TIME-RESOLVED H$^-$ BEAM EMITTANCE MEASUREMENT AT THE SNS LINAC USING A LASER COMB*

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Abstract

We proposed and demonstrated a novel technique to measure time-resolved transverse emittances of the hydrogen ion (H$^-$) beam in a 1-GeV high-power accelerator. The measurement is performed in a nonintrusive manner by using a laser comb – laser pulses with controllable multilayer temporal structure. The technique has been applied to the transverse emittance measurement of 1-GeV H$^-$ beam at the Spallation Neutron Source (SNS) high energy beam transport (HEBT). More than 20 time-resolved emittances have been simultaneously measured within a macro-pulse, a single mini-pulse, or a single bunch of the 1.4-MW neutron production H$^-$ beam from one measurement.

INTRODUCTION

Emittance measurement is an important diagnostics for improvement of beam halo and beam loss in the particle accelerator [1]. At the Spallation Neutron Source (SNS) accelerator, laser-based nonintrusive beam emittance measurement has been implemented for the H$^-$ beam diagnostics [2]. A schematic of the measurement setup is shown Fig. 1. It is in principle a slit-detector emittance scanner except that the conventional slit is replaced by a focused laser beam (laser wire). A pulsed laser beam is used to photo-detach a small portion of the H$^-$ beam, creating a slice of the H^0 beam. The H^0 slice is separated from the main beam path and interacts with a metal wire scanner that detaches the electron from the hydrogen atoms. Scanning of laser beam and metal wire positions provide the position and divergence angle of the H^0 slice, which can be used to reconstruct the transverse phase space information of the H^0 beam. As the H^0 beam preserves the same emittance of the original H$^-$ beam, the measurement leads to the determination of the H$^-$ beam emittance. The laser-based measurement is nonintrusive and has been routinely used to diagnose the neutron production H$^-$ beam.

The neutron production H$^-$ beam in the SNS accelerator has a complicated time structure spanning a range from picoseconds to a millisecond. A time-resolved emittance measurement can be used to study emittance variations along the macro-pulse, within a single turn or a single micro-bunch of the operational H$^-$ beam. Such a capability is valuable for precise interpretation of the measured transverse emittance, meaningful comparison between measurement and simulation, or comparison between measurements at different locations. In this work, we propose and experimentally demonstrate that, by taking advantage of multi-layer temporal structures in both ion and laser beams and properly controlling the phase between them, one can simultaneously measure multiple emittance slices within a macro-pulse, a single turn, or a single micro-bunch of an operational H$^-$ beam from a single scan.

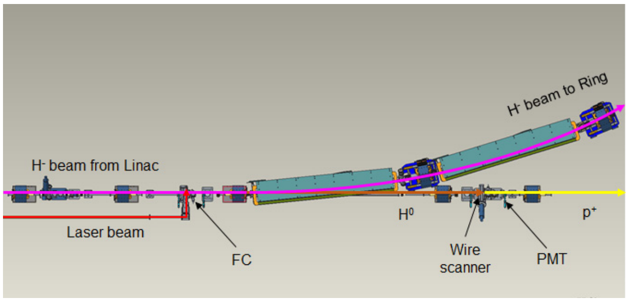

Figure 1: Layout laser-based emittance measurement setup at the SNS linac.

MEASUREMENT PRINCIPLE AND INSTRUMENTATION

A laser comb in this work refers to laser pulses containing multi-layer temporal structure with a controllable pulse width and pulse spacing. The principle of the beam diagnostics using a laser comb is illustrated in Fig. 2 with the SNS H$^-$ beam waveforms as a reference. A typical laser comb used in the experiment contains 20 - 30 pulse packets (comb teeth) with a controllable comb span and repetition rate of comb teeth. The laser comb is synchronized with the H$^-$ beam macro-pulse and has a repetition rate of 30 Hz in this work. Each comb tooth contains micro-pulses which are phase locked to the H$^-$ beam bunches. During the emittance measurement, individual laser comb teeth interact with different time sheets of the H$^-$ beam and create time-resolved H^0 beam slits. The detection is gated to the laser comb so that the detector outputs from individual temporal slices of the H$^-$ beam are properly processed to reconstruct the time-resolved emittances.

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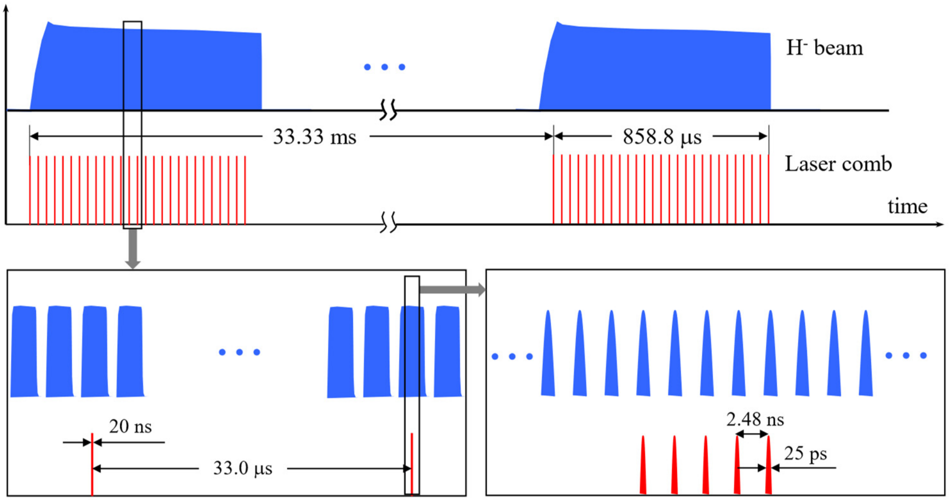

Figure 2: Temporal structure of the laser comb used for H- beam diagnostics. Top: baseline of H- beam macro-pulse at 60 Hz and laser comb macro-pulses at 30 Hz in this work. Bottom left: waveforms of H- beam mini-pulses and laser comb teeth. Bottom right: waveforms of H- beam bunches and micro-pulses inside a laser comb tooth.

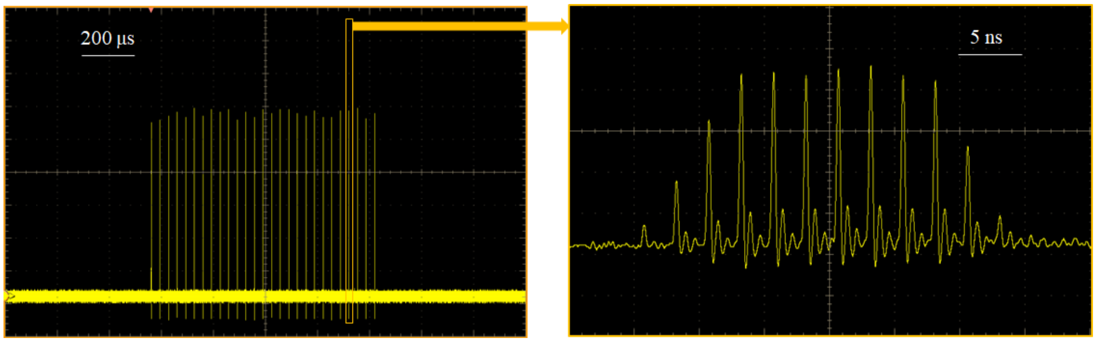

Figure 3: Temporal structure of the laser comb. Left: laser comb with a comb span of 35 mini-pulses (~ 33 us) consisting of 27 comb teeth. Laser comb repeats at 30 Hz in the used in the H- beam diagnostics. Right: micro-pulses within individual laser comb tooth.

The laser comb is generated from a customized hybrid fiber-solid state laser system at a master oscillator power amplifier (MOPA) configuration which consists of a seed laser, a fiber-based preamplifier, pulse picker, and solid-state based power amplifiers [3]. A typical waveform of the light output from the final amplifier is shown in Fig. 3. Peak power of a few megawatts is normally used in the measurements.

MEASUREMENT RESULTS

The emittance measurement is conducted at the HEBT section of the SNS accelerator. The laser is placed outside the accelerator tunnel and the laser beam is delivered to the measurement station through a ~ 60-meter long free-space laser transport line. Figure 4 shows typical emittance plots of the 1.4 MW neutron production H- beam measured using a laser wire.

For emittance measurement using laser combs, both the Faraday cup and PMT output signals are digitized using a National Instruments (NI) PCI-5124 card at a sampling rate of 200 mega samples/sec. A revised data acquisition driver scheme has been developed to accommodate laser combs with a large span. The modification and additional code optimizations were able to reduce the overhead and allow laser comb data processing to proceed at up to 60 Hz (repetition rate of the SNS H- beam macro-pulses) of laser triggering.

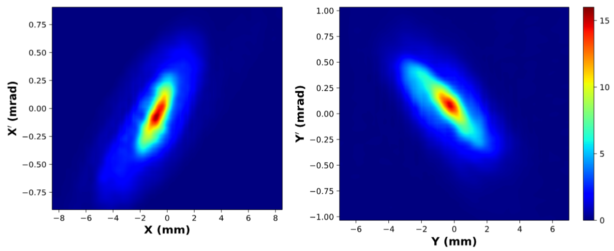

Figure 4: Typical emittance plots of 1.4 MW neutron production H- beam measured with laser wire.

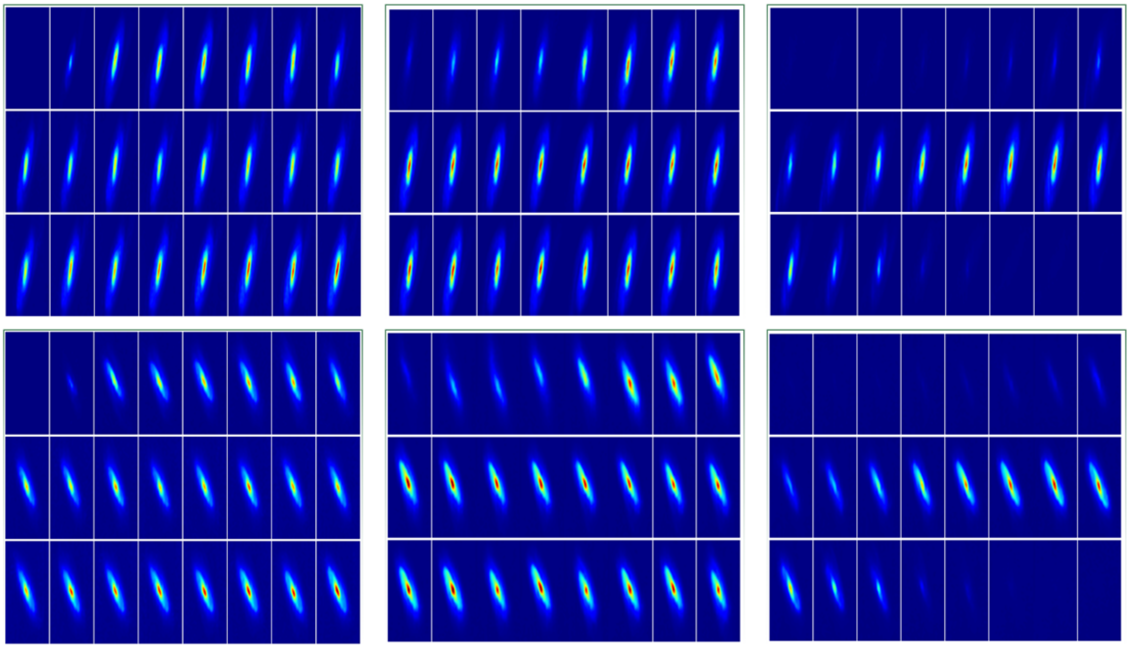

Figure 5: 24 slices of horizontal (top) and vertical (bottom) emittances simultaneously measured over the ramp-up region of a macro-pulse (left column), a single turn (center column), and a single bunch (right column) of 1.4 MW neutron production H$^-$ beam. The time spacing is 4.7 µs, 3.3 ns, and 20 ps for three measurements, respectively.

In Fig. 5, we list three examples of time-resolved emittance measurement using laser combs. In each case, a total of 24 emittances were obtained from a single scan. The left column in Fig. 5 shows emittances measured over the ramp-up region of the H$^-$ beam which consistes of a continuous expansion of the mini-pulse duration at the beginning of a macro-pulse. The laser comb used in this measurement consists of 24 comb teeth with a spacing of ~ 4.7 µs (equivalent to 5 mini-pulses) while each laser comb tooth contains 9 micro-pulses which are in-phase with the micro-bunches of the H$^-$ beam. We calculated the integrated beam intensity and Twiss parameters from the measured phase space data. As expected, the beam intensity shows a fast surge at the beginning of the beam ramp-up. The emittance values show a quick growth during the first 20 mini-pulses and stabilize after the ramp-up.

The center column in Fig. 5 shows the time-resolved emittance measurement performed over a single mini-pulse, or a single turn of the H$^-$ beam by properly shifting the comb teeth frequency from the H$^-$ beam mini-pulse frequency. Here, the laser comb teeth repetition rate is set to 30.273 kHz which is 3 Hz lower than the 35th sub-harmonic of the H$^-$ beam mini-pulse frequency. As a result, each laser comb tooth interacts with the H$^-$ beam mini-pulse at 3.3 ns later than its predecessor.

Finally, we show the time-resolved phase space measurement over a single bunch of the H$^-$ beam in the right column of Fig. 5. The phase of the micro-pulses inside the laser comb teeth is achieved by modulating the phase delay between the seed laser and the RF reference of the H$^-$ beam. As a result, each laser comb tooth will interact with the H$^-$ beam at a different phase relationship in the micro-pulse (bunch) level. Since the phase scanning rate is very small (~ 10^{-6}), we can well assume that all micro-pulses inside one laser comb tooth are interacting with the H$^-$ beam bunches at the same phase delay. The measurement results clearly show a continuous variation of the intensity from the rising edge to the falling edge of the H$^-$ beam bunch.

CONCLUSION

We have described a novel technique of time-resolved emittance measurement of the H$^-$ beam by using a laser comb. The proposed technique has been applied to the emittance measurement on the 1-GeV, 1.4-MW neutron production H$^-$ beam at the SNS high energy beam transport. We have experimentally demonstrated that more than 20 slices of emittances over a macro-pulse, a single mini-pulse, or even a single bunch of the H$^-$ beam can be simultaneously obtained. Our experiment strongly supports that the laser-based nonintrusive beam diagnostics can provide unique information about the high-energy, high-power particle beam.

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