloscope measures high frequency signals. In the LBSM designed at SNS MEBT, a train of short pulses of light from a mode-locked laser synchronized to the 5th sub-harmonic of 402.5MHz (SNS beam frequency) interacts with every 5th micro-bunch of the 2.5 MeV H^- beam and strips a small portion of electrons from each pulse. The detached electrons are guided into an electron detector with an electrostatic deflector (operated at ±800 V). The amount of detected charge is proportional to the ion density within the light-ion interaction region. By scanning the laser phase with respect to the linac clock, the longitudinal bunch shape of the ion beam is reproduced. A schematic of the system is shown in Fig. 6.

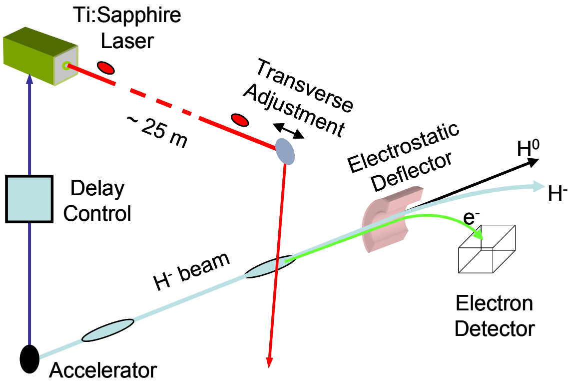

Figure 6: Schematic of MEBT laser bunch shape monitor.

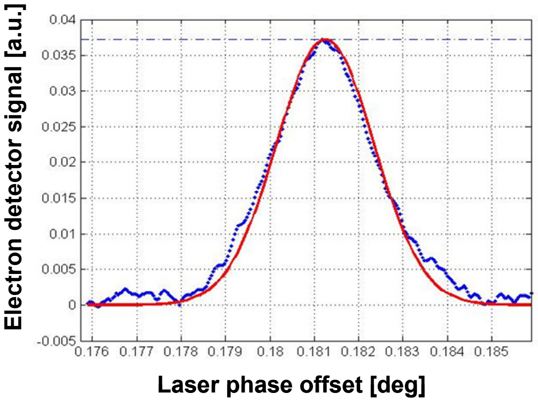

Figure 7: Preliminary bunch shape measurement result using a mode-locked laser. The measured pulse width is about 110 ps.

The principle of measurement has been verified in preliminary experiments [5]. An example is shown in Fig. 7. The laser used in the experiment is a mode-locked Ti:Sapphire laser with the pulse width measured to be ~2.5 ps. The timing jitter of the laser was measured to be around 1 ps when locked to the external 80.5 MHz signal. Currently two options of laser beam transport are studied. The first one is to use a series of relay mirrors to deliver the laser beam to the measurement site. The drawback of this free space transport line is that the laser beam suffers from instabilities due to mechanical vibration. An alternative approach is to use an optical fiber to deliver the laser beam. This approach is currently explored in the laboratory, and the launch efficiency, pulse width broadening, and beam quality of the fiber transmission are experimentally investigated.

DISCUSSIONS

While basic investigation and laboratory stage demonstration of the laser based beam diagnostics have been conducted over a decade [6,7], only very few systems have reached an operational level of application. The primary challenge in the development of such diagnostics is to obtain stability of laser beam through a sound design of optical transport line, a reliable control, and a high level automation of the system in an accelerator environment that accompanies radiation risk and prohibits normal access to the system during the operation. In the following, we discuss a number of technical challenges in the implementation of laser based diagnostics.

Laser Beam Pointing Stability

Variations in laser beam position can be a serious problem in experiments employing laser-based diagnostics. In some cases, the laser beam has to be delivered to the measurement station through a long transport line and even a small drift can cause the laser beam to miss the downstream optics. Therefore, stabilization of the laser beam with a feedback system is essential. In the SNS laser wire and laser emittance system, an active stabilization scheme has been implemented to help in this regard [8]. The laser beam is steered by a mirror mounted on a piezo tilt platform which works at frequencies of 100 Hz or above. Meanwhile, the laser beam position is monitored by multiple Gigabit Ethernet cameras along the transport line. The images from those cameras are analyzed to extract the laser beam center position which, after comparing with the reference position, generates an error signal that is sent as feedback to the piezo controller to stabilize the laser beam position. 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 (~250 m from laser).

Laser Safety

In all laser based diagnostics systems, the laser beam is completely enclosed in a 4” tube through the LTL. Laser operation safety is reinforced by remote access protection (which disables laser operation or blocks the laser beam when the beam pipe is opened) in addition to the standard operational procedure system. The maximum possible optical intensity delivered on the surfaces of all optics including the vacuum window is kept an order of magnitude lower than the damage threshold. However, on a few occasions, we spotted abnormal vacuum readings caused by the laser beam hitting the edge of the vacuum window. We conducted a series of investigations on this issue and found out that the abnormal readings were due to the desorption of dusts or adhesive impurities on the windows by the laser beam. As a result, such abnormal readings occur mainly when the first few laser pulses hit the edge of the vacuum window.

Influence of Radiation

Radiation countermeasure is critical for operating in a high energy hadron accelerator. In our system, all the optics, stepper motors, actuators, power meters, cameras and electronics are enclosed within quarter-inch thick stainless steel boxes. Within the past 5 years, we have not identified any radiation-caused failure to the coating of optics, stepper motors (Ultra Motion D-B.125), motorized flippers (New Focus 8892) which are installed in close proximity to the H^- beam line. For the power meter heads (Ophir L50(150A)) and Gigabit Ethernet cameras (Prosilica GE640) which are installed about 5 feet away from the H^- beam line, only one camera (of the total 4) was not functioning properly due to possible radiation damage. For the picomotor actuators installed 5 feet away from the beam line, we found out the open-loop model (New Focus 8301) survived the radiation while the closed loop model (New Focus 8310) was more vulnerable to radiation due to the damage of its encoder. In the previous design of the laser emittance measurement system [9], a compact Q-switched laser system (Big Sky U1064-HN) was installed inside the HEBT tunnel next to the measurement station. The laser driver (ICE450) was found to be radiation damaged within the first few days after the installation. It is not clear whether the laser head is more radiation resilient.

CONCLUSION

We have described the system configuration, commissioning results, and the present status of three types of laser based H^- beam diagnostics developed at SNS. Compared with conventional beam diagnostics methods, the laser based technology reduces the risk of cavity contamination, permits measurements on the production beam, offers advantages in speed, resolution, and flexibility. The commissioning experience at SNS strongly suggests that the laser based ion beam diagnostics can be brought to operational level of application with careful design and engineering effort. We expect more laser based diagnostics tools will be applied to accelerator facilities as a result of the exploitation of the fast growing laser technology.

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