LASER WIRE BEAM PROFILE MONITOR AT SNS*

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Abstract

We report the experimental implementation, measurement results and analysis of the hydrogen ion (H^-) beam profile diagnostics with a laser wire in the spallation neutron source (SNS) superconducting linear accelerator at the Oak Ridge National Laboratory. The advantages of the laser beam profile monitor at SNS include non-invasive measurement, longitudinal beam scan over minipulses, and the capability of measuring H^- beam profiles over multiple energy levels (200 MeV - 1 GeV) using a single laser source.

INTRODUCTION

The superconducting linear accelerator (SCL) at the SNS accelerates the negative hydrogen ion (H^-) beam pulse from 187 MeV to 1 GeV with a peak beam current of 38 mA [1]. For the diagnostics of high-brightness particle beams as necessary for the SNS, nondestructive methods have to be developed [2].

Since the outer electron of H^- is bound only by 0.75 eV, photons with an energy above this threshold level can be used to partially neutralize H^- beams. This property can be exploited to determine the transverse phase space distribution with high time and space resolutions. The interaction of laser light and H^- ions detaches a small number of electrons which are separated magnetically from the rest of the beam and are measured by an electron detector. We call such a laser-based measurement system a laser wire in comparison with the physical carbon wire. The main merits of the laser wire over a solid wire scanner are that it does not use a physical wire that could contaminate the superconducting surface and it can operate at full operational H^- beam power.

LASER WIRE SYSTEM SETUP

Figure 1 shows an outline of the entire laser wire system. The SNS SCL consists of 23 cryomodules which boosts the H^- energy from 187 MeV to 1 GeV. There are 9 laser wire (LW) stations installed along the SCL beam line. The first four LW stations are installed after the first four cryomodules (each cryomodule drives three medium-beta cavities), the next four LW stations are located after cryomodules 12-15 (each drives four high-beta cavities), and the last LW station is placed at the end of the SCL. The LW stations are arranged so that the H^- beam at different energy levels (200 MeV – 1 GeV) can be measured.

In our system, a Q-switched Nd:YAG laser operating at 1.06 um is used as the light source. The laser has a repetition rate of 30 Hz and a pulse width of 7 ns. The laser pulse energy is controlled by a set of polarization optics elements and typical pulse energy level is 50 - 200 mJ. Using a Q-switched laser source will provide enough pulse energy within a short time period so that a sufficient number of electrons can be detached, which significantly increases the detection efficiency and accuracy.

The laser is located outside the SCL tunnel and the laser beam is directed by mirrors through the laser transport line (LTL) pipe to one of the 9 LW stations. Along the LTL path, three cameras are installed to monitor the position of the laser beam. The first camera is installed at the entrance of the linac tunnel and the cameras 2 and 3 are located at about 125 m and 210 m away from the tunnel entrance, respectively. The mirror at the entrance box is controlled in both axes with a feedback signal from cameras 2 or 3 to stabilize the beam position. At the end of the LTL pipe, a power meter is

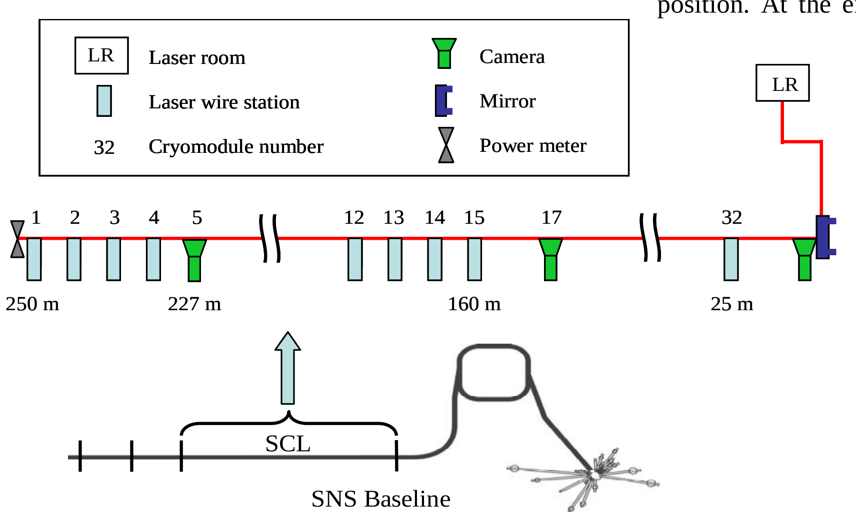

Figure1: Outline of the laser wire system installed in the SNS superconducting linac. Distances in the figure are from the laser room.

*This manuscript has been authored by UT-Battelle, LLC, under contract DE-AC05-96OR22464 with the U.S. Department of Energy.
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installed to show the laser power propagation efficiency through the pipe. All cameras, mirror actuators, power controller, and power meters are network controllable and accessible from the SNS central control room.

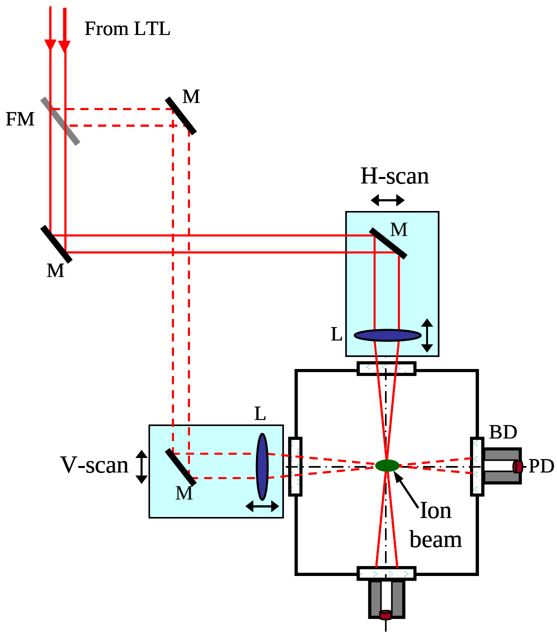

Figure 2: Schematic of laser wire station. L: lens (*f*=200 mm), M: mirror, FM: flip-mirror, BD: beam dump, PD: photodiode.

Figure 2 shows a schematic of a LW station. Each station contains a light pick-up box where a motorized mirror slides in and out of the LTL path to pick-up or unblock the laser beam, a beam division box where a flip-mirror is controlled to be 'IN' and "OUT" to switch the laser beam between horizontal and vertical scans, and two beam scan boxes. Inside each beam scan box, two motorized linear stages are installed with the first stage adjusting the position of the focus lens while the second one performing the scan of the laser beam across the ion beam. The laser beam enters the vacuum chamber through a vacuum window (laser port) and interacts with the ion beam at the focal plane of the laser beam. After the interaction, the laser beam is blocked by a beam dump. A photodiode is installed at the center of the beam dump to receive a small portion of the laser beam. The photodiode output is used for laser beam alignment and also gives an indication signal of laser beam presence during the operation.

MEASUREMENT RESULTS

In parallel with the hardware implementation, an operational software platform has been developed. The software control program allows the user to interact with the control and data collection as a single instrument that can make measurements in different locations along the SCL. The user can specify LW station, scan axis, lens position, collecting magnet field strength, linear resolution, and number of samples at each position of the profile desired. Recent improvements in the software have raised the sample rate from 1 Hz to near 15 Hz, allowing more detailed scans to be completed in a reasonable time.

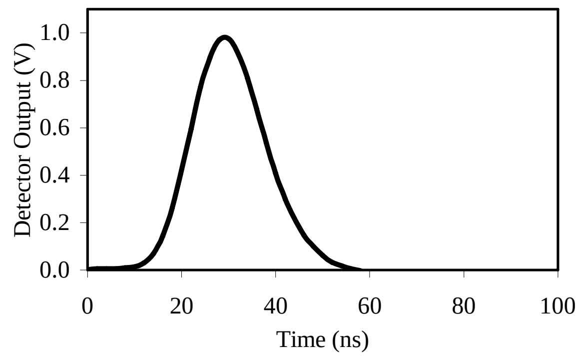

Figure 3: Raw signal from the electron detector.

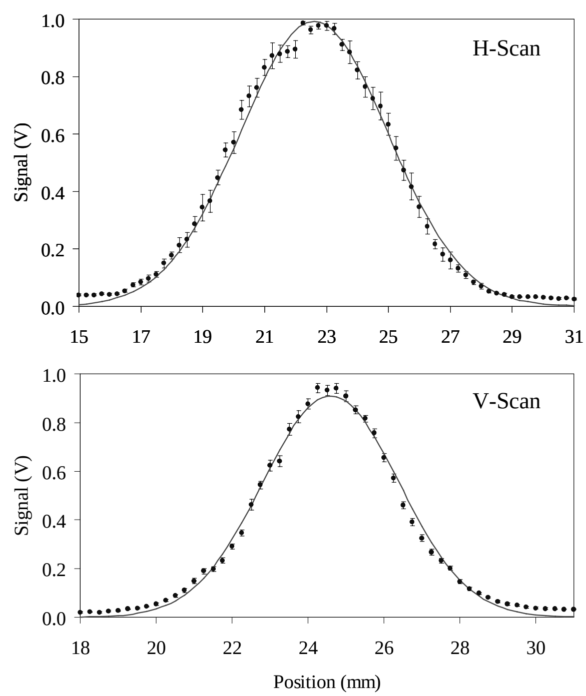

Figure 4: Typical profile measurement at LW14. Dots are measurement data and lines are Gaussian fitting.

Figure 3 shows the raw signal detected by the Faraday cup. The detector output is averaged over a few tens of nanoseconds. The peak value or the area integration corresponds to the electron number detached by the laser beam. We verified that those two quantities match each other to a high accuracy. By scanning the position of the laser wire across the ion beam, a peak shape of signal rate is obtained as a function of the laser beam position. Figure 4 shows a measurement of the beam profile at an ion beam energy of 550 MeV. The measured signal is averaged over many laser shots to account for time jitter.

The temporal structure of the ion beam at the SNS linac consists of 50 ps long micropulses separated by ~2.5 ns and gated into minipulses of about 650 ns long. The minipulses repeat at 1.058 MHz and are bunched into one macropulse at a length of 1 ms. The SCL produces such 1 ms long, 38 mA peak macropulses at a repetition rate up to 60 Hz for accumulation in the ring [1]. An advantage of using laser wire is its capability of longitudinal scan, i.e., to measure beam profiles at different macro-/minipulses or even different segments within one minipulse. This is achieved by controlling the laser timing. In our system, the firing of the laser flash lamps is delayed relative to a precursor signal for the macropulse. The laser Q-switch trigger is delayed relative to the lamp firing and synchronized with a micropulse signal. Figure 5 shows an example of longitudinal beam scan among a single minipulse. The measurement shows large changes of the beam parameters at both edges of the minipulse as well as a slight shift of the beam position within the pulse. There is also In principle it is possible to address each individual micropulse by using laser pulses with a pulse width of less than 2.5 ns and controlling the laser pulse timing at a nanosecond resolution.

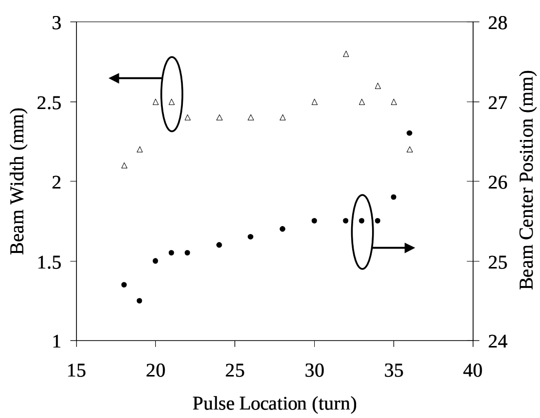

Figure 5: Ion beam size/position scanning at different segments of a single minipulse. 1 turn = 30 ns.

DISCUSSIONS

Using the numerical modeling developed before [3], we have conducted a detailed theoretical analysis of the photo-neutralization process by including the realistic laser beam profile, laser beam propagation and collimation, and spatial stability. At a laser pulse energy of 100 mJ, the photodetachment efficiency is calculated to be about 5% for a 1 GeV ion beam and 7.5% for a 200 MeV ion beam. Previous work [4] indicated that the laser beam size at the interaction point has a significant effect on the measurement performance. Specifically, in the case when the laser beam waist is too small, the Rayleigh range would become smaller than the ion beam size and this will cause unfolding of the ion beam size. In our case, such effect is negligible since the ion beam size is within millimeter range which is much larger than the focused laser beam size (10-50 um). Our calculations demonstrated that the laser beam size can be changed within three orders of magnitude without any noticeable outcome to the measured profile.

On the other hand, due to a very long LTL path, the laser beam pointing instability becomes a critical factor to the measurement performance. Two types of laser beam instabilities exist in our system: fast instabilities due to inherent laser pulse shot-to-shot variations and slow drifts due to mechanical/thermal effects along the LTL. Such beam instabilities, in particular the fast variations, can cause significant measurement errors. Our study indicates that this effect can be suppressed by optimizing the position of the focus lens, i.e., the focal plane location inside the chamber. Figure 6 shows the calculated results of the beam size measurement error (in unit of the nominal ion beam width σ) caused by the laser beam instability as a function of the defocus amount (in unit of the focal length) of the lens. Here we assumed the center of the laser beam fluctuates randomly within 1 cm on the surface of the lens. It is clear that the effects of the laser beam instabilities can be effectively trimmed down by focusing the laser beam at the center of the ion beam path. Details of the simulation will be reported elsewhere.

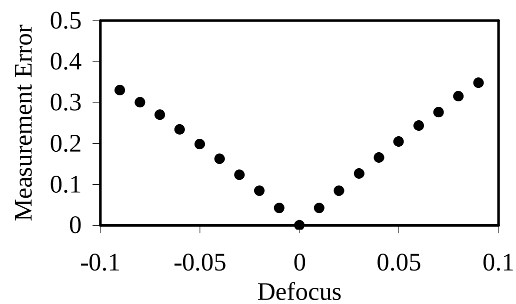

Figure 6: Calculated result of the beam size measurement error caused by the laser beam instability as a function of the lens defocus.

SUMMARY

We have described a laser wire beam profile diagnostics system implemented in the SNS superconducting linear accelerator. The system measures hydrogen ion beam profile at 9 locations corresponding to different energy levels from 200 MeV to 1 GeV by using a single Q-switched laser source. With this setup, it became possible to separately measure the size of an individual minipulse or different segments within one minipulse.

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